ClimaMED

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Coordinating Institution	BENAKI PHYTOPATHOLOGICAL INSTITUTE
Coordinator	Dr. Maria K. Doula
Address	St. Delta Str., n° 8, 145 61, Kifissia, Attica, Greece
Telephone No	+30 210 8180321
Fax No:	+30 210 2842 129
E-mail:	mdoula@otenet.gr; m.doula@bpi.gr
Project web site:	https://life-climamed.eu/

Innovative technologies for climate change mitigation by Mediterranean agricultural sector	
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Summary	This deliverable ensures that the ClimaMED results are translated into clear, usable knowledge for the agricultural sector. Its purpose is to connect scientific evidence with practical and policy needs, enabling MINAGRIC and stakeholders to apply real monitoring data and targeted recommendations in planning for a low-emission, climate-resilient future for Greek agriculture.

Contents

1. Introduction

Agriculture is one of the most impactful sectors shaping Greenhouse gas (GHG) dynamics at the global scale, with direct impacts on atmospheric concentrations of CO_2, CH_4 and N_2O. In the Mediterranean region, this influence is amplified by the distinctive combination of climatic stressors - high temperatures, prolonged dry periods, irregular rainfall patterns and increasing frequency of extreme weather events. These conditions intensify microbial activity, enhance volatilization and respiration pulses, and increase the energy required for irrigation and field operations, making Mediterranean agriculture prone to higher GHG emissions per unit of production compared with temperate systems.

Mediterranean cropping systems are further characterized by structural challenges: small and fragmented farm holdings, reliance on intensive tillage, repetitive phytosanitary treatments, the extensive use of synthetic fertilizers, and high dependency on fossil-fuel-based mechanization. Together, these factors generate frequent and pronounced fluctuations in GHG fluxes, particularly during fertilization events, irrigation pulses, soil disturbance and biomass burning. As a result, understanding the emission behavior of Mediterranean agricultural practices is essential for designing targeted and realistic mitigation strategies.

The LIFE ClimaMED project addresses this need by implementing an innovative, field-based monitoring framework capable of providing real-time, high-resolution (Tier 3) measurements of CO_2, CH_4 and N_2O emission. Rather than relying solely on modelling or periodic sampling, the project developed a permanent LiDAR-based monitoring device. Using this system, the project monitored a representative network of pilot fields across Greece, covering the main Mediterranean crops: olives, grapes, pistachios, cereals and open-field vegetables. These case studies provide a cross-comparison of how different management regimes, climatic settings and crop-specific agronomic requirements influence GHG emissions. For example, perennial orchards such as olives and pistachios show strong emission peaks associated with pruning-residue burning and repeated use of pesticides, while vineyard emissions are closely linked to tillage intensity, nitrogen fertilization and irrigation energy use. Open-field vegetable systems, which involve high operational frequency and short rotation cycles, demonstrate some of the most intense GHG fluctuations, whereas cereal systems exhibit emission patterns dominated by nitrogen fertilization and irrigation of water-demanding species such as maize.

The analysis of these systems allows for the identification of specific agricultural practices that significantly increase GHG emissions, as well as those with clear mitigation potential. This deliverable synthesizes the findings into a structured set of best practices and targeted recommendations. It examines, for each crop type, the operational hotspots responsible for increased emissions and translates these findings into practical mitigation strategies, covering fertilizer optimization, improved irrigation efficiency, machinery-use reduction, integrated pest management, and non-burning residue handling.

Beyond farm-level recommendations, this deliverable formulates concrete proposals for the Ministry of Rural Development and Food (MINAGRIC), aligned with the Common Agricultural Policy (CAP) 2023–2027 and EU climate objectives. These proposals include the design of crop-specific eco-schemes, targeted investment measures, strengthened advisory services, cooperative mechanisms for residue and machinery management, and activity-based monitoring frameworks. By integrating evidence-based agricultural practices with policy-relevant instruments, the document provides a roadmap for transitioning Mediterranean agriculture toward lower-emission systems.

In Greece, the Ministry of Rural Development and Food (MINAGRIC) has begun to integrate climate-aligned measures into national agricultural policy, signaling a clear political commitment to reducing GHG emissions in the primary sector. Within the national CAP Strategic Plan 2023–2027, Greece has introduced a suite of eco-schemes that support environmentally responsible practices such as improved residue management, reduced chemical inputs and crop-specific climate interventions. Additionally, targeted support schemes, such as the recent incentive for reducing the carbon footprint of strategic crops, demonstrate the Ministry's intention to gradually embed climate mitigation into direct farmer payments. Although these initiatives are still evolving, they represent an important foundation for the adoption of low-emission agronomic practices and provide a national policy context into which the ClimaMED recommendations can be effectively integrated.

Overall, this deliverable demonstrates that reducing GHG emissions in Mediterranean agriculture is both feasible and measurable when management practices are redesigned with climate efficiency in mind. Through detailed emissions monitoring, robust analysis of cultivation practices and targeted policy interventions, Mediterranean farming systems can significantly decrease their climate footprint while maintaining productivity and resilience.

2. Pilot fields: Agricultural practices and GHG emission

2.1 Olive orchards

The three olive orchards monitored in LIFE ClimaMED, located in Crete, the Peloponnese and Central Macedonia, offer the opportunity to understand how contrasting agricultural practices shape GHG emissions in perennial Mediterranean systems. Although all three fields cultivate the same crop, their management profiles differ profoundly, reflecting the broad heterogeneity of Mediterranean agro-ecosystems. By integrating (a) farmers' questionnaires and inputs in the specific GIS app developed by BPI in the framework of specific project Action and for each years of its duration; (b) the deliverable of C2 Action "Report on the SOC related baseline conditions of pilot fields"; (c) the deliverable of C1 Action "Products' Environmental footprint (olives, pistachios, grapes, cereals and vegetables)" which provides life-cycle inventory results for all crops studied; and (d) the deliverable of the same Action "Report on GHGs emissions from the pilot fields (seasonal and annual total emissions, GWP)", it becomes possible to trace with high clarity the mechanisms through which farming decisions translate into real GHG dynamics, an approach consistent with similar studies in Mediterranean olive systems (López-Bellido et al., 2016; Aguilera et al., 2021).

The olive orchard in Kato Valsamonero, Crete, represents a low-input mixed system characterized by the continuous coexistence of olive trees with free-ranging livestock. Sheep, rabbits and hens move freely across the field almost throughout the year, depositing manure directly onto the soil surface. No mineral fertilizers are applied, and the orchard is not irrigated, which eliminates emissions associated with pumping and fertilizer production. Nevertheless, despite its low-input nature, the Crete orchard exhibits substantial biological emissions due to enteric fermentation, manure deposition and enhanced soil respiration. Soil analyses reveal an exceptionally high organic matter content (>5%), reflecting years of continuous organic inputs, a pattern widely documented in Mediterranean manured orchards (Michalopoulos et al., 2020), which stimulate GHG emissions due to increased microbial activity (Mairech et al., 2021). These patterns were visible in the GHG flux diagrams derived from LiDAR measurements, as well as the short-lived CO_2 peaks associated with the burning of pruning residues, a culturally persistent but environmentally damaging practice that has been repeatedly highlighted in Mediterranean literature for its disproportionate climate impact (Aguilera et al., 2021; Bartzas et al., 2025). These pulses appear in the diagrams as prominent CO_2 spikes of short duration but high magnitude (Fig.1.).

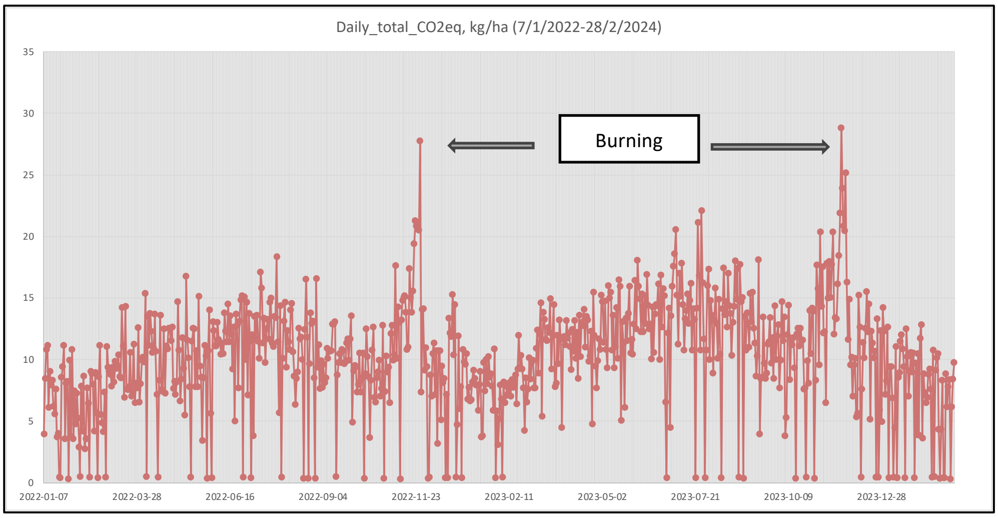

Figure 1. Daily total emissions for the mixed olive orchard-livestock in Rethymnon, Crete (7/1/2022-28/2/2024).

Such measurements verify that burning is not merely a direct source of CO_2 but also a catalyst for multi-gas emissions, creating disproportionate contributions to the orchard's annual emissions.

A different pattern emerges in the olive orchard of Skoura in the Peloponnese, which represents a medium-intensity production system. Here, moderate fertilization, shallow tillage, mechanical harvesting and occasional manure application form the core management practices. Livestock is present but not as intensively as in Crete. In this orchard, the GHG profile arises from the cumulative effect of fuel combustion, mechanized operations and the repeated burning of pruning residues. The LCA results position Skoura close to Crete in terms of total annual GHG emissions, approximately 3.8 t CO_2eq per hectare, yet the sources differ substantially. Whereas emissions in Crete are predominantly biological, the emissions in Skoura are operationally driven, reflecting fuel use, tillage, irrigation and burning. This comparison mirrors findings from Spanish and Italian orchards where mixed systems show intermediate GHG profiles shaped by multiple sources (López-Bellido et al., 2016; Aguilera et al., 2021).

The olive orchard in Pontoheraklia, Central Macedonia, represents the opposite extreme: a high-input, fully irrigated, mechanized system. This orchard relies heavily on synthetic fertilizers, with substantial annual applications of compound mineral fertilizer generating indirect N_2O emissions through soil nitrification and denitrification, reactions extensively described in the IPCC Guidelines (IPCC, 2006; IPCC, 2019). More importantly, the frequent irrigation requirements of the orchard demand intensive use of diesel-powered pumps. The LCA results demonstrate that annual emissions exceed 12 t CO_2eq per hectare, roughly four times those observed in the mixed systems of Crete and Skoura. In this orchard, the absence of livestock does not reduce overall emissions; instead, fossil-fuel consumption for irrigation dominates so strongly that it alone accounts for the majority of the orchard's carbon footprint. Burning of pruning residues, which also occurs here, further increases the total GHG emissions, aligning with evidence from studies across the Mediterranean basin that identify residue combustion as one of the principal emission hotspots (Aguilera et al., 2021; Bartzas et al., 2025).

When analyzed collectively, these three orchards reveal a coherent pattern: management intensity, rather than crop type, is the primary determinant of GHG emissions in Mediterranean olive systems. Low-input orchards are not inherently low-emission when livestock is present, especially under unmanaged grazing. Medium-intensity orchards distribute their emissions across machinery, irrigation, soil disturbance and burning. High-intensity irrigated orchards generate disproportionately high emissions through fossil-fuel use, overshadowing biological sources. These findings echo those from broader Mediterranean studies, which conclude that irrigation energy use, fertilizer regimes and residue management explain the majority of olive orchard GHG variability (Mairech et al., 2021; Aguilera et al., 2021).

The scientific literature across Greece, Spain, Italy and North Africa corroborates these findings. Studies have shown that increasing soil organic matter, eliminating burning, adopting deficit irrigation and recycling prunings through shredding can significantly reduce the environmental footprint of olive orchards (López-Bellido et al., 2016; Michalopoulos et al., 2020; Mairech et al., 2021; Bartzas et al., 2025). These conclusions align closely with the ClimaMED results and highlight that Mediterranean olive systems possess both challenges and opportunities for transition towards lower-emission, climate-resilient management.

Priority list of practices requiring improvement

- Eliminate the burning of pruning residues and replace it with shredding and soil incorporation.
- Implement controlled manure and grazing management, including reduced animal pressure and composting of manure before application.
- Reduce synthetic nitrogen fertilizer use, replacing it with organic amendments or precision nutrient management.
- Lower energy consumption for irrigation and machinery, prioritizing renewable or low-energy alternatives such as solar pumping.
- Reduce the frequency and intensity of soil tillage to minimize soil disturbance and carbon loss.
- Enhance soil organic matter inputs through ground cover, mulching and recycling of plant residues.

2.2 Vineyards

The three vineyard sites included in the LIFE ClimaMED monitoring network, Siva (Crete), Thourio (Central Greece) and Dilinata (Kefalonia), represent three distinct agro-ecological contexts of Mediterranean viticulture. Together they provide a composite picture of how management intensity, soil properties, input regimes, and biomass management shape GHG emissions. Despite the common crop, the vineyards differ markedly in age, soil fertility, input strategies, and mechanization levels, which allows a robust assessment of the relationship between vineyard practices and both LCA-based and LIDAR-based flux recording.

The Siva vineyard in Heraklion (Crete) is a mature, 10-year-old, semi-organic system established after a long history of olive cultivation. The vineyard is characterized by clay-loam soils with moderate organic matter, minimal synthetic inputs, systematic use of green manure, low irrigation (2–4 events per year only if necessary), and incorporation of pruning residues into the soil. Soil fertility is maintained predominantly through organic inputs (2 m^3 of mixed vetch–pea–broad bean biomass per 0.1 ha and 2 t ha^{-1} of mixed cow–sheep manure every second year), resulting in a system that is biologically active and less reliant on mineral fertilizers. These practices contribute to enhanced below-ground carbon inputs and moderated emissions.

In contrast, the Thourio vineyard in Central Greece is managed as a relatively intensive, high-yield system producing approximately 40 t ha^{-1}. The management is centered on annual applications of NPK fertilizer (12-12-17), frequent tillage (3–4 passes per year), several fungicide sprays during spring and early summer, and green pruning with petrol-powered equipment. Although residue management is partial, green residues and weed biomass remain on the soil while winter pruning residues are removed, the overall carbon balance is constrained by low soil organic matter and frequent disturbance. The LIDAR fluxes display emission pulses closely aligned with tillage operations, spraying and spring vegetative growth during cultivation period, demonstrating the high temporal sensitivity of the system to mechanical and chemical inputs (Fig. 2).

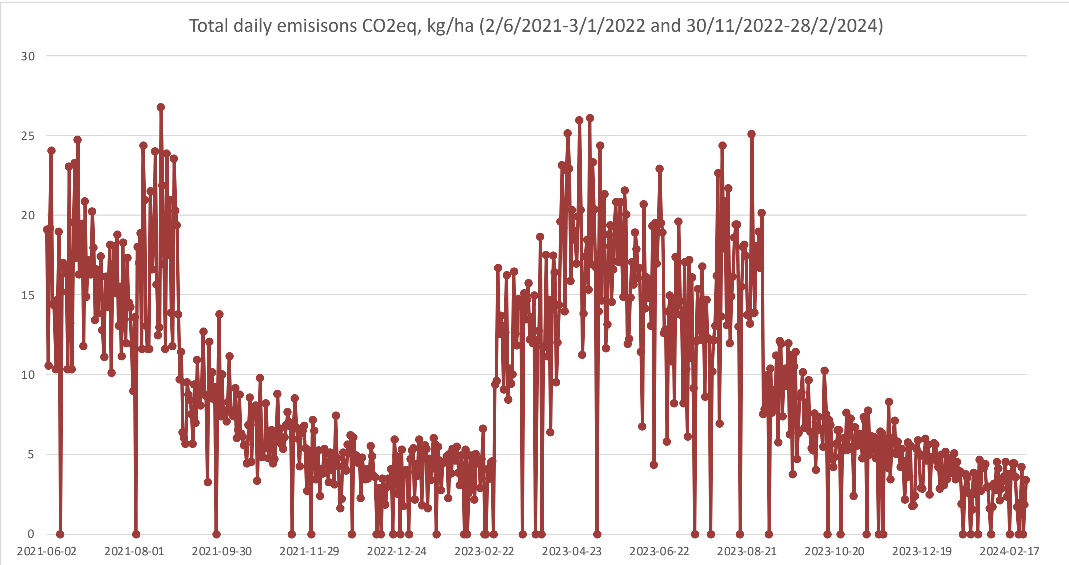

Figure 2. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (2/6/2021-3/1/2022 and 30/11/2022-28/2/2024) from the vineyard in Thourio.

The vineyard in Dilinata (Kefalonia) represents a newly established system transitioning toward full organic certification. The soil is clay-loam with low organic matter, moderately high calcium carbonate content, and limited nutrient availability. No synthetic fertilizers are applied; instead, sheep manure is used as the primary nutrient source, with complete absence of irrigation. The field underwent a two-year period of natural vegetation prior to planting, which provided initial organic matter, but tillage and soil disturbance during re-establishment have contributed to rapid mineralization and CO_2 release. Fuel use remains moderate, but LCA results indicate that repeated tillage for weed management and the incorporation of fresh residues generate significant CO_2eq contributions, reflected in the relatively high baseline emission estimates of 6.265 t CO_2eq ha^{-1} yr^{-1}.

Across the three vineyards, the combination of LCA and LIDAR data provides a coherent interpretation of how

At Thourio, emissions show sharp increases in early spring (tillage, fertilization), mid-spring (fungicide applications), and late spring (green pruning), aligned with the intensive management calendar (Fig. 2). The magnitude of daily CO_2eq peaks recorded in Fig.2 mirrors the LCA findings, which identify mineral fertilizers and diesel use as dominant contributors. This pattern is highly consistent with international studies showing that frequent soil disturbance and synthetic N fertilization are the strongest drivers of vineyard GHG emissions in warm climates (Payen et al., 2021; Bianchi et al., 2022). The absence of mulching or composting of prunings further reduces potential carbon retention.

In Dilinata, the LCA confirms that organic inputs, despite their long-term benefit for SOC, create measurable short-term CO_2 emissions when incorporated, which is consistent with findings from organic Mediterranean vineyards transitioning from natural vegetation (Aguilera et al., 2020; Chiti et al., 2021). The absence of irrigation reduces energy-related emissions but also maintains soil nutrients at sub-optimal levels, contributing to low yields and limited biomass return to the soil.

The three vineyards collectively demonstrate that GHG emissions in Mediterranean viticulture are strongly shaped by the intensity and timing of management operations. Organic or low-input systems (Siva, Dilinata) show lower background fluxes but higher decomposition events after organic matter additions, while intensive systems (Thourio) display short-term peaks aligned with mechanical and chemical operations. Soil organic matter and previous land use exert a strong legacy effect: fields with a history of continuous vegetation cover may exhibit smoother flux profiles, while recently disturbed fields (Dilinata) may show instability and higher mineralization rates.

Priority list of practices requiring improvement

- Reduction of tillage frequency, especially deep and repeated ploughing, which produces the highest CO_2 flux peaks across all vineyards.
- Optimization of synthetic fertilizer use, including split applications or partial replacement with compost to reduce N-driven emissions.
- Systematic retention and mulching of pruning residues, to enhance SOC and reduce removal-related carbon losses.
- Enhancement of groundcover management, shifting from bare soil periods to permanent or semi-permanent cover crops to stabilize emissions.
- Improved integration of organic amendments, ensuring incorporation under conditions that minimize rapid mineralization (moisture control, smaller doses).
- Limitation of unnecessary tractor passes, particularly during periods of high soil moisture, which amplify respiration and fuel-related emissions.
- Optimization of irrigation scheduling (when applicable) to avoid moisture-pulse emissions.

2.3 Cereals

The LIFE ClimaMED cereal pilot fields form ranges from a highly irrigated, high-yield maize field in Pyrgos, to an irrigated but moderately intensive wheat rotation in Elateia and a low-input rainfed oats–lupin system in Kefalonia. Together they illustrate how different combinations of fertilization, irrigation, tillage, residue management and rotations shape the GHG footprint. Similar contrasts between intensive and low-input Mediterranean cereals have been highlighted in several regional assessments (Soussana et al., 2010; Mairech et al., 2021).

In Central Greece, the Elateia field is a 1 ha plot embedded in a multi-year rotation (wheat–alfalfa–maize–cotton), managed with moderate mineral fertilization and mixed irrigation (rain guns and drip). The farmer applies a compound 9-22-22 fertilizer and ammonium sulphate as split applications during winter, reflecting a pattern consistent with typical Mediterranean fertilizer regimes described in wheat systems (Poggi et al., 2020). Fungicides are applied in March–April, while soil preparation relies on shallow ploughing and several cultivators passes. Harvest is fully mechanized, and straw is generally removed, limiting potential soil organic matter returns. This aligns with evidence showing that straw removal reduces SOC inputs and increases soil respiration responses after tillage (Taghizadeh-Toosi et al., 2014). No residue burning takes place and no livestock is present.

The Peloponnese pilot at Agios Ioannis represents an intensively managed 1.1 ha maize system on clay-loam soil, irrigated with high-pressure gun sprinklers. Management includes substantial nitrogen inputs, repeated tractor operations and mechanized harvesting. Baseline assessments point to high fuel consumption and electricity demand for pumping as the dominant drivers of GHG emissions. These structural drivers strongly match what Mediterranean maize LCA studies report as the principal contributors to GWP, energy for irrigation and nitrogen fertilizer manufacture and use (Payen et al., 2021).

In contrast, the Troyanata field in Kefalonia is a 1 ha rainfed oats system enriched with lupin as green manure. A modest dose of compound fertilizer is applied at sowing, with no irrigation and no pesticides. Tillage is deeper but infrequent and residues are retained, supporting organic matter recovery. This design is consistent with the low-input, legume-supported systems documented in dryland Mediterranean environments where N-fixation and residue retention help sustain yields under minimal external inputs (Aguilera et al., 2020; Chiti et al., 2021).

The Life-cycle assessment across the three sites highlights the trade-off between input intensity, yield and GHG emissions. Per unit of product, the rainfed oats system exhibits the highest carbon footprint (~0.585 kg CO_2-eq kg^{-1}) due to modest yields, consistent with observations that low-yield Mediterranean cereals typically show higher product-based GWP despite low absolute emissions (Mairech et al., 2021). Wheat in Elateia shows lower GWP (~0.49 kg CO_2-eq kg^{-1}), while high-yield maize in Pyrgos has the lowest intensity (~0.16 kg CO_2-eq kg^{-1}), illustrating the yield-dilution effect described in Mediterranean cereal LCA literature (Bianchi et al., 2022). Per hectare, however, the intensive maize system has the highest annual GHG emissions (~2.98 t CO_2-eq ha^{-1}), driven by irrigation energy and nitrogen fertilization. Wheat systems show intermediate emissions (~0.46 t CO_2-eq ha^{-1}), while oats–lupin displays the lowest (~0.11 t CO_2-eq ha^{-1}). These values align closely with Mediterranean meta-analyses identifying irrigation and nitrogen as the strongest hectare-scale emission drivers in cereals (Sanz-Cobeña et al., 2017).

LiDAR recordings of GHG fluxes over Elateia (Fig.3) and Pyrgos (Fig. 4) provide a dynamic picture of how operations drive emissions. In Elateia, a rise in CO_2-eq occurs following winter fertilization, precisely the pattern predicted by field-scale studies that show fertilization stimulates both autotrophic and heterotrophic respiration (Rey et al., 2011). Spring spraying generates also peaks, while harvest produces smaller but distinct pulses due to fuel combustion and canopy disturbance. Annual LiDAR emissions of ~2.13 t CO_2-eq ha^{-1} are consistent with the LCA once methodological differences are accounted for.

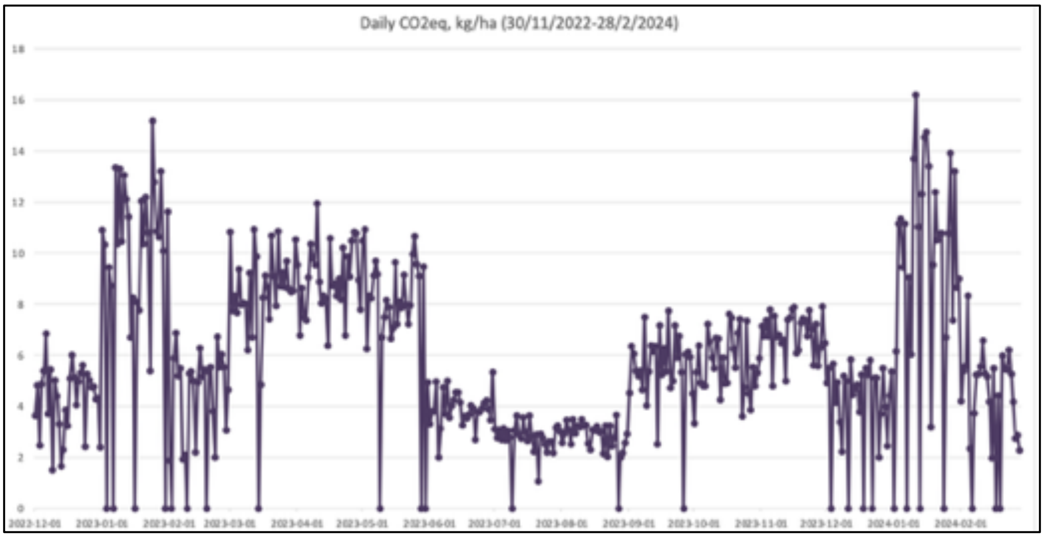

Figure 3. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (30/11/2022-28/2/2024) from the wheat field in Elateia.

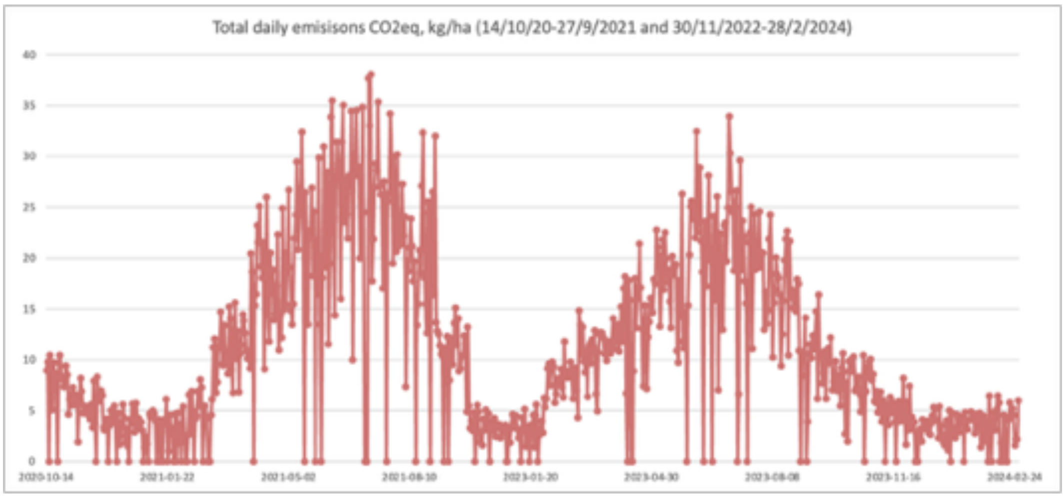

Figure 4. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (14/10/2020-27/9/2021 and 30/11/2022-28/2/2024) from the corn field in Peloponnese, Pyrgos.

In Pyrgos, LiDAR monitoring over two seasons captures the highly seasonal CO_2-eq dynamics of irrigated maize: near-zero winter fluxes followed by rapid increases from April onwards, with extreme peaks during June–July when irrigation, fertilization and canopy development coincide. These patterns closely mirror those reported in Mediterranean maize systems, where irrigation events and nitrogen inputs drive intense CO_2 and N_2O pulses (Payen et al., 2021).

The introduction of a compost amendment (~20 t ha^{-1}) in February 2023 provides a unique real-world demonstration of compost-induced GHG responses. The LiDAR record shows an emission window, with CH_4 production reflecting transient anaerobic microsites during decomposition, consistent with measurements from Mediterranean compost-amended arable soils (Aguilera et al., 2020). At the same time, reduced tractor hours in the subsequent season result in lower cumulative emissions, directly demonstrating the mitigation potential of optimized field operations (Fig. 5).

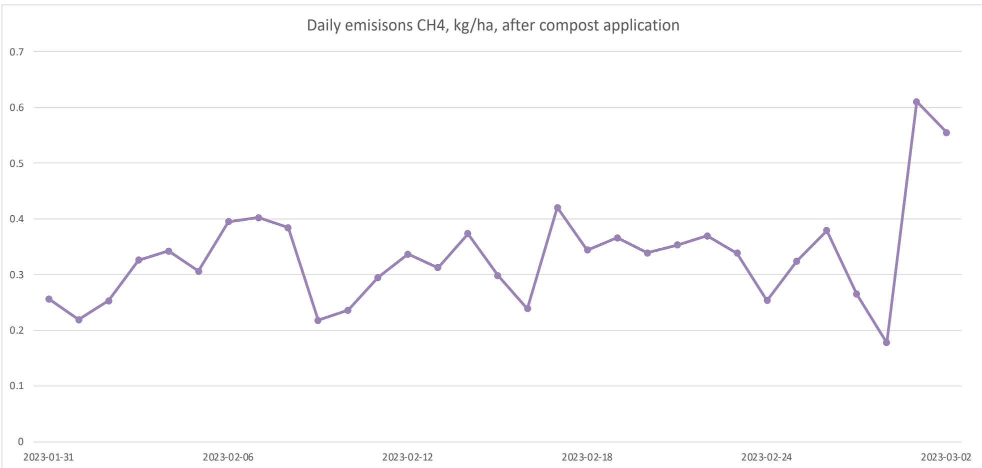

Figure 5. Methane (kg/ha) due to compost application in February 2023 at the corn pilot field in Peloponnese, Pyrgos.

The Troyanata field was not equipped with LiDAR, but its SOC status, rotation design and low annual emissions (0.11 t CO_2-eq ha^{-1}) align with other Mediterranean legume-supported systems capable of maintaining low GHG profiles when external inputs are minimal (Chiti et al., 2021).

Priority list of practices requiring improvement

- Optimize nitrogen fertilization through reduced application rates, split doses and soil-guided strategies.
- Improve irrigation efficiency by replacing gun sprinklers with low-pressure or drip systems and improving scheduling.
- Enhance residue and compost management, avoiding burning and favoring incorporation with balanced N supply.

- Reduce tillage intensity and tractor passes to lower both fuel use and mineralization.
- Expand legume-based rotations and cover cropping to improve SOC and reduce reliance on mineral N.
- Consolidate crop protection operations to minimize machinery passes and emissions linked to spraying.

These priorities provide a clear roadmap for transforming cereal cultivation from "typical" Mediterranean arable systems into demonstrators of low-emission, SOC-enhancing production, while remaining compatible with farmers' yield and economic objectives.

2.4 Vegetables

The vegetable pilot fields monitored under LIFE ClimaMED, located in Tympaki (Crete), Pyrgos–Katakolo (Peloponnese), and Heronia (Central Greece), represent the diversity and complexity of Mediterranean open-field horticulture. Although the specific crops cultivated during the project years varied (including sweet potato, lettuce, tomato, zucchini, carrots and other short-cycle vegetables), the agronomic reality is that farmers practicing open-field vegetable production frequently rotate crops from one season to the next. This rotational flexibility, typical of Mediterranean horticulture, leads to a management system characterized not by the identity of a single crop, but by a stable pattern of practices: high nutrient inputs, intensive irrigation, frequent soil disturbance, multiple pesticides applications, and rapid biomass turnover. Such structural characteristics exert a dominant influence on GHG dynamics, more so than the botanical identity of any given vegetable species (Aguilera et al., 2020; Castellano-Hinojosa & Strauss, 2022).

Across all three pilot fields, farmer questionnaires indicate a broadly consistent management profile. Mineral nitrogen fertilizers, most commonly ammonium nitrate, urea and NPK blends, are applied either before planting or as split applications during crop development. Organic amendments such as manure or compost are occasionally used but not systematically integrated, reflecting the typical pattern of Mediterranean horticulture where synthetic N remains the primary driver of yield (Sanz-Cobeña et al., 2017). Frequent irrigation is a defining feature: in Crete and the Peloponnese, vegetables were irrigated with high-pressure gun sprinklers or drip systems at intervals ranging from every 2–3 days in summer to weekly schedules in cooler months. Soil preparation was intensive, involving repeated ploughing, rotavation and bed formation, often conducted several times per year as crop cycles change. Crop protection practices included multiple insecticide and fungicide applications, closely aligned with the rapid phenology and high susceptibility of vegetable crops to pests and diseases. Residue management varied: some farmers incorporated crop residues, while others removed or burned them, with burning being a practice that continues to appear in Mediterranean horticulture despite legal restrictions.

The LCA analysis of the vegetable pilot fields reveals a characteristic pattern for Mediterranean horticulture: high emissions per hectare, driven primarily by fertilizers, irrigation energy and field operations. When normalized per unit of product, emissions vary widely depending on yield, since yields in vegetables can fluctuate strongly between seasons and between crop types. However, per-hectare emissions provide a clearer picture of system-level climate intensity. Similar to findings in southern Spain and Italy (Aguilera et al., 2020; Payen et al., 2021; Mairech et al., 2021), vegetables in Tympaki and Pyrgos show GHG profiles dominated by (i) CO_2 from fertilizer production, (ii) direct N_2O emissions following N application, (iii) CO_2 from fuel combustion during frequent soil preparation, and (iv) energy use for irrigation (Bartzas et al., 2025)

The Tympaki field, cultivated with sweet potato in one of the project years, is characterized by moderate nitrogen inputs and relatively stable drip irrigation. Sweet potato is known to produce high biomass, and residue incorporation after harvest provides organic matter to the soil, contributing to SOC recovery. However, the LCA results indicate that even in fields using organic fertilization, the cumulative effects of multiple tillage operations, mechanized ridging, drip system maintenance and tractor pass contribute significantly to GHG emissions. These findings align with studies indicating that even organic horticulture systems can exhibit substantial emissions if tillage intensity and frequent irrigation are maintained (Bhatia et al., 2020).

The Pyrgos–Katakolo field represents a more intensive system- per hectare emissions are high- with multiple crop rotations, high fertilizer use and substantial irrigation requirements. The presence of short-cycle vegetable crops amplifies operational intensity, as soil is repeatedly disturbed, irrigation lines are installed and removed, and pesticide applications are frequent. This is consistent with Mediterranean horticultural LCAs, which repeatedly show that field operations can contribute 20–40% of total GWP in short-cycle crops (Castellano-Hinojosa & Strauss, 2022).

The Heronia field, although cultivated with vegetables during one project year, demonstrates the same structural pattern: nitrogen-driven emissions dominate, intensified by irrigation frequency and mechanical soil preparation. Even when fertilizer quantities are moderate, the absence of long-term ground cover and the repeated disturbance of soil lead to elevated mineralization rates, which increase emissions in line with established evidence from Mediterranean horticultural soils (Mairech et al., 2021).

LiDAR-based monitoring in vegetable systems provides consistent temporal features. For Pyrgos–Katakolo (Fig. 6), the CO_{2eq} (kg/ha) emitted the entire monitoring period (30/11/2022-28/2/2024). The interval March–August captures the full window during which tomato-related soil respiration, fertilizer-induced emissions, irrigation-related impacts, and machinery operations actively influence field-level GHG dynamics. Low fluxes can be seen in winter which increase from March (sowing and early growth), peaking between May and July (maximum canopy, irrigation, frequent pesticide applications and mechanical harvesting), and declining after August as the field returns to a low-activity state

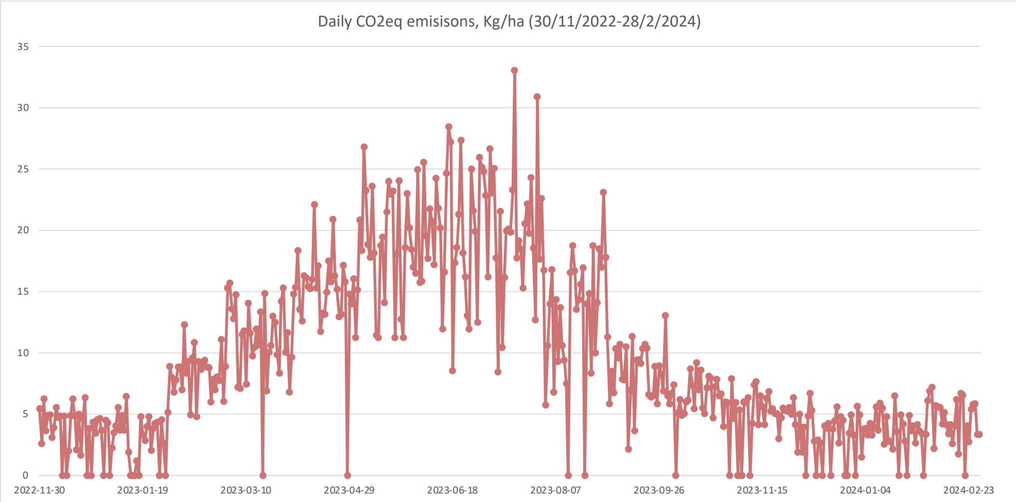

Figure 6. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (30/11/2022-28/2/2024) from the tomatoes field in Peloponnese, Katakolo.

Farmer's practices in Tympaki field (Fig. 7) were also well captured by the LIDAR device. Moderate fluxes during winter can be seen, due to green manure growth, increasing emissions in spring during tillage and incorporation of the cover crop, high fluxes from May to September driven by vegetable and potato growth, harvesting operations, and intermediate emissions in October–November during the transition between cash crops and cover crops.

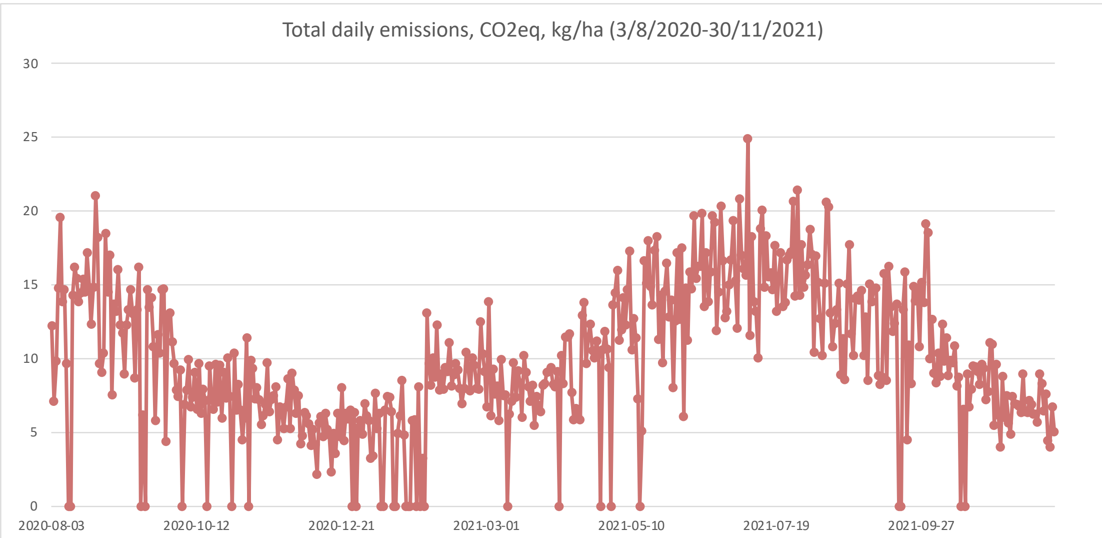

Figure 7. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (3/8/2020-30/11/2021) from the vegetable field in Tympaki.

These findings mirror extensive Mediterranean literature showing that vegetables represent one of the most GHG-intensive crop groups due to their input requirements and high production intensity (Mairech et al., 2021; Aguilera et al., 2020).

Therefore, the Mediterranean open-field horticulture is inherently high-emission per hectare, driven by the combination of:

- high nitrogen inputs,
- frequent irrigation,
- repeated soil disturbance,
- rapid decomposition of residues,
- and intensive machinery use.

Priority list of practices requiring improvement

- Reduce mineral nitrogen inputs and adopt split applications, soil testing, or partial substitution with compost.
- Improve irrigation scheduling and transition from high-pressure sprinklers to drip systems where possible.
- Minimize soil disturbance by reducing the frequency of tillage and adopting conservation horticulture approaches.
- Shred and incorporate residues instead of burning, and integrate compost/organic matter to support SOC.
- Consolidate pesticide applications and reduce tractor passes to minimize fossil-fuel emissions.
- Introduce cover crops or temporary ground cover between vegetable cycles to stabilize SOC and reduce erosion.

2.5 Pistachio orchards

The three pistachio orchards monitored in LIFE ClimaMED, located in Aegina Island, Nea Ambliani (Lamia region) and Pontoherakleia (Central Macedonia), represent a rare opportunity to examine GHG dynamics in Mediterranean *Pistacia vera* systems across highly contrasting agro-ecological, climatic and management conditions. Although all three orchards cultivate the same species, their agronomic behavior, environmental constraints and management intensity differ sharply, leading to distinct GHG signatures when evaluated through field data, LCA inventories and LiDAR monitoring. This diversity mirrors observations from international Pistacia vera studies showing large emission differences depending on water availability, pest pressure, fertilization strategy and residue management (Behboudian & Treeby, 2020; Salami et al., 2021).

The Aegina orchard represents a traditional, decades-old pistachio system embedded in the semi-arid microclimate of the Saronic Gulf. The orchard is irrigated and experiences high pest and disease pressure, particularly during humid years, necessitating frequent pesticides applications, typically 4–6 sprays per year according to LCA records. Such patterns are consistent with published work showing that Greek pistachio orchards, especially those on Aegina, face significant fungal and bacterial challenges, leading to recurrent copper-based treatments (Psarrakis et al., 2019; Matsi et al., 2020). Fertilization intensity is moderate, consisting of single annual basal applications. Soil disturbance is infrequent; pruning occurs annually and residues are generally removed rather than incorporated. Overall, the system exhibits a "medium-input" profile: limited irrigation and fertilizer inputs but frequent pesticides applications driven by phytopathological constraints.

The Nea Ambliani orchard in Central Greece reflects a more modernized, fully irrigated pistachio system with systematic canopy management, structured fertilization and high inputs. The orchard is irrigated during the dry season using drip lines, receiving multiple fertigation events. Nitrogen inputs are higher than in Aegina, consisting of mineral fertilizers applied in early spring and supplemented throughout the season. Pest management is regular, with 7–9 sprays per year. The orchard undergoes more frequent soil management operations, including mowing, surface tillage and mechanized pruning. This combination of irrigation, fertilization and phytosanitary intensity aligns with what the literature describes as "high-input Mediterranean nut orchards," which tend to produce elevated direct and indirect GHG emissions (López-Bellido et al., 2016; Aguilera et al., 2020).

The Pontoherakleia orchard, located in Central Macedonia, lies between the two extremes. It is a partially irrigated system with moderate nitrogen fertilization and relatively few pesticides applications (2–3 per year). Soil preparation is occasional and pruning residues are often removed. Management intensity is therefore "intermediate," characterized by limited inputs but higher rainfall and cooler temperatures compared to Aegina, leading to different seasonal emission dynamics.

The Life-cycle assessment across the three orchards highlights sharp differences in per-hectare GHG emissions linked to irrigation, fertilization and plant protection intensity. The orchard in Nea Ambliani exhibits the highest per-hectare emissions, dominated by upstream CO_2 equivalents from fertiliser manufacture, energy use for irrigation and multiple pesticide applications. These findings closely match LCA results from irrigated pistachio systems in Italy, Iran and California, where irrigation and nitrogen dominate total GWP (Behboudian & Treeby, 2020; Salami et al., 2021).
In Aegina, emissions per hectare are lower in absolute terms due to the lower fertilizer inputs, but the LCA reveals that repeated spraying contributes a significant share of the total footprint. This pattern agrees with literature documenting that pesticides applications can represent up to 30–40% of orchard GHG emissions in low-input perennial systems (Mazzi et al., 2019).

The Pontoherakleia orchard shows the lowest total emissions among the three due to limited irrigation and moderate fertilization. However, yield levels are also lower, highlighting the trade-off between low per-hectare emissions and higher per-kilogram emission intensities that characterize many low-input Mediterranean orchards (Aguilera et al., 2020).

GHG fluxes from the ClimaMED LiDAR system offer valuable temporal resolution, revealing emission patterns consistent with perennial nut trees under Mediterranean conditions.

For Nea Ambliani orchard (Fig. 8, the monitoring period (22/10/2020–22/10/2021was a high-production year, emissions were distributed according to pistachio phenology and management intensity, including fertilization, pesticide spraying (April–July) and harvest-related activities (August). All these activities are reflected in Fig.8, where increased emissions are recorded.

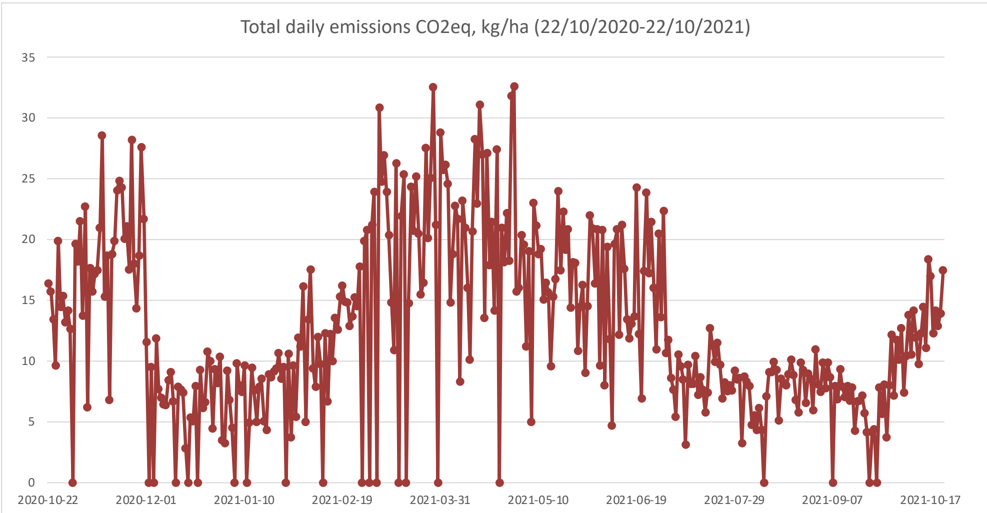

Figure 8. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (22/10/2020-22/10/2021 from the pistachio orchard in Lamia.

GHG emissions in Fig. 9, for the pistachio orchard in Aegina Island follow a seasonal pattern strongly linked to pistachio phenology and management intensity:

- February - June: highest emissions, due to active root growth, soil microbial processes and fertilizer applications.
- October - November: a peak coinciding with autumn fertilization and the first rains.
- July - August: lowest emissions, due to drought stress and reduced biological activity.
- December pruning and burning

These temporal fingerprints confirm that pistachio orchards, particularly irrigated ones, exhibit dynamic GHG profiles strongly influenced by operations, moisture pulses and nitrogen availability.

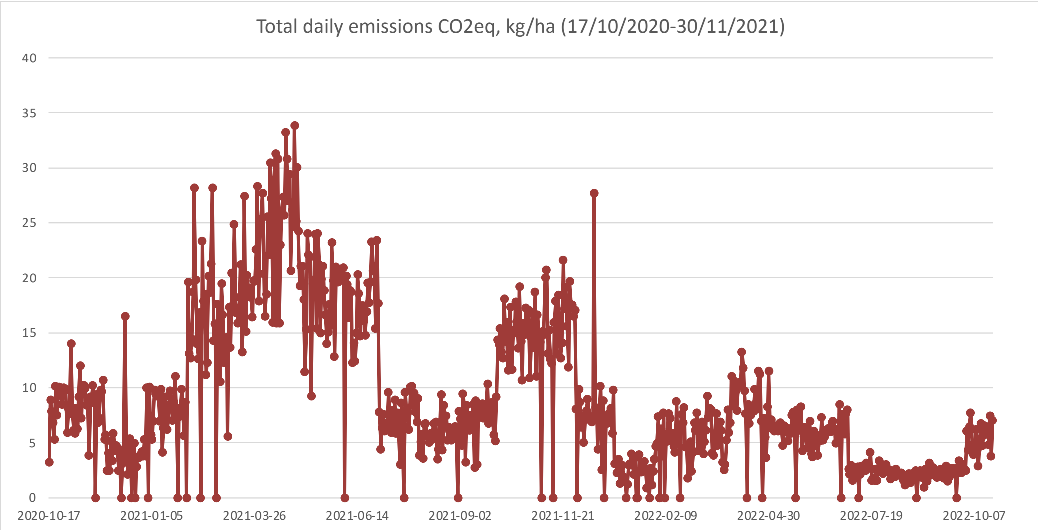

Figure 9. Daily CO_{2eq} (kg/ha) emitted the entire monitoring period (22/10/2020-22/10/2021 from the pistachio orchard in Aegina Island.

Priority list of practices requiring improvement

- Reduce nitrogen fertilization rates and align applications with phenological demand, using split doses and soil analyses.
- Optimize irrigation practices in irrigated orchards (e.g., improved scheduling, pressure reduction, or alternative energy sources).
- Rationalize pesticides application, reducing unnecessary passes through targeted application timing and integrated pest management.
- Manage pruning residues through shredding and soil incorporation, rather than removal or burning, to enhance soil organic matter.
- Reduce tractor operations, especially during wet periods, to limit fuel-related CO_2 and soil disturbance.
- Expand groundcover management to stabilize soil carbon and reduce erosion.

3. Good practices for GHG reduction-Proposals to MINAGRIC

3.1 Olive orchards

Building on LIFE ClimaMED findings and on Mediterranean literature (Aguilera et al., 2020; López-Bellido & Wery, 2016; Salvati & Bajocco, 2017), a set of concrete management practices can be recommended to reduce emissions in olive groves.

Elimination of pruning-residue burning and promotion of shredding, mulching and composting

Description and benefits

Burning of pruning residues is one of the clearest emission hotspots in the ClimaMED olive orchards, producing short but extremely intense CO_2 peaks and adding to particulate and air-quality problems. Shredding prunings and either incorporating them into the soil or using them as mulch returns carbon and nutrients to the soil, improves structure and water retention, and reduces erosion. Mediterranean LCA and field studies consistently show that eliminating burning and recycling prunings substantially improves the GHG balance of olive groves and increases SOC over time (Aguilera et al., 2020; Mazzi et al., 2019).

Implementation options

- Purchase or cooperative use of tractor-mounted or self-propelled shredders.
- Leaving shredded prunings in the tree row as surface mulch, or lightly incorporating them in the inter-row.
- Centralized composting of prunings, alone or mixed with other organic wastes such as olive pomace, with the finished compost brought back to orchards.

Difficulties and constraints

- Initial investment in shredders or composting infrastructure.
- Need for training on safe, practical use of shredders and on composting management.
- In steep or terraced groves, machinery access can be limited.

Controlled manure and grazing management in mixed olive–livestock systems

Description and benefits

Moving from unmanaged grazing to controlled stocking rates, planned grazing periods and composted manure application can keep the benefits of such mixed systems (high SOC, reduced need for mineral fertilizers) while limiting GHG and water-quality risks. Similar "silvo-pastoral" systems in Mediterranean orchards show good potential for SOC maintenance when grazing pressure is moderate (Mairech et al., 2021; Psarrakis et al., 2019).

Implementation options

- Establish rotational grazing instead of permanent free access.
- Define maximum livestock units per hectare.
- Collect part of the manure in simple covered yards, compost it and apply it in measured doses.

Difficulties and constraints

- Requires coordinated management.
- Farmers may perceive rotational systems as more labor-demanding.

Optimized fertilization: reduced mineral N, soil testing and organic sources

Description and benefits

Even in medium-input systems, applying more nitrogen than trees can use leads to GHG emissions and accelerates SOC decomposition. Aligning N doses with measured soil and leaf nutrient status, using split applications and substituting part of mineral N with organic sources can strongly reduce the fertilizer-related GHG component (Aguilera et al., 2020; Matsi et al., 2020). Mediterranean studies show that moderate N rates combined with cover crops and organic amendments can maintain or increase yields while improving SOC (López-Bellido & Wery, 2016).

Implementation options

- Regular soil and leaf analyses.
- Splitting N applications (early spring + after fruit set).
- Progressive partial substitution of mineral N with compost.

Difficulties and constraints

- Cost of analyses and advisory services.
- Need for safe composting of olive-mill residues.
- Farmers may fear yield reductions.

Reduced tillage and use of spontaneous or sown cover crops

Description and benefits

Frequent tillage accelerates SOC mineralization and increases erosion. Maintaining a spontaneous or sown herbaceous cover between tree rows has been shown in Spain, Italy and Greece to increase SOC, reduce erosion and often improve water infiltration, with neutral or positive effects on yields (Aguilera et al., 2020; Rey et al., 2011; Salvati & Bajocco, 2017).

Implementation options

- Replace deep ploughing with shallow or strip tillage.

- Maintain spontaneous vegetation and control it by mowing.
- Introduce legumes or grass–legume mixtures where water availability allows.
- Alternate cover crops between rows to reduce water competition in dry areas.

Difficulties and constraints

- Farmers often fear water competition; species and timing must be adapted to local rainfall.
- Mowing equipment may be needed for steep or terraced landscapes..

Improved irrigation efficiency and energy use in irrigated olive orchards

Description and benefits

Improving water-use efficiency and moving from diesel pumps to electric or solar-powered systems directly reduces GHG emissions and improves water productivity. Similar patterns are documented in irrigated olive systems across the Mediterranean (Behboudian & Treeby, 2020; López-Bellido & Wery, 2016).

Implementation options

- Transition to low-pressure drip irrigation.
- Scheduling irrigation based on soil-moisture sensors.
- Replacing diesel pumps with solar or grid-connected pumps.

Difficulties

- High initial investment.
- Limited grid access in remote areas.
- Technical complexity of setting up monitoring tools.

Rationalization of machinery use and phytosanitary treatments

Description and benefits

Tractor passes for spraying, tillage and harvesting contribute significantly to fuel-related emissions. In addition, repeated pesticide treatments in disease-prone areas increase the LCA footprint. Integrating pest monitoring, decision-support tools and combined field operations can reduce both fuel use and input volumes (European Commission, 2022).

Implementation options

- Use pest and disease thresholds and forecasting tools.
- Combine compatible field operations in a single pass.
- Promote low-drift equipment and proper sprayer calibration.
- Use GPS-guided systems where available to reduce overlapping
- Maintain machinery and calibrate sprayers to reduce fuel and chemical use

<u>Difficulties</u>

- Requires advisory services and decision-support tools.
- Perception that more frequent operations increase yield security.

Proposals to MINAGRIC

To move from pilot evidence to widespread adoption, the above practices must be supported by targeted policy instruments. The Greek CAP Strategic Plan 2023–2027 already includes eco-schemes and agri-environment-climate measures that can be used or adapted to olive-grove mitigation and SOC building, in line with EU-wide CAP guidance (European Commission, 2022; European Court of Auditors, 2021).

1. Design and strengthen eco-schemes specifically for olive groves. Eco-schemes should reward:

- non-burning of prunings,
- maintenance of groundcover,
- reduced tillage.
- nitrogen optimization based on soil/leaf analysis.

Payment levels should reflect extra costs and income foregone, following examples from Spain and Italy (Montero et al., 2020; FAO, 2022).

2. Support investment in machinery and renewable energy. Targeted grants for shredders and mulchers, composting infrastructure, drip irrigation and soil-moisture sensors, solar-powered pumps.

3. Integrate olive-grove carbon farming into national CAP instruments. Develop a national "olive carbon farming" scheme aligned with the EU Carbon Removal Certification Framework (FAO, 2022; European Commission, 2022).

4. Strengthen advisory services and training, focusing on cover crops and reduced tillage, composting, irrigation efficiency, integrated nutrient management.

5. Phase-out burning of prunings with a realistic transition. Gradual restrictions combined with subsidies for shredders and cooperative services.

6. Embed GHG and SOC monitoring. Use the ClimaMED methodology for Tier-3 monitoring of eco-schemes, ensuring payments correspond to real improvements.

3.2 Vineyards

Across the three ClimaMED sites, common emission drivers emerge: nitrogen fertilization, intensive soil preparation, frequent tractor use, and irrigation, especially in warmer regions. Conversely, SOC accumulation is favored by permanent or seasonal groundcover, reduced tillage, incorporation of prunings, and moderating synthetic fertiliser inputs. These observations are consistent with regional studies showing that vineyard GHG balances are highly sensitive to soil and canopy management choices (Bosco et al., 2011; Barba et al., 2021).

Below, a set of key mitigation practices is presented. These concrete management measures can be recommended to reduce emissions in vineyards (for practices similar to those applied in olive orchards, see the relevant section above).

Elimination of burning of pruning residues and adoption of shredding / incorporation
(same as for olive orchards)

Reduced tillage and use of cover crops (spontaneous or sown)
(same as for olive orchards)

Optimized fertilization: reduced mineral N, soil testing and organic sources
(same as for olive orchards)

Irrigation efficiency and energy reduction
(same as for olive orchards)

Machinery-use rationalization and combined field operations
(same as for olive orchards)

Integrated pest management (IPM) and reduced pesticide inputs

Description and benefits

Phytosanitary applications in the ClimaMED vineyards were substantial. Transitioning to IPM, based on monitoring thresholds, forecasting models and selective treatments, reduces chemical use and associated emissions. Studies confirm that Mediterranean vineyards adopting IPM reduce pesticide use by 20–50% while maintaining yields (Barba et al., 2021).

Implementation options

- Install pheromone traps, disease models and weather stations.
- Use resistant varieties when replanting.
- Train producers in selective applications and low-drift technologies.
- Use decision-support tools for pests' disease prediction.
- Switch to selective low-dose formulations where possible.
- Combine compatible treatments in fewer passes.

Difficulties

- Requires advisory support and digital tools; small producers often lack access.
- High disease pressure years may still require chemical interventions.

Proposals to MINAGRIC

MINAGRIC must embed the above practices in CAP measures, advisory services and investment support.

1. Vineyard-specific eco-schemes in the CAP Strategic Plan. Eco-schemes should reward:

- non-burning and shredding of vine prunings,
- maintenance of groundcover or sown cover crops,
- reduced tillage,
- nitrogen optimization based on soil/leaf analysis.

2. Investment support for low-emission vineyard practices. Targeted Pillar II-style grants should fund shredders for vineyard residues, composting infrastructure, drip-irrigation systems and soil-moisture sensors, solar-powered pumps, GPS-guided machinery, in alignment with EU recommendations for climate-targeted CAP spending (European Commission, 2022).

3. Integrate vineyards into national carbon farming schemes. Develop a "vineyard carbon farming" pathway in Greece that rewards measurable emission reductions and SOC increases, using the ClimaMED monitoring system as a Tier-3 tool.

4. Strengthen advisory services and regional demonstration networks. Create vineyard-focused advisory modules on cover cropping under Mediterranean drought, compost use and N optimization, IPM and digital tools for disease forecasting, machinery calibration and route optimization. Demonstration vineyards, such as the ClimaMED pilots—should act as learning hubs.

5. Phase-out burning of vine prunings with realistic support. A gradual prohibition of burning, combined with eco-scheme payments for non-burning, subsidies for shredders, cooperative residue-management services.

6. Require light SOC and GHG monitoring for climate-related payments. Every vineyard receiving support for carbon-related measures should monitor GHG and SOC at 5-year intervals and adopt simplified activity reporting based on the ClimaMED methodology.

3.3 Cereals

During LIDAR monitoring of the pilot cereals fields of LIFE ClimaMED, emissions peaks were recorded during fertilization, tillage operations and periods of rapid residue breakdown. Below is a structured set of mitigation options tailored to Mediterranean cereals.

Residue retention and controlled incorporation (instead of burning or full removal)

Description and benefits

Residue handling determines the intensity of microbial decomposition pulses visible in GHG fluxes. Burning or removing residues reduces surface protection and increases the amplitude of CO_2 pulses after tillage or rainfall. Shredding and incorporating residues in controlled doses moderate decomposition rates and avoid burning-related CO_2 spikes. Mediterranean studies confirm that residue retention reduces GHG emissions over the cropping cycle (Aguilera et al., 2020; Taghizadeh-Toosi et al., 2014).

Implementation options

- Chop wheat straw or maize stalks and incorporate them shallowly.
- Avoid burning; use shredders or mulchers.
- Apply residues gradually to reduce nitrogen immobilization.

Difficulties

- Straw can interfere with seeding if poorly managed.
- High C:N residues may require adjusted N application timing.

Reduced tillage and conservation soil management

Description and benefits

Reducing tillage intensity or frequency lowers fuel consumption and moderates soil-respiration surges. Mediterranean studies show that conservation tillage reduces total GHG emissions substantially by reducing machinery use and limiting aeration-induced CO_2 pulses (Aguilera et al., 2020; Chiti et al., 2021).

Implementation options

- Replace deep ploughing with shallow cultivation.
- Use strip-tillage or minimum tillage in wheat and maize.
- Use roller-crimpers to terminate vegetation instead of repeated tillage.

Difficulties

- Weed control must be adapted.
- Some machinery adjustments may be needed.

Optimized nitrogen fertilization and reduced over-application

Description and benefits

Nitrogen fertilization was the largest single emission contributor in all ClimaMED cereal fields. Over-application of N leads to enhanced GHG fluxes and indirect GHG emissions from fertilizer manufacture. Mediterranean studies confirm that matching N supply to crop demand, splitting applications and avoiding excessive basal N reduce emissions significantly (Sanz-Cobeña et al., 2017; Poggi et al., 2020; Bianchi et al., 2022).

Implementation options

- Base fertilizer rates on soil nitrogen tests or periodic soil analyses.
- Split N applications:
- Wheat: basal + tillering + stem elongation
- Maize: early vegetative + pre-tasseling
- Use stabilized organic fertilizers in low-input systems.

Difficulties

- Requires advisory support.
- Farmers may perceive yield risk; demonstration fields help overcome hesitancy.

Irrigation efficiency and reduced fossil-fuel pumping
(same as for olive orchards)

Legume integration as a tool for lowering synthetic nitrogen demand

Description and benefits

Legume rotations reduce synthetic N needs and spread fertilization more evenly across the cropping system, as it was shown in the pilot field in Troyanata, in which the oats–lupin rotation demonstrated much lower fertilizer use and consequently lower GHG emissions.

Implementation options

- Introduce vetch, fava bean, or lupin into rotations.
- Alternate cereals and legumes annually.
- Terminate legumes with shallow tillage or rolling to avoid disruptive soil disturbance.

Difficulties

- Market access for pulses may limit large-scale adoption.
- Harvesting equipment may need adjustments.

Machinery optimization and reduction of redundant field passes
(same as for olive orchards)

Proposals to MINAGRIC

Mediterranean cereals, especially irrigated maize and intensively managed wheat, generate some of the highest GHG emissions among arable crops. To enable nationwide improvements, MINAGRIC can integrate the following policy measures aligned with the CAP Strategic Plan 2023–2027 and EU climate commitments (European Commission, 2022; European Court of Auditors, 2021).

1. Eco-schemes specifically for GHG reduction in cereals. Payments should reward residue retention (no burning), reduced tillage, nitrogen optimization (soil testing + split applications), precision fertilization technologies, legume rotations as a tool for lowering synthetic N use.

2. Investment support for irrigation efficiency and renewable pumping, funding drip/low-pressure systems, soil-moisture sensors, solar-powered pumping for maize and irrigated wheat.

3. Integration of cereals into national GHG mitigation schemes. Develop a cereal-focused mitigation pathway using the ClimaMED methodology for CAP climate payments.

4. Strengthened advisory services by creating modules on reduced tillage, N-splitting, improved irrigation scheduling, machinery optimization.

5. Cooperative machinery-sharing platforms to promote shared access to shredders, strip/minimum tillage seeders, precision sprayers.

6. Simple GHG monitoring requirements. Require minimal activity reporting (fertiliser amounts, irrigation hours, machinery passes) for participation in cereal-related eco-schemes.

3.4 Vegetables

The vegetable pilot fields of LIFE ClimaMED represent three characteristic expressions of Mediterranean open-field horticulture. Although crop identity rotated annually (sweet potato, lettuce, tomato, zucchini, carrots and other short-cycle vegetables), the underlying management logic remained stable: high nitrogen inputs, frequent irrigation, repeated soil disturbance, multiple pesticides treatments and rapid biomass turnover. These features strongly shape GHG emissions, more so than the specific vegetable species cultivated, a pattern widely recognized in Mediterranean horticultural research (Aguilera et al., 2020; Castellano-Hinojosa & Strauss, 2022; Mairech et al., 2021).

A set of practices tailored to Mediterranean open-field vegetables are:

Elimination of residue burning and promotion of residue incorporation / composting

Description and benefits

Residue burning, still observed episodically in open-field vegetable systems, creates intense, short-lived CO_2 emission peaks. Incorporating residues or composting them increases SOC, improves soil structure and enhances water retention. Studies in Mediterranean horticulture show that composting and residue incorporation reduce GHG emissions over multi-year cycles and support soil biological activity (Bhatia et al., 2020).

Implementation options

- Shredding residues with small mobile choppers.
- Incorporating residues into beds before planting the next crop.
- Using cooperative composting facilities for high volumes of crop waste.

Difficulties

- Labor and machinery needs between successive short cycles.
- Risk of nitrogen immobilization if residues are very carbon-rich unless combined with balanced fertilization-need for expert advice.

Reduced soil disturbance and adoption of conservation horticulture

Description and benefits

Frequent deep tillage was recorded at all three ClimaMED sites. typical practice of Mediterranean horticultural fields, which, however, mineralizes organic matter rapidly under warm conditions (Rey et al., 2011). Reducing tillage frequency or depth, and integrating shallow cultivation, strip tillage or minimal-tillage systems, slows SOC losses, reduces GHG emissions and improves soil structure.

Implementation options

- Replace deep ploughing with shallow rotavation only when necessary.
- Maintain partial groundcover between cycles when agronomically feasible.
- Introduce reduced-tillage planting beds for repetitive crops (lettuce, zucchini).

Difficulties

- Difficult in heavy soils or when preparing beds for delicate seedlings.
- Weed pressure may increase initially before stabilizing.

Optimized nitrogen fertilization and partial substitution with organic sources

Description and benefits

Nitrogen fertilization is the largest emission driver in vegetable systems. Excess mineral N leads to high indirect CO_2 from fertilizer production and direct N_2O emissions. Mediterranean literature shows that aligning N supply with crop demand, using split applications and complementing mineral N with compost or organic fertilizer can significantly reduce emissions without compromising yield (Sanz-Cobeña et al., 2017; Poggi et al., 2020).

Implementation options

- Use soil nitrate rapid tests or regular soil/leaf analyses.
- Apply N in 2–4 smaller doses instead of one large basal dose.
- Integrate compost or manure at stable, controlled doses.

Difficulties

- Advisory support is often required for proper N scheduling.
- Organic amendments must be well-stabilized to prevent phytotoxicity.

Irrigation efficiency: improved scheduling and reduced pumping emissions
(same as for olive orchards)

Integrated pest management (IPM) and rationalized pesticide use
(same as for olive orchards)

Use of organic mulches and soil-improving amendments

Description and benefits

Mulching with compost, shredded residues or other organic materials improves SOC, reduces soil evaporation and moderates temperature, important benefits for Mediterranean climates. Studies consistently show that mulching reduces soil CO_2 peaks after irrigation and smoothens temperature-driven respiration pulses (Aguilera et al., 2020; Bhatia et al., 2020).

Implementation options

- Apply composted material between rows or on bed surfaces.
- Combine mulching with reduced tillage.

Difficulties

- Availability of affordable organic materials.
- Risk of bringing weed seeds if materials are not properly composted.

Proposals to MINAGRIC

Mediterranean open-field horticulture is one of the most GHG-intensive agricultural sectors due to its high input use, frequent operations and short cultivation cycles. To support widespread adoption of mitigation practices, MINAGRIC can embed the following actions into national policy frameworks, fully aligned with the CAP Strategic Plan and EU climate objectives :

1. Introduce a dedicated eco-scheme for low-emission horticulture. Payments should reward elimination of residue burning, reduced tillage, groundcover or mulching between cycles, nitrogen optimization based on soil testing, drip irrigation and efficient scheduling.

2. Targeted investment support for equipment and infrastructure. Supported investments should include shredders and composting units for vegetable residues, drip-irrigation systems and sensors, solar-powered pumps for irrigated horticulture, precision sprayers and GPS-guided tractors.

3. Integrate vegetables into national carbon-farming schemes. Given the large SOC losses associated with intensive tillage, vegetables are strong candidates for SOC-linked payments. The ClimaMED monitoring system can act as a Tier-3 monitoring basis.

4. Strengthen advisory services and farmer training to provide specialized training on low-tillage horticulture, compost use and residue management, irrigation optimization, PM and selective spraying. Regional demonstration fields should illustrate cost–benefit outcomes and build farmer confidence.

5. Create cooperative or municipal services for residue management to prevent burning. Local services could offer on-site shredding, collection of residues, shared composting facilities.

6. Embed GHG and SOC monitoring into climate-related payments. Require light-touch GHG and SOC monitoring every 3–5 years for farms receiving soil-related payments. The ClimaMED protocol can provide harmonized methods.

3.5 Pistachios

The LIFE ClimaMED pistachio pilot fields represent the dominant types of Mediterranean pistachio production. Across these systems, the LiDAR measurements and LCA results consistently revealed that GHG emissions are driven by: (i) intensive pesticide spraying, (ii) high diesel use for machinery and irrigation, (iii) nitrogen fertilization, and (iv) pruning-residue handling. These patterns mirror international evidence showing that pistachio systems, although perennial, can exhibit high emission intensities when pest pressure and mechanized operations are frequent (Behboudian & Treeby, 2020; Mairech et al., 2021).

A set of practices tailored to Mediterranean pistachio orchards are:

Elimination of pruning-residue burning and adoption of shredding / mulching
(same as for olive orchards)

Rationalization of pesticide spraying through IPM
(same as for olive orchards)

Optimized nitrogen fertilization and reduced over-application
(same as for olive orchards)

Reduced soil disturbance and modification of orchard floor management

<u>Description and benefits</u>

Reduced tillage lowers fuel use and decreases the amplitude of respiration peaks. For areas similar to Aegina, the challenge is rocky and terraced terrain rather than deep tillage, but excessive weed removal still increases machinery use.

Implementation options

- Shift from deep ploughing to light cultivation or mowing.
- Maintain low-growing vegetation in inter-rows where feasible.
- Reduce frequency of weed-control passes.

Difficulties

- Fear of increased pest habitat.
- Steep terraces limit mechanization options.

Machinery-use optimization and reduction of redundant passes
(same as for olive orchards)

Proposals to MINAGRIC

Mediterranean pistachio systems present a unique combination of high pest pressure (especially in islands), fragmented holdings, and diverse soil conditions. To enable GHG-efficient production, MINAGRIC can adopt the following measures:

1. Eco-schemes tailored to pistachio orchards by rewarding non-burning of prunings, reduced tillage or vegetation cover maintenance, IPM adoption and reduced spraying frequency, nitrogen optimization (soil and leaf analysis).

2. Investment support for island and mainland orchards. Subsidies shredders and mulchers, sprayer modernization and calibration tools, renewable-powered pumps where irrigation exists.

3. Integration of pistachio orchards into national GHG-mitigation scheme by exploiting the ClimaMED LiDAR-based methodology for GHG-related CAP payments in perennial nut crops.

4. Strengthening advisory services in pistachio pest management to support for fungal-disease forecasting, selective pesticide strategies, monitoring-based interventions, combining multiple field operations to reduce fuel use.

5. Cooperative services for residue management. Particularly for islands shredding services shared across small orchards and communal stations for residue handling.

6. Activity-based GHG reporting. Require basic reporting of fertilizer use, spraying frequency, and machinery passes to participate in pistachio-related eco-schemes.

4. Horizontal measures for GHG emissions reduction

Beyond crop-specific interventions, several horizontal measures can significantly strengthen the transition of Mediterranean agriculture toward lower GHG emissions. Together, these cross-cutting measures provide the structural backbone needed to scale up the crop-specific recommendations identified in this deliverable and enable a consistent, country-wide reduction of agricultural GHG emissions:

1. Establishing a national digital farm-activity registry, fully synchronized with GHG monitoring systems, would allow systematic reporting of fertilization events, machinery use, irrigation volumes and pesticide applications, providing a supporting database to the LIFE ClimaMED monitoring system.
2. Expanding cooperative service models (shared shredders, calibrated sprayers, mobile advisory units, soil and irrigation diagnostics) would reduce redundant field operations, particularly in the small and fragmented holdings that characterize Mediterranean landscapes.
3. Targeted support for precision agriculture technologies (GPS-guided machinery, variable-rate fertilization, remote irrigation control) can reduce input use and fuel consumption while improving agronomic performance.
4. A national training and certification scheme for climate-efficient agronomic practices would equip farmers and advisors with updated knowledge on reduced tillage, low-emission fertilization strategies, and integrated pest management.
5. Horizontal incentives for replacing outdated machinery with low-emission engines, electrified equipment or cooperative machinery pools can yield measurable reductions in fossil-fuel emissions across all crop systems.

Digital transformation

A comprehensive digital transformation of the agricultural sector can also act as a horizontal lever for reducing GHG emissions across all crop types. Apart from the LIFE ClimaMED system and the Central Monitoring and Management Tool (CMMT) the following tools and application could be effective for mitigating GHG emissions at individual or collective level (Upterra, 2025)[1]:

1. Advanced decision-support systems enable farmers to optimize fertilization based on soil, leaf and water analyses, directly lowering GHG emissions from excessive nitrogen use.
2. Digital tools that evaluate organic materials and crop residues support safe and climate-efficient reuse pathways, minimizing emissions from biomass handling and waste disposal.
3. Platforms capable of calculating carbon, water and waste footprints at crop, farm or cooperative level provide producers with science-based metrics of their environmental performance and allow the design of targeted mitigation strategies. Particularly important are climate-mitigation planning tools that allow farms or groups of farms to explore **zero-emission pathways** by simulating the impact of alternative

[1] https://upterra.eu

practices, input reductions and energy transitions, functionality similar to "zero-impact" scenario builders used in modern climate-planning environments.
4. Cluster-oriented planning modules that allow **collective zoning**, enabling groups of farms or entire regions to coordinate low-emission strategies, harmonies input management and jointly reduce machinery use or fossil-fuel dependence.

Digital infrastructures that integrate fertilization optimization, irrigation efficiency, crop–climate suitability analysis, GHG scenario modelling and cooperative planning offer a unified toolbox for climate-smart agriculture, supporting farmers, advisors and public authorities in moving towards measurable emission reductions and long-term resilience.

5. Policy framework and strategic recommendations

5.1 Policy Box 1- National legislative adoption of ClimaMED GHG monitoring

Law 5184/2025 — Government Gazette A' 34/06.03.2025
Greece has formally established a national framework for the monitoring and utilization of GHG emissions from agriculture through Law 5184/2025. Under Part D (Articles 30–33), the Ministry of Rural Development and Food introduces a national GHG recording system, integration of Tier-3 methodologies, recognition of continuous-field instruments (LiDAR, automated GHG sensors), and legal basis for their use in policy and reporting.

5.2 Policy Box 2 - Priority mitigation practices per crop

A summary of the most effective mitigation practices
• Olives: eliminate residue burning, reduce tillage, optimize N, IPM.
• Vineyards: reduce deep tillage, controlled N fertilization, efficient irrigation.
• Cereals: improved N management, reduced fossil fuel use, stubble retention.
• Vegetables: rationalize irrigation, integrate pest management, reduce machinery passes.
• Pistachio: eliminate burning, rationalize sprays, reduce tillage, optimize machinery use.

5.3 Policy Box 3 - Monitoring, reporting, verification (MRV) framework

ClimaMED provides a Tier-3 ready MRV platform. This can be integrated to support CAP eco-schemes and can be adopted as a standard for agricultural GHG monitoring and verification.

5.4 Policy Box 4 - Recommendations to MINAGRIC for CAP 2027–2034

- Introduce crop-specific eco-schemes.
- Integrate real-time GHG monitoring in payment systems.
- Incentivize non-burning, reduced tillage, and efficient fertilization.
- Expand advisory capacity and digital tools.
- Support machinery upgrades and cooperative equipment models.

5.5 Policy Box 5 - Financial instruments and incentives

Existing frameworks (CAP eco-schemes, investment measures) already support environmental upgrades.

Future incentives should cover shredders, reduced-tillage equipment, low-drift sprayers, precision fertilization tools, and real-time GHG monitoring devices.

5.6 Policy Box - Horizontal measures

- National digital farm-activity registry for reporting fertilization, irrigation, spraying and machinery use.
- Cooperative service models (shared shredders, calibrated sprayers, mobile advisory teams).
- Precision agriculture technologies (GPS-guided machinery, variable-rate fertilization, remote irrigation control).
- National training and certification programme for low-emission agronomic practices.
- Renewal of agricultural machinery with low-emission engines, electric tools or cooperative machinery pools.
- Integrated advisory and monitoring services supporting wide-scale adoption.

5.7 Policy Box - Horizontal digital measures

- Decision-support systems for optimized fertilization based on soil, leaf and water analysis.
- Digital platforms for evaluating organic materials & crop residues.
- Carbon, water & waste footprint tools at crop, farm and cooperative level.
- Zero-emission scenario planners simulating low-emission pathways.
- Collective zoning & cluster planning tools coordinating strategies across farms.
- Integrated digital packages combining fertilization, irrigation, crop–climate suitability and GHG modelling.

6. Conclusions

The LIFE ClimaMED project demonstrates that GHG emissions from Mediterranean agriculture are measurable, manageable and reducible when equipped with high-resolution monitoring tools and evidence-based agronomic practices. Across all five pilot crop types, olives, vineyards, cereals, vegetables and pistachios, two consistent patterns emerge:

1. Emission hotspots are strongly linked to management choices, particularly to nitrogen fertilization, irrigation energy use, soil disturbance, machinery operations, and residue handling (especially burning). These practices, rather than crop type itself, are the principal determinants of field-level GHG intensities.
2. Significant mitigation potential exists across all systems, and most effective measures are agronomically feasible, already recognized in Mediterranean literature, and in many cases yield co-benefits such as improved soil health, reduced input costs and enhanced resilience to climate stress.

The combination of LCA and LiDAR-based Tier-3 monitoring provides a uniquely robust understanding of how real-time farmer decisions translate into GHG dynamics. The LiDAR system proved capable of capturing short-lived but extremely intense emission pulses, after tillage, fertilization, irrigation, residue burning or compost incorporation, events typically invisible to conventional inventories. This validates the importance of continuous, field-level GHG monitoring in supporting future CAP eco-schemes, carbon-farming payments and national MRV frameworks.

Across all pilot systems, the most effective mitigation strategies include:

- eliminating burning of prunings and residues
- reducing tillage intensity and maintaining groundcover
- optimizing nitrogen through soil/leaf analysis and split application
- improving irrigation efficiency and reducing fossil-fuel pumping
- adopting integrated pest management to reduce unnecessary spraying
- rationalizing machinery use and consolidating field operations
- recycling organic materials to increase soil organic carbon.

These measures are consistent with EU climate objectives, the CAP Strategic Plan 2023–2027, the upcoming CAP 2027–2034 reform, and the emerging EU Carbon Removal Certification Framework.

The findings also highlight the increasing role of digital tools, including fertilization decision-support systems, footprint calculators, zero-emission scenario planners and collective zoning platforms, in guiding both farm-level decisions and regional planning.

Overall, the ClimaMED results demonstrate that GHG-efficient Mediterranean agriculture is both feasible and scalable when supported by targeted practice adjustments, strengthened advisory mechanisms and a coherent national policy framework. The findings generated through continuous monitoring and field-level assessments provide the Ministry of Rural Development and Food (MINAGRIC) with a solid evidence base for enhancing climate-oriented governance in the agricultural sector. By integrating real-time GHG data, advanced digital tools, and structured recommendations for policy design, ