An LCA approach for determining the carbon farming potential of the Mediterranean viticulture and the effect on grape quality

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Abstract

Carbon (C) storage and capture in soils along with a reduction of farm-related GHG emissions are key processes for climate change mitigation. There is a growing global interest to assess the C sequestration potential of important crops, such as vines (*Vitis vinifera*) due to their importance to the global economy, but in many cases emissions due to inputs production and grape quality are neglected. In this work, the potential of Mediterranean viticulture for GHG emissions mitigation and C storage in biomass and soil is examined, using as a model the indigenous cultivar Xynisteri in vineyards on the island of Cyprus. The C balance was determined at vine and vineyard levels, as well as vine-grape quality attributes, under different management practices. A tool for GHG emissions estimation in vineyards was produced, based on the Cool Farm Tool and the relevant literature for perennial crops. The tool was designed to be easily used by the farmers and support the implementation of C farming, using the LCA approach and also incorporating nutrient cycling (e.g., C, N). Our results show that existing conventional viticulture could be easily transformed into zero-emissions viticulture via smart agricultural practices such as reducing N fertilizers, in line with the Farm to Fork Strategy, using less fuel while adopting no-tillage and maintaining field margin vegetation at the farm level. This study stresses the importance of the LCA use when dealing with C sequestration projects. It shows that a reduction of farm inputs could lead to a (non-irrigated) vineyard low-input~~s~~ system supporting firstly, a lifetime C storage equal to 25.124 tons CO_2-eq ha^{-1} or 0.837 tons CO_2-eq ha^{-1} $year^{-1}$, and secondly assisting in climate change mitigation and adaptation for Mediterranean viticulture. This approach could be used for the design of eco-schemes related to C farming, under the new Common Agricultural Policy (CAP).

1. Introduction

Agriculture, forestry and other land uses (AFOLU) are linked to food, feed and timber production. The greenhouse gas (GHG) emissions from this sector at the global scale are equal to 21% of the total emissions (12 $GtCO_2eq$) (Lamb et al., 2021). The AFOLU sector emissions increased at a 3% annual rate since 2010 (Lamb et al., 2021), basically due to land use changes and soil management that favours organic material decomposition (e.g., tillage). Carbon (C) storage in soils has been identified as a key process for emissions mitigation (Chabbi et al., 2017; Paustian et al., 2019; COWI, 2021; Mattila et al., 2022). It can be achieved with carbon farming which deals with the management of carbon pools, flows and GHG fluxes at the farm level, to mitigate climate change (COWI, 2021). However, there are important knowledge gaps, related to the nature and decomposition rates of organic materials to be used (Lehmann and Kleber, 2015), as well as technical and socio-economic aspects (Poulton et al., 2018). The well-known global initiative “4 per 1000”, targets to 0.4% increase in soil organic carbon annually (Chenu et al., 2019; Mattila et al., 2022). Nevertheless, increasing organic material in the soil might lead to altering the nutrient balance in the agricultural soils and disrupt plant nutrition (e.g., C/N balance, N and P availability) (van Groenigen et al., 2017). Despite open questions for further research, there is strong interest in promoting C farming in practice (Chabbi et al., 2017).

In the EU, the European Green Deal, the Farm to Fork Strategy and the Circular Economy Package make clear that the AFOLU sector needs more and better incentives for managing carbon, to drive the necessary transformational change towards 2050. Additionally, carbon farming is included in the Member States’ CAP (Common Agriculture Policy) Strategic Plans. Common and clear rules for monitoring, reporting and verification and the use of the results from carbon farming activities will be also crucial for reducing GHG emissions from the food production sector (Montanarella and Panagos, 2021). In addition, the system should be studied from cradle to grave as C storage in the soil could be linked to high emissions for inputs production, energy and water use. On the other hand, strengthening farmers' knowledge of soil and land management is essential for successful soil C management (Ingram, 2008; Mattila et al., 2022). Moreover, farm advisors should be able to incorporate recent scientific findings into farm management practices (COWI, 2021). In Table S1 (supplementary material), examples of mitigation actions at the farm level to manage carbon and GHG fluxes are presented. Equally important, farmers’ goals and ambitions might be far away from promoting C storage (Mattila et al., 2022). Initiatives, such as 4-per-1000, should work on a global level, requiring approx. 570 million (10^6) farms to participate, with 94% of these~~,~~ smaller than 5 ha~~ to participate~~ (Lowder et al., 2016). The magnitude of the aforementioned C initiatives makes it imperative to find collaboration networks of farms transitioning to C farming (Mattila et al., 2022).

Viticulture has global importance in terms of land use with 7.45 Mha of vineyards globally (Payen et al., 2021). At the EU level, member states hold a 63% share of the global wine production (OIV, 2019), followed by the USA, Argentina, and Australia. The area of vineyards in the EU is approx. 3 million ha and the wine trade balance was about 12 billion euros in 2018 (OIV, 2019). Due to its global distribution, viticulture could significantly contribute to the global efforts to offset atmospheric greenhouse gas concentrations via C sequestration to mitigate climate change (Payen et al., 2021). An average C sequestration rate reported in the literature is 7.53 Mg CO2-eq ha^{-1} yr^{-1} to a soil depth of 30 cm (Payen et al., 2021). Most of the research however is conducted in the top producing countries (e.g., Spain, Italy, France) where high input~~s~~ viticulture is typically applied and irrigation is also practiced, which favours biomass production. Research on C sequestration in non-irrigated viticulture located in semi-arid climates and islands is missing. Moreover, using an LCA approach to account for the GHG emissions due to the inputs used provides a more holistic view, as high C sequestration could be linked to high GHG emissions due to fuel, fertilizer and machinery use. What is also understudied is the contribution of field margins in C storage, which is also important for soil health and biodiversity conservation. Finally, although there is a lot of published work on GHG emissions and C storage in farming systems, the effect of the management practices on product quality (e.g., grape quality) is typically ignored.

Commented [AH1]: Please check… as this seems impossible for soil alone but is possible with woodland if both soil C and above ground biomass are considered.. As mineral soils are around 140Mg C per ton in grassland and forest this coil C sequestration rate would not be for long.

Additionally, provided that the majority of the vine-growers need support to implement C farming, a tool to guide them in the selection of management practices that reduce GHG emissions and enhance C storage in soil and biomass could be needed. Global initiatives with a strong scientific basis, such as the Cool Farm Alliance (https://coolfarmtool.org/) and the Cool Farm Tool (CFT) could be employed for the shift towards C farming. The CFT is a scientifically based GHG, water and biodiversity calculator for farmers (Hillier et al., 2011). It has been proved to be one of the best farm-focused GHGs calculators (Whittaker et al., 2013). The tool is currently not fully appropriate for calculations in perennial crops.

In Cyprus, as in most Mediterranean countries, viticulture and winemaking are essential for the economy and rural development (Zomeni et al., 2018; Litskas et al., 2020). Most vineyards on the island are located in high nature value farmland (HNVf) areas, i.e., agricultural areas important for the conservation of species and habitats of EU importance (Zomeni et al., 2018). Climate change and vineyard abandonment are considered long term threats to viticulture on the island (Chrysargyris et al., 2018a, 2018b). Soil degradation and desertification are threatening soil resources. Therefore, soil and farm management towards C storage is important for the sustainability of agriculture on the island. Currently, even if organic material is occasionally applied in the vineyards (animal manure in most cases), the farmers are not familiar with C farming and they lack the know-how to implement such schemes. Moreover, the Eastern Mediterranean and the Middle East are global climate change ‘hot spots’ based on the results of global climate models (Lelieveld et al., 2016; Lange, 2019). In this framework, viticulture in the island will be impacted and the cultivation of indigenous vine cultivars, such as Mavro, Xynisteri and Maratheftiko, is very important in terms of adaptation to climate change, as they are more suited for the dry environment of the island and require fewer inputs (e.g., water, fertilizers~~) in comparison to~~) than the introduced international varieties, including Cabernet Sauvignon or Thompson seedless table grapes (Litskas et al., 2017).

Additionally, changes in tillage practices and inputs for viticulture required to apply C farming might affect plant physiology, growth and production as well as qualitative characteristics, such as polyphenols and antioxidants content. Polyphenols' composition and their concentration in grapes and wines are influenced by different factors including grape variety, edaphoclimatic conditions~~,~~ and cultivation practices (Chrysargyris et al., 2018a). Tannins are naturally occurring compounds that exist inside grape skins, seeds and stems. Tannins are complex polymeric compounds that are responsible at least in part for many of the sensory attributes of wines, particularly red wines. They also work as antioxidants and protect the wine from quality deterioration (Chrysargyris et al., 2018a). The composition of these compounds in grapes depends on many factors, including grape variety, water status, and other environmental/climatic ~~variability~~variables.

To contribute to the research in semi-arid and island areas, this study investigated the potential for C storage and GHG emissions reduction in Mediterranean viticulture, using the island of Cyprus and the indigenous variety Xynisteri as models. The objectives were 1) to determine the annual C balance in the vine and the vineyard scale under different management practices, 2) to study the effects of C farming practices on grape quality, 3) to build and test a tool for GHG emissions calculations in vineyards, based on the CFT, 4) explore and propose scenarios for mitigating GHG emissions in the vineyard and to store C to the soil.

2. Materials and Methods

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2.1. Study area

The experimental vineyard of 0.6 ha was located at Pachna, Limassol, Cyprus (34^{o} 46΄ 36΄΄ N 32^{o} 47΄ 54΄΄; Figure 1). The planting density for the bush vines was 2 x 2 m (2500 vines/ha). Soils in the region are classified as Calcaric cambisols and Calcaric regosols (Camera et al., 2017). Climatic attributes during the period April-October 2020, were obtained by a weather station placed in the vineyard. Temperature (average ± Standard Deviation; SD) was 25.6 ^{o}C (±4.8), relative humidity (RH) 41.0 % (±20.7), wind gust 6.6 km/h (±7.2) and prevailing wind direction was SE (Southeast).

Figure 1. Experimental vineyard/study area.

2.2. Experimental design

In the experimental vineyard, 3 treatments were established during the season of October 2019-September 2020:

A: Reduced tillage (once per year at the depth of 40 cm) for organic material incorporation (80% goat manure and 20% winery waste) to replace 50% of the N applied with synthetic fertilizers.

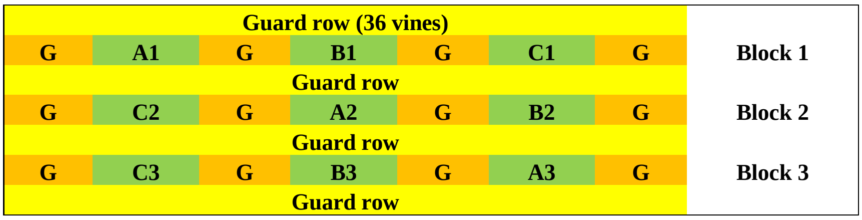
B: Reduced tillage (once per year; 40 cm) for organic material incorporation to replace 100% of the N applied with synthetic fertilizers.

C: Tillage 3 times/year (40 cm) and application of synthetic fertilizer (Control).

More information on the inputs related to these treatments can be obtained in section 2.6 (see Table 3). Treatment C is close to what is typically applied in Xynisteri grapes in Cyprus.

In treatments A and C, the synthetic fertilizer was ammonium sulfate $[(NH_4)_2 SO_4]$ 21-0-0 at a rate of 60 (treat. A) and 120 (treat. C) kg N/ha/year. In treatments A and B, organic fertilizer was applied to supply 60 and 120 kg N/ha/year, respectively. Organic fertilizer properties are provided in section 2.3.2. The application of K and P synthetic fertilizers was not considered in this study.

The experimental design is presented in Figure 2. Therefore, three blocks containing 36 vines each, in a straight row, were established. In each block, 3 plots of 8 vines (each plot) were the 3 different treatments (A, B, C). For each treatment 3 replications (e.g., A1, A2, A3) were established. Among the plots, 3 vine plants (per plot) served as guards (G). In addition, one guard row (36 vines each) was separating the 3 blocks.



Guard row (36 vines)							
G	**A1**	**G**	**B1**	**G**	**C1**	**G**	**Block 1**
Guard row							
G	**C2**	**G**	**A2**	**G**	**B2**	**G**	**Block 2**
Guard row							
G	**C3**	**G**	**B3**	**G**	**A3**	**G**	**Block 3**
Guard row							

Figure 2. Experimental design. In each block, the orange (G) represents 3 vine guards (a total of 12) and among them, the 3 treatments (A, B, C) are placed (8 vines per treatment). Among the blocks, guard rows were established (36 vines).

2.3. Soil, fertilizer properties and C balance determination

2.3.1 Soil properties

The soil properties were determined before the experiment, after samplings were conducted in September 2019. Therefore, six composite soil samples were collected from the experimental vineyard, at a soil depth of 40 cm to determine physicochemical parameters. The soil was immediately (40 minutes) transported to the lab, air-dried and hand-sieved to pass a 2 mm mesh. Equivalent calcium carbonate ($CaCO_3$) was determined using the calcimeter method. Electrical conductivity (EC) and pH were determined according to a 1:1 soil to solution ratio, employing a portable pH/EC-meter (HI 98130 HR, Hanna Instruments, USA). Total nitrogen (N) was determined utilizing Kjeldahl (BUCHI, Digest automat K-439 and Distillation Kjelflex K-360, Switzerland). Soil type (percentage of sand, silt and clay) was measured by the hydrometer method with Bouyoucos scale and organic matter content was determined after the Walkley-Black volumetric method. Phosphorus (P) was determined spectrophotometrically (Multiskan GO, Thermo Fisher Scientific, Vantaa, Finland). Calcium (Ca) and magnesium (Mg) by an atomic absorption spectrophotometer (PG Instruments AA500FG, Leicestershire, UK). In Table 1, soil physicochemical data are provided.

Table 1. Soil physicochemical properties in the experimental vineyard. Average values and standard deviation (n=6) are provided for the composite samples collected from a depth of 0-40 cm.

pH	EC (µS/cm)	Clay (%)	Sand (%)	Silt (%)	OM (%)	OC (%)	N%
7.6 (0.1)	441 (166)	42 (4)	30 (2)	28 (3)	5.8 (0.1)	4.08 (0.26)	0.15 (0.01)
C/N	**%$CaCO_3$**	**N g/kg**	**Na g/kg**	**K g/kg**	**P g/kg**	**Ca g/kg**	**Mg g/kg**
27.2 (1.4)	34.9 (2.2)	1.46 (0.11)	0.12 (0.01)	0.57 (0.08)	0.03 (0.02)	1.82 (0.85)	0.13 (0.02)

OM: Organic Matter; OC: Organic Carbon; EC: Electrical Conductivity.

2.3.2 Fertilizers properties

Synthetic fertilizer was ammonium sulfate [$(NH_4)_2$ SO_4] 21-0-0 and was applied at 60 and 120 kg N/ha in treatments A and C, respectively and it was purchased from a commercial supplier, located in Pachna, Limassol. The organic material used as fertilizer was a mixture of goat manure and winery waste, in an 80/20 ratio. Total organic carbon (TOC) was determined in each of the two materials (4 composite samples each) using the TOC analyzer TOC-VCSH of Shimadzu coupled with Solid Sample Module – 5000A. The DIN EN 13137:2001 (Characterization of Waste. Determination of Total Organic Carbon (TOC) in Waste, Sludges and Sediments) protocol was used for this analysis (ISO 13137, 2013). The other parameters determined in these two materials were: pH, EC (µS/cm) and N%, following the same protocols as those used for the soil samples.

Table 2. Physicochemical properties for the organic material. The average value and standard deviation (n=4) are provided.

pH	**EC (µS/cm)**	**C %**	**N%**	**C/N**
7.52 (0.09)	2833 (221)	47.58 (0.5)	2.66 (0.31)	17.86 (2.59)

2.3.3 Carbon balance determination

2.3.1.1 Vine level

For determining the C balance at the vine level, the following approach was used:

C balance = Inputs – Outputs = (C stored in the above and below-ground biomass) – (Root respiration) (***Equation 1***)

During the growing season of 2020, the above-ground biomass was directly measured by destructive sampling in 9 vines (3 per treatment). The dry weight (dw) of leaves, lateral shoots, primary shoots, and bunches was measured at their final stage of development (end of September for the variety Xynistetri in the Pachna region). The samples were transported to the lab, within one hour after their collection. Then, they were weighed and placed in the oven (60 ^{o}C) until a constant weight was obtained (typically 72-100 h). It was assumed that 50% of the dw is Carbon (Brunori et al., 2016; Ma et al., 2018). Root biomass was quantified in June 2020 after taking soil core samples at a depth of 0-40 cm, in selected areas where the soil was kept free of weeds (by hand) during the growing season. All fine (annual) roots were removed to produce a pooled sample from 4 vines per treatment. In total, 9 root samples (3 pooled samples x 3 replications) were collected. The samples were transported within 45 minutes to the lab, and they were used for root respiration measurements. Then, they were weighed and placed in the oven (60 ^{o}C) until a constant weight was obtained. The C content was considered as 50% of the root dry weight biomass (Brunori et al., 2016; Ma et al., 2018). Total root biomass was calculated considering root renewal in a volume of 0.4 m^3 $vine^{-1}$ (depth 0.40 m; width canopy 1.0 m; length 1.0 m). Therefore, deeper roots were not considered in the calculations. Root respiration (CO_2 production) was determined in the collected root samples using the methodology presented in Chrysargyris et al. (2017) and Brunori et al. (2016). A dual gas analyzer (International Control Analyser Ltd, Kent, UK) was used. The root samples were placed in a plastic container (sealed) at room temperature for 1 h and afterwards, the container's air was withdrawn for 40 s through a hole on the container, whilst recording the % CO_2. The respiration rate was computed according to the volume and weight of the root samples.

2.3.2.2 Vineyard level

For determining the C balance at the vineyard level, the following approach was used:

C balance = Inputs – Outputs = (C stored in the above and below-ground biomass) + (C addition with the organic fertilizer) – (Root respiration) – (Soil respiration) (***Equation 2***)

Litter decomposition (C release) and pruning or other plant residues C were not taken into consideration. C stored in the above/below-ground biomass and root respiration was determined as previously presented (section 2.3.1.1).

The amount of C added with the organic fertilizer was estimated based on its N content to supply the vines according to the requirements of treatments A and B. The N% content of the organic material (Table 2) was 2.66% dry weight (d.w.) To add 0.048 kg N per vine (120 kg N/ha; 2500 vines/ha), 1,805 g of organic material dw were required (=48 x 100/2.66). Since the water content of the organic material was 30% before its application in the vineyard, 2,346 g wet weight (ww) of organic material were applied per vine in the treatment B and half of this (1173 g ww) in treatment A. In our approach, it was assumed that the N release rate from the organic fertilizer is similar to that of the synthetic. According to the C content of the organic material, 0.852 (= 1.805 x 0.4722) and 0.426 kg C (= 1.805 x 0.4722 / 2) were added per vine, in treatment B and A, respectively. The C pool, according to the soil C content and soil bulk density and prior C addition with the organic fertilizer, was estimated to be 19.59 kg C per vine, according to the soil samples analysis (Table 1).

Finally, for determining soil microbial respiration, three treatments were prepared in a 720 ml glass jar (mesocosm), according to the treatments established in the vineyard (A, B, C; see section 2.2) and after using the same soil (300 g dw) and fertilizers (organic and synthetic) as that in the vineyard experiment. Treatments were replicated (x3) and that resulted in 9 mesocosms in total. Mesocosms were rewetted to 20% per dry weight with distilled H_2O and were let to equilibrate for 4 days at 20 ^oC in dark. After that, mesocosms were incubated for 60 days at 20 ^oC. Soil moisture was maintained by adding the required amount of H_2O and headspace gas samples were taken regularly. Headspace CO_2 concentration was determined by attaching an infrared gas monitor (Li800, Li-cor, USA) through headspace fittings attached to an air-tight closed mesocosm. The accumulated CO_2, approx. after 30 mins of mesocosm closure, was converted to an hourly rate (C-CO_2 mg/Kg/h) and interpolated to a cumulative flux (C mg/Kg) assuming a linear relationship between measurements.

2.4. Climatic parameters and soil water

Soil temperature (ºC) and volumetric water content (cm^3/cm^3) measurements were obtained at a weekly interval, typically at 10-11 am, during the period April – September 2020 (18 measurements in total for this period). Stainless steel and analogue soil thermometers (ETI Ltd, West Sussex, UK) were used. They were placed in the soil (20 cm depth) and allowed to equilibrate before measurement for 30 mins. Three measurements per replication (n = 3 measurements x 3 replications x 3 treatments = 27; see paragraph 2.2 for the treatments) were made at each of the time points. Soil samples (n = 27) were additionally obtained to determine soil volumetric water content and soil bulk density (using a 7 x 10 cm ring; 384.65 cm^3). They were weighed and dried at 105 ºC for 48h to obtain the dry weight. The gravimetric soil water content was determined and converted to volumetric, using the average value obtained for the soil bulk density $\rho_b = 1.2$ g/cm^3. Soil temperature and moisture (average values) graphs for the 3 treatments are presented in Figure S1.

Climate characteristics of the vine-growing area were evaluated after establishing a weather station in the vineyard (Watchdog 2700 weather station; Spectrum Technologies, Inc.) by computing the climatic indexes: 1) the thermal Index of Winkler (WI), 2) the Heliothermal Index of Huglin (HI), 3) the Cool night index (CI) which is a night coolness variable that takes into account the mean minimum night temperature during ripening phase (August-September) and 4) the number of days with maximum temperatures above 30 ºC, expression of drastic climatic events. The period for the calculations was from 1 April to 31 October 2020. The formulas for the calculations:

$$WI = \sum_{1/4}^{31/10} (T_{mean} - 10) \quad (\textbf{Equation 3})$$

$$HI = K \sum_{1/4}^{31/10} \frac{(T_{mean} - 10) + (T_{\max} - 10)}{2} \quad (\textbf{Equation 4})$$

T_{mean} = daily mean temperature °C

T_{max} = daily maximum temperature °C

baseline temperature = 10 °C

K = parameter dependent on the latitude of the location; in the case of Cyprus, its value is 1.02.

2.5. Grape qualitative attributes

To check if the applied treatments will lead to different grape quality, berries were harvested based on their ripening stage with sugar concentration reaching ca. 24 ^{o}Brix. Collected berries were placed in nylon bags (100 berries from each of the 3 plots/treatment), kept at a chilled temperature to prevent dehydration at the field, and transferred within 40 min to the laboratory. At the lab, berries from all treatments, were weighted and then either used for measurements or were frozen and conserved at -20 °C until analysis.

The pH, Total soluble solids (TSS), and titratable acidity (TA) were determined according to the methods described by the International Organization of Vine and Wine (OIV, 2012). TSS was determined with a portable digital refractometer (Master Baume 2594, Atago, Japan). The pH values were measured with a pH meter (HI 2222, Hanna Instruments, Inc., Woonsocket, Rhode Island, USA). TA was determined potentiometrically (titration with 0.1 mol L^{-1} NaOH up to pH 8.1) as described in Chrysargyris et al. (2016). All measurements were carried out in triplicate. The content of ascorbic acid (AA) was determined by the 2,6-dichloroindophenol titration method according to (Deng et al., 2005) and results were expressed as mg of ascorbic acid per 100 mL of grape juice (mg of AA 100 mL^{-1} grape juice).

Polyphenols were extracted by a modified method described by (Du et al., 2012). Fresh grapes were homogenized with 80% acetone and extraction was assisted with an ice sonication water bath for 10 min. Samples were centrifuged at 4,000 *g* at 4 °C for 15 min and supernatants were stored at -20 °C until use, for the analysis of total phenolics. Total phenolic content was measured as described above and results were expressed as equivalents of gallic acid per g of fresh weight (mg of GAE g^{-1} Fw). Condensed tannins were determined using the Bate-Smith assay as described by (Bate-smith, 1981) at 550 nm and results were expressed as g of condensed tannins per litre of grape juice (mg of condensed tannins per 100 mL grape juice).

2.6. The GHG emissions tool for viticulture and modelling work

2.6.1. The GHG emissions tool

In parallel to the annual C balance determination work, an excel tool was developed (Supplementary Material) to determine the carbon footprint of grapes and design management practices that increase C storage and minimize GHG emissions from vineyards. Its development was based on 1) the Ledo et al. (2018) perennial GHG model, 2) data from Cypriot viticulture to adjust the model to Mediterranean non irrigated vines, 3) the Cool Farm Tool (CFT; Hillier et al., 2011; www.coolfarmtool.org). The CFT is used worldwide for estimating the GHG impacts of agricultural production and is largely based on IPCC Tier 1 quantification methods (Hillier et al., 2011; Whittaker et al., 2013). Its most recent version supports carbon farming projects development worldwide. Therefore, data elements required to calculate direct emissions from fertilizers, pesticides, energy usage, land management/land-use change, and transportation were collected in the interface and processed through the Cool Farm Tool Application Programming Interface (API).

The current version of the online CFT has limited capabilities for incorporating GHG emissions from perennial crop production, specifically concerning biomass growth and residue management. Therefore, a new tool was developed to support perennials modelling. Accordingly, data related to vine growth and grape production were applied to the perennial GHG model developed by Ledo et al. (2018). This tool was programmed in python, within an additional API that makes it user-friendly. This tool simulated the growth of the vines over the life cycle of the crop and the emissions that resulted from different biomass managements, i.e., removed from the farm, burned, composted, or chipped and spread on the soil. The data relating to the vine's growth were obtained from the experimental vineyard and additional data for Xynisteri cultivation in Cyprus were used. These data involved biomass production from Xynisteri vines, soil characteristics and natural vegetation. For this purpose, we have also used data from 4 vines that were uprooted in the experimental vineyard. In these plant samples, dry weight was determined, and C content was estimated as described in paragraph 2.5.

GHG estimates from the perennials tool (i.e. biomass and perennials residues management) plus GHG from farm management (fertilizers, energy use) from the online CFT were combined within the API excel tool to provide a summary estimate of overall emissions or sequestration associated with vineyard management. These estimates were also reported in terms of emissions intensities (CO_2-eq kg^{-1} of grapes and CO_2 ha^{-1} of vineyards). In the CO_2-eq determination, this approach also takes into account the presence of natural vegetation in the vineyard margins (e.g., bushes, trees). The presence of natural vegetation and its annual growth, in terms of trunk increase (cm), was used. The LCA approach followed by the tool is from cradle to winery gate.

2.6.2. Modelling work

The tool was used to explore scenarios for different management practices that would bring a reduction of the GHG emissions from viticulture and therefore to select practices that increase C storage in the vineyard soil, thus supporting C farming in the case of Mediterranean vine cultivation.

2.6.2.1. Modelling based on the experiment treatments

In Table 3, the management practices relevant to the 3 different treatments (A, B, C) are presented. The data that is presented in Table 3, are those required to run the tool and perform LCA from cradle to farm gate.

Table 3. Management practices for the 3 treatments. These data were used to run the excel tool.

Treatment	Input/practice	Value	Comments
A (N requirements provided by 50% organic + 50% synthetic fertilizer; reduced tillage)	Fertilizer (21-0-0) Goat/sheep manure & winery wastes 80/20 w.w.	60 kg N/ha & 60 kg N/ha	286 kg fert. and 2,933 kg org. material incorporated once (mid-February)
	Tillage	Reduced (1 per year)	Rotary cultivator at the depth of 40 cm
	Energy use	150 L diesel/year/ha	Machinery for the field practices (pesticides application; tillage; field visits)
B (100% organic fertilizer; reduced tillage)	Goat/sheep manure & winery wastes 80/20 w.w.	120 kg N/ha	5,866 kg/ha w.w. org. material
	Tillage	Reduced (1 per year)	Rotary cultivator at a depth of 40 cm
	Energy use	200 L diesel/year/ha	Machinery for the field practices (pesticides application; tillage; field visits)
C (100% synthetic fertilizer; tillage 3 times per year)	Fertilizer (21-0-0)	120 kg N/ha	572 kg product incorporated once (mid-February)
	Tillage	3 times per year	Rotary cultivator at the depth of 40 cm
	Energy use	200 L diesel/year/ha	Machinery for the field practices (pesticides application; tillage; field visits)
Common data for the 3 treatments			
	Soil characteristics	Texture: clay 3<SOC<6 % Moisture: Dry Drainage: Good pH: 7.5	-
	Pesticides application	4 times/season	Insecticides a cypermethrin; Acetamiprid 20%; applied according to label for grapes (500l spraying machine) Sulfur 100-150 kg/ha
	Irrigation water	0 m^3/year	Rainfed vineyard; 600 mm/year typical for the area.
	Pruning	0.1-1 kg (w.w.) per vine	Once per year
	Residue management	100% of litter left on the ground. Prunings 50% incorporated with rotary cultivator and 50% burned.	Annual shoots incorporated into the soil via soil cultivation (rotary cultivator)
	End of life	The vines removed from the field	Use for fuelwood
	Natural vegetation	100 shrubs/ha and an annual increase of 1 cm at ~~brest~~breast height	Field margins; Species: *Quercus coccifera subsp. Calliprinos, Quercus alnifolia, Quercus infectoria, Olea europea, Pistacia*

		terebinthus, Prunus dulci Estimated annual trunk diameter growth 1 cm.
Transportation	3,800 kg grapes ha^{-1} for 20 km	With a light goods vehicle (diesel)
Yield per vine	1.52 kg	Average for the last 3 years
Vines/ha	2,500	Planting density 2 x 2 m; bush vines
Vineyard life	30 years	

2.6.2.2. Zero emissions viticulture scenario

Treatment C, which is considered a typical situation in the case of indigenous grape varieties cultivation in Cyprus, was used to explore management practices for achieving zero emissions grape production. Accordingly, the following were explored:

a) Reduction in N fertilizers use to reduce soil emissions and GHG from the fertilizer production and distribution processes.
b) Adopting no-till that covers some of the vineyard area.
c) Reduction in fuel use due to no-till, reducing the pesticides application and the transportation (visits of the farmer to the vineyards and adopting more fuel-efficient means for produce transportation to the winery, e.g., delivering to wineries closer to the farm).

2.6.2.3. Carbon storing scenario

A second scenario was studied, for reducing GHG emissions and increasing C storage, also based on the treatment C of the experiment (Table 3). The focus was to propose practices that could lead to benefits for the farmers due to increased C storage in the vineyard. Therefore, the following practices were examined:

a) 50% reduction in N fertilizer (60 kg N/ha)
b) 75% reduction in pesticides (1-time sulfur)
c) All pruning material incorporated into the soil
d) 50% of the vineyard under no-tillage (for the whole life of vines)
e) 150 L diesel/year/ha max in the vineyard
f) 100% (+100 trees/ha) increase in vegetation (trees, shrubs) in the vineyard margins

2.7. Data treatment and statistical analysis

Kruskal-Wallis tests were used to test the null hypothesis that the medians of C content (kg C) in grapes, stalks, berries, leaves, stem, shoots and roots within each of the 3 treatments (A, B, C) are the same. This is also performed for Above ground C and total C in vines, root and soil respiration as well as grape quality attributes. The pairwise comparisons among the 3 treatments were made using the Bonferroni procedure at the 95% confidence level.

Statgraphics Centurion V19 (STATPOINT) was used for the data treatment and analysis.

2.8. Assumptions and limitations of this research

The main assumptions and limitations of the field study are provided below:

- The year 2020 measurements (8-year-old vines) are representative of the average annual of the whole life cycle of grapes.
- The rate of nutrients released from organic fertilizer is similar to that of synthetic (typically, nutrient release rate is slower in organic materials).
- C content in plant tissue is 50% of the dry weight.
- C due to litter addition/decomposition to the soil was not taken into account in the annual C balance experiment.
- Soil respiration is ~~like what was~~similar to that observed in the mesocosm experiment and only CO_2 was considered (not N_2O, CH_4, NH_3)
- The life of the vineyard for Xynisteri is assumed to be 30 years.

3. Results

3.1. Climatic parameters and soil moisture

The thermal Index of Winkler (WI), the Heliothermal Index of Huglin (HI), and the Cool night index (CI) values were 2901, 2917 and 22.8 °C indicating a microclimate more suitable for table grapes, already expected for the study location. In Figure S2, the T_{max} is plotted and 43% of the days during the period 1 April to 31 October 2020 had a temperature above 30 °C. Soil water content was high at the beginning of the season (0.5 cm^3/cm^3), due to the winter rainfall, and decreased to 0.2 cm^3/cm^3 during the period June-September (Figure S1). Soil Temperature range was 17-30 °C (20 cm soil depth) during the experimental period. Irrigation was not applied and rain was zero, during the period June-September 2020.

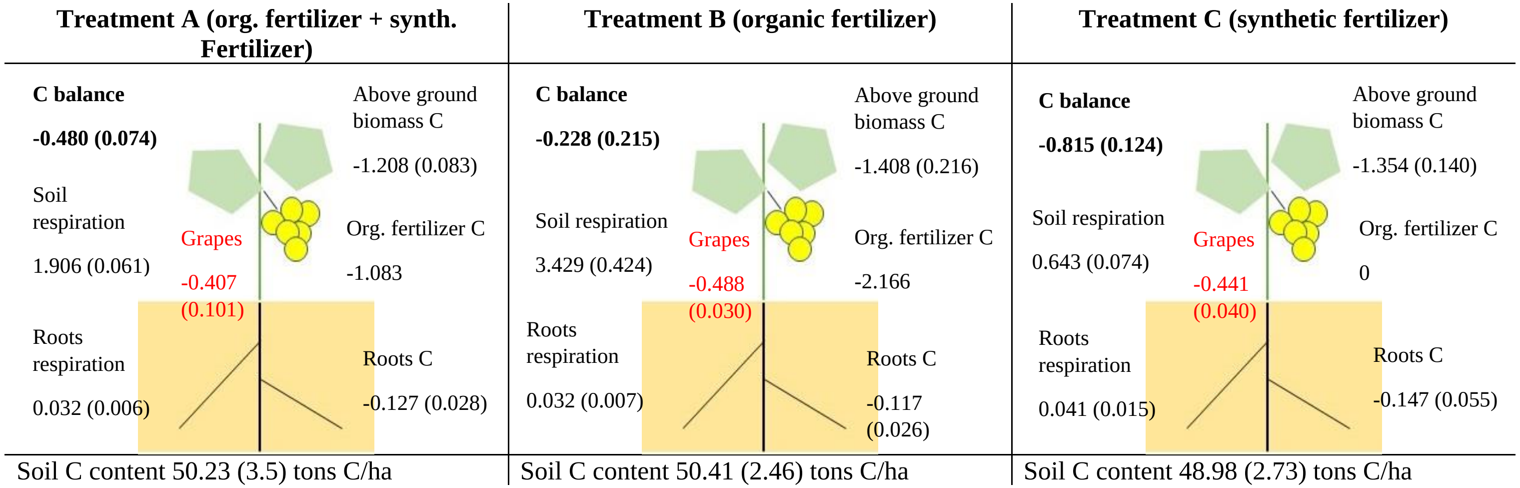
3.2. C balance at the vine and the vineyard level

In Figure 3, the results for the determination of C balance in Xynisteri vines (field measurements) are presented for the 3 treatments at the vineyard level (kg C ha^{-1} $year^{-1}$; 2500 vines ha^{-1}). In Figure S3 the C balance results are provided in kg C per vine. In Figure S4 the measured biomass C (kg C) that is stored annually per vine plant and treatment is presented while in Figure S5, soil (Fig. S5a) and root (Fig. S5b) respiration are presented. Considering soil and roots respiration as C outputs and organic material addition plus annual biomass (above and below ground) as inputs, the balance (average and standard deviation) was -0.480 (0.074), -0.228 (0.215) and -0.815 (0.124) tons C ha^{-1} year^{-1} for treatments A, B and C, respectively. Carbon storage in grapes (fruit) was not taken into account as they are exported from the system. Soil respiration increased in treatments A and B, where organic material was added, in comparison to the treatment C. After the end of the period, soil organic C was slightly increased in treatments A and B.

3.2. Effects of different management practices on grape quality

In Figure 4, the effects of the 3 treatments on the grape's qualitative characteristics are presented. There were no statistically significant differences (Kruskal-Wallis test) for the grape quality parameters among the 3 different treatments applied in the vineyard. The average (standard deviation; SD) pH values obtained were 3.7 (0.026), 3.6 (0.095) and 3.6 (0.153) for treatments A, B and C, respectively. Total Soluble Solids (TSS) average values (SD) were 21.9 (2.16), 22.7 (2.94) and 18.8 (2.71) ^{o}Brix, for treatments A, B and C, respectively. Phenols average (SD) values for treatments A, B, and C were 3.2 (0.42), 2.5 (0.47) and 2.8 (0.32) g GAE/g fw (fresh weight), respectively. Tannins average (SD) values were 0.38 (0.05), 0.38 (0.05) and 0.37 (0.02) g/L in treatments A, B and C, respectively. Ascorbic acid average values (SD) were 0.5 (0.02), 0.4 (0.07) and 0.4 (0.02) mg AA/100 mL in treatments A, B and C, respectively. Finally, titratable acidity average values (SD) were 3.5 (0.25), 3.7 (0.44) and 4.5 (0.46) g tartaric acid/L in treatments A, B and C, respectively.

Figure 3. Carbon balance in Xynisteri vines (average values in tons C/ha and standard deviation; n=3). Berries (grapes; red colour) are not included as they are removed from the system at harvest.



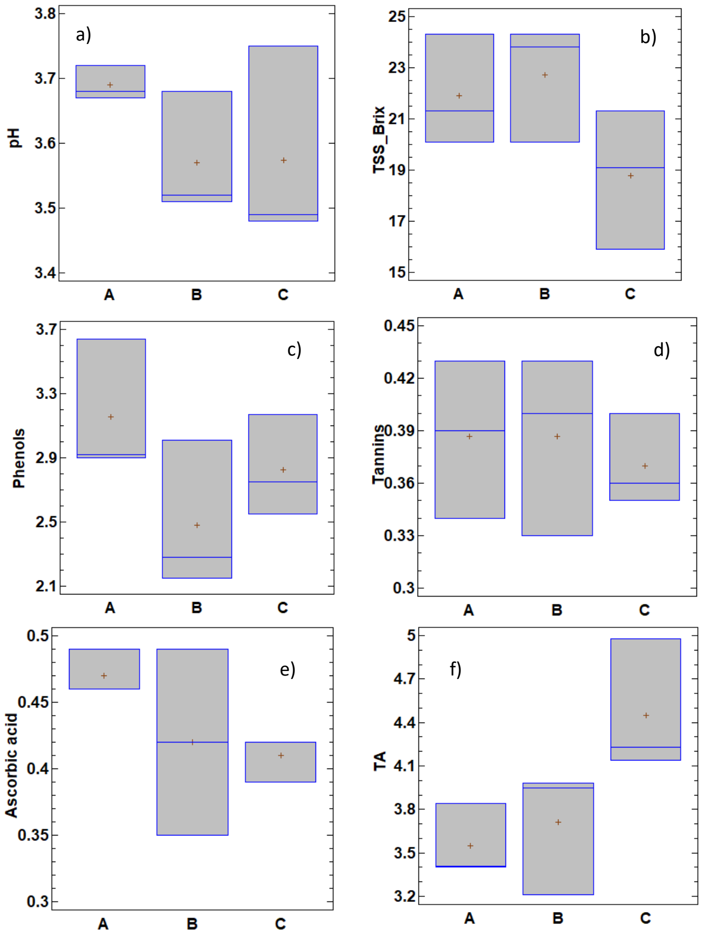


Figure 4. Grape qualitative characteristics for the 3 treatments. a) pH, b) Total Soluble Solids - TSS (°Brix), c) phenols (g GAE/g fw), d) condensed tannins (g/L), e) Ascorbic acid (mg AA/100 mL), f) Titratable Acidity - TA (g tartaric/L).

3.4. GHG emissions for the different management practices

In Figure 5, the parameters and management practices that form the GHG emissions are presented, as obtained after applying the GHG tool for the three treatments (A, B, C) and given as kg CO_2-eq ha^{-1} year^{-1}. In Figure S6, vine biomass (modelled) is presented (Fig. S6a) as well as the partition in wood, roots and leaves (Fig. S6b). The comparison of the measured and modelled biomass C is presented in Figure S7. The tool also takes into account C storage due to litter, roots and pruning material addition to the soil, equal to -0.064, -0.048 and -0.208 tons CO_2 ha^{-1} year^{-1}, respectively and assumed the same for the 3 treatments. Soil emissions were 0.410, 0.314 and 0.535 tons

CO_2-eq ha^{-1} $year^{-1}$, for the treatments A, B and C, respectively. Energy related emissions were 0.402 for the treatment A and 0.536 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatments B and C, respectively. Emissions related to the production of fertilizers were 0.161, 0 and 0.322 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatments A, B and C, respectively. Transportation and pesticides production and use emissions where equal to 0.026 and 0.010 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatments A, B and C, respectively. Finally, land management related emissions, due to C storage in vineyard margins and tillage, were 0.016 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatments A and B and -0.355 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatment C. Due to vines removal and use as fuel wood after the end of the life cycle (30 years), the C stored in the vine wood was not taken into account. Therefore, the annual balance was 0.705, 0.581 and 0.754 tons CO_2~~2~~-eq ha^{-1} $year^{-1}$ for the treatments A, B and C, respectively. Using a typical production of 3.8 tons ha^{-1} $year^{-1}$ for this vineyard, the emissions per kg of grape were 0.186, 0.153 and 0.198 kg CO_2-eq kg^{-1} for the treatments A, B and C, respectively. Finally, the emissions for the life cycle (30 years total) of the vineyard (cradle to winery door) were 21.160, 17.437 and 22.614 tons CO_2-eq ha^{-1} for the treatments A, B and C, respectively.

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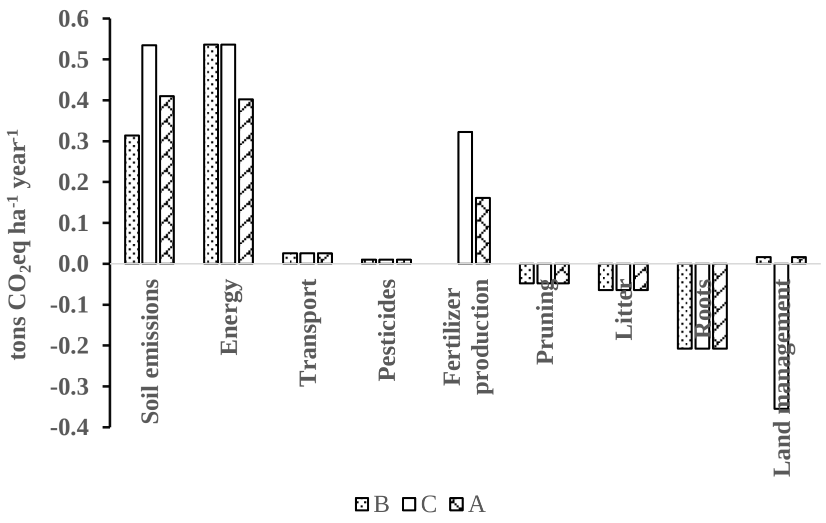

Figure 5. Contribution of parameters and management practices to the CF; data in kg CO_2-eq ha^{-1} $year^{-1}$. A, B, C are the 3 treatments.

3.5. Carbon farming

3.5.1. Zero emissions grapes

Based on treatment C (see Table 3), which is typical for the study area, zero-emission grapes could be produced, based on the GHG excel tool, by applying the following practices:

- 33% reduction in the N fertilizer (80 kg N ha^{-1}).
- No tillage in 30% of the vineyard area.
- 18% reduction in diesel fuel used (170 L ha^{-1} year^{-1}) for vineyard tillage, spraying and transportation.
- Reducing pesticides applications (active substances) to 2 times per year.

In Table 4, the results for the zero-emissions scenario are presented, after modifying the management practices (of treatment C).

Table 4. CO_2eq emissions (kg per ton) for the case of zero emissions grape production.

Metric	**kg CO_2eq ton^{-1}**
Biogenic Emissions[1]	-84
Land-use change related emissions[2]	-215
Fossil fuel related emissions[3]	186
Soil emissions	113
Total	0

[1] Plant biomass C remaining in the soil (litter, roots, pruning)

[2] Tillage and field margins vegetation

[3] Energy in the field, transportation, pesticides and fertilizers production

In Figure 6, the contribution for each of the management practices and parameters in the emissions for the case of zero-emissions grape production are presented.

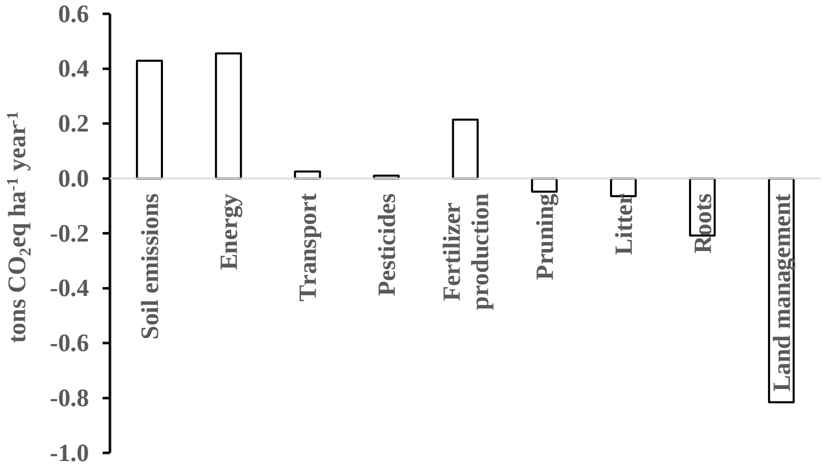

Figure 6. Contribution of parameters and management practices to the CF; data in kg CO_2-eq ha^{-1} $year^{-1}$ for the zero-emissions grape production scenario.

3.4.2. C farming

A second scenario was studied, for increasing C storage, also based on the treatment C (Table 3). The focus was to propose practices that could be adopted in eco schemes and will lead to benefits to the farmers due to increased C storage in the vineyard. Therefore, according to the GHG excel tool, the following practices should be adopted:

- 50% reduction in N fertilizer (60 kg N/ha)
- 75% reduction in pesticides use (1-time sulfur)
- All pruning's and end of life wood added to the soil
- 50% of the vineyard no-till and cultivation to incorporate residues
- 150 L diesel/year in the vineyard
- 100% (total 200 bushes/ha) increase in vegetation (trees, shrubs) in the vineyard margins

The adoption of the above will lead to total CO_2 savings equal to 25.124 ton CO_2eq ha^{-1} (for 30 years vineyard life cycle).

Table 5. CO_2eq emissions per ton of grapes per year for the scenario of C credits.

Metric	**kg CO_2eq ton^{-1}**
Biogenic Emissions[1]	-95
Land-use change related emissions[2]	-382
Fossil fuel related emissions[3]	156
Soil emissions	101
Total	-220

[1] Plant biomass C remaining in the soil (litter, roots, pruning)

[2] Tillage and field margins vegetation

[3] Energy in the field, transportation, pesticides and fertilizers production

In Figure 7, the contribution for each of the management practices and parameters in the CO_2eq emissions or savings are presented.

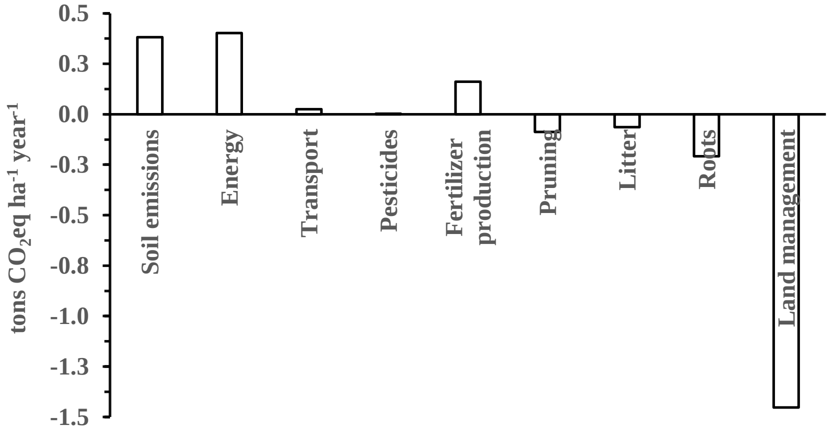

Figure 7. Contribution of parameters and management practices to the CF; data in kg CO2-eq/ha/yr for the C credits scenario.

4. Discussion

According to the C balance determination at the vine plant level, above-ground biomass plays important role in C sequestration (Figure 3). However, we only accounted for the annual C balance and considered only the roots present in the 0-40 cm layer of the soil. Vines have extensive and deep-root systems (reaching down to 5-10 m on arid Cypriot soils to exploit water) which also allows for direct transfer of OC into the subsoil which reduces risks of SOC ~~mineralisation~~mineralization due to the reduced microbial activity at ~~higher~~ deeper soil depths (Ledo et al., 2020). Trunk C storage was not taken into account in our measurements, although we performed preliminary measurements (data not shown) by destructive sampling in 4 vines, as it is typically used as fuelwood at the end of life of the vineyard and the C is returned back to the atmosphere. Per vine, we measured 0.5 kg of C (or 1.83 kg CO_2) stored annually above ground (grapes were not taken into consideration as they are removed from the system) and 10% of this was additionally found in the annual roots, at 0-40 cm depth. Annual roots remain in the soil and a part of this enriches the SOM. Most of the annual above-ground biomass is removed after pruning. This means that the management of pruning material is important for enriching the soil with organic matter.

Commented [AH3]: Does this displace fossil fuels or is it current practice (could add more C benefits

Per ha of vineyards, our measurements showed that the above-ground biomass removes 1.2 – 1.4 tons C annually. Depending on the management practices and the climatic conditions, a part of this C could be stored in the soil as organic material. Nevertheless, incorporating the pruning into the soil, is not the best available option for C storage in vineyards (Payen et al., 2021). However, we estimate (litter bags; data not shown) that 50% of the biomass added annually in the soil remains after one year.

This practically means that if the pruning material is incorporated in the vineyard soil, then 0.6-0.7 tons C ha^{-1} year^{-1} could be stored. This value is close to the benefit that is expected from using cover crops in semi-arid environment (Mattila et al., 2022). However, our results should be considered as the first results from Cypriot vines, in a semi-arid environment and non-irrigated viticulture. Multi-year data, under variable management practices, cultivars and soil-climatic data could give a clearer picture regarding C management (Smith et al., 2008).

In a similar study taking place in Italy, the C balance ranged between -1.7 to 4.75 ton C ha^{-1} year^{-1} (Brunori et al., 2016), for the case of irrigated grapes. In our case, this range was -0.228 to -0.815 ton C (or Mg) ha^{-1} year^{-1} and the difference is attributed to higher biomass production and soil respiration in the Italian study. The C pool in the soil in our experiment was measured 48.98 – 50.41 Mg ha^{-1} (Figure 3) at the depth of 0-40 cm. However, this value is lower than what was reported in the study of Brunori et al. (2016) where C content was 44.16 – 73.35 Mg ha^{-1}, only considering the first 20 cm.

Although there is data availability on the C storage in vineyards, the effect of different management practices related to C farming on grape quality is not studied. Grape juice quality characteristics are most important to produce high-quality wines (Chrysargyris et al., 2018b), which is the added value for the wine industry. For this purpose, we have determined the parameters pH, TSS, Phenols, Tannins, Ascorbic Acid and Titratable Acidity, for the 3 different management practices as proxies for grape quality. No significant difference was observed for the above parameters in the three different management practices tested. Although limited data exist for grape quality parameters (in Cypriot indigenous varieties) under different management practices, our results were similar to the study of Chrysargyris et al. (2020) where irrigation and tillage were tested for Chardonnay and Xynisteri. The pH was slightly increased in treatment A, in comparison to B and C. In the work of Chrysargyris et al. (2020), irrigation under no-tillage increased the pH of grape juice. Regarding the TSS in grape juice, they were increased in treatments A, B where organic material was added and reduced tillage was applied. Treatment C showed similar values to that previously observed in research with Xynisteri in Cyprus, where different tillage regimes were studied (Chrysargyris et al., 2020). Phenols had a lower value in treatment B, where organic material and reduced tillage were applied. Irrigation and no-tillage significantly increased phenols in the study of Chrysargyris et al. (2020). The management practices applied in our experiment did not affect tannins in grape juice, which is an important quality parameter. Ascorbic Acid (AA) content was increased in treatment A, where fertilizer and organic material were simultaneously applied, as nutrient sources. Finally, Titratable Acidity (TA) was reduced in the treatments where reduced tillage and organic material were applied. Despite minor changes in grape juice quality parameters and because no significant differences were observed, we can conclude that shifting to reduced tillage and replacing synthetic fertilizers with organic, does not affect important quality parameters in Xynisteri grapes. Our results are complementary to the work of Chrysargyris et al. (2020) where a more in-depth analysis was conducted regarding tillage and irrigation regimes in

Xynisteri. Grape quality should be taken into consideration for proposing C farming schemes for the Mediterranean viticulture.

Regarding the modelling work results, different management practices affect the CO_2 emissions of grapes produced, from a LCA perspective. This approach offers a holistic evaluation of C balance in vineyards and should be taken into consideration in the design of C farming schemes. Land management, which in our case was captured as soil tillage practices and vineyard margin vegetation is considered highly important for mitigating GHG emissions from viticulture. Additionally, field margins are very important for ecosystem services provisioning and biodiversity maintenance. Preserving vineyard margin vegetation during the lifetime of the vineyard (30 years) could lead to C storage of 0.355 tons CO_2-eq ha^{-1} $year^{-1}$.

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In the modelling study, vine growth was considered not to be affected by the management practices. This was supported by the measurements conducted (Figure S3) where no significant differences were observed among the three treatments for biomass production. Accordingly, CO_2eq storage in the soil that result from roots biomass, litter and pruning residue management are considered the same for the three treatments (Figure 5) and they are equal to 0.304 to 0.675 tons CO_2eq ha^{-1} $year^{-1}$.

Pesticides application was the same among the three treatments as well as the related GHG emissions (Figures 5). Treatment C had the highest emissions related to fertilizers production (industrial process). Treatment A, had half the emissions of C, as the synthetic fertilizer was reduced by 50%. Finally, treatment B had zero emissions related to fertilizer production. This is a simplification, as we were not able to account for the emissions related to goat manure production, which was kept outside the facility for one year. Anaerobic conditions in manure leads to CH_4 emissions. The organic material from the winery (e.g., stalks, lees) was immediately mixed with the manure, thus emissions from production are practically zero. Soil emissions were modelled according to N fertilizer use (N_2O, NH_3 emissions) and organic matter decomposition, due to soil tillage. Therefore, higher soil emissions were observed for treatment C (Figure 5), which is typically practiced in Xynisteri cultivation in Cyprus. Emissions related to the transportation of the final product to the winery were the same among the three treatments. Energy use was slightly reduced in treatment A, due to lower amounts of synthetic and organic fertilizer applied, in comparison to treatments B and C. Overall, the emissions for treatments A, B and C were 0.186, 0.153 and 0.198 kg CO_2eq kg^{-1} for the treatments A, B and C, respectively or 21.160, 17.437 and 22.614 tons CO_2-eq ha^{-1} for the life cycle of the vineyard and for the treatments A, B and C, respectively. These results indicate the role of vineyards as CO_2 emitters and promoting low input~~s~~ viticulture (reduce fertilizers and energy), preserving the vineyard margins and shifting to no-till viticulture could support zero emissions farming. The role of non-irrigated viticulture based on indigenous varieties is very important for this shift (Litskas et al., 2017).

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In more detail, treatment C represents what is typically applied in Xynisteri grapes production in the study area. In treatments A and B, reducing and replacing synthetic fertilizers with organic and adopting reduced tillage leads to drastic GHG emissions reduction. However, the use of organic material should be carefully considered as it could trigger ~~flush~~ flash CO_2 emissions due to increased soil respiration (Figure 3). To modify management practices in treatment C and propose a way of producing zero emissions grapes, we concluded that this is possible after a 33% reduction in synthetic N fertilizer use, no-till in 30% of the vineyard area and 18% reduction in fuel consumption for tillage, pesticides (50% reduction; only 2 times per year) application and transportation. As presented in Figure 6, C storage in the soil and plant biomass resulting from roots, litter, pruning residues incorporation, reduced tillage and preserving vineyard margins vegetation (trees and bushes) is equal to the emissions resulting from fertilizer production, pesticides production and use, transportation, fuel use and soil emissions due to N fertilizers and organic matter decomposition. This modelling exercise also highlights the importance of the LCA approach in C farming, as C sequestration is increased to 1.135 tons CO_2eq ha^{-1} $year^{-1}$ but emissions due to energy and fertilizer production and use result to GHG emissions which offset this benefit.

Moving towards the adoption of C farming schemes in viticulture, we estimated that is feasible to save 25,124 kg CO_2-eq ha^{-1}, in total for the life cycle of the vineyard, after a 50% reduction in synthetic fertilizers and pesticide use, pruning (after the life cycle) incorporation, no-tillage applied in 50% of the vineyard area, using maximum 150L diesel per year and maintain 200 bush trees ha^{-1}~~,~~ as vineyard margin vegetation (Figure 7). In this case, the C storage in the soil is maximized for our system, to reach 1.812 tons CO_2eq ha^{-1} $year^{-1}$. These practices support C sequestration in vineyards and could be tested in eco schemes proposed in the new EU Common Agricultural Policy (CAP).

5. Conclusions

Treatment C which is close to the practices typically applied in Xynisteri vineyards could be relatively easily transformed towards Zero emissions viticulture. For this, reduced tillage and preserving natural vegetation is the key and it is also beneficial for ecosystem services provisioning and biodiversity protection. When applying organic material to replace synthetic fertilizer, the increased soil emissions (as well as the production of the organic fertilizer; emissions during production) should be considered. There were no significant differences among the treatments, in grape quality attributes which ~~favours~~favors the application of C farming in viticulture. However, further research is required to obtain a clear picture, e.g., measure C sequestration in natural vegetation; study the decomposition of organic material and the soil respiration (field data) over a period of several years to account for inter annual variation. In addition, field measurements should be made of N_2O emissions which were not included in this study. Moreover, the design of eco-schemes related to C farming should also consider GHG emissions due to fertilizers and energy, after applying LCA at least from cradle to farm gate. Overall, the results of this work support the design of eco-schemes relevant to C farming.

Acknowledgements

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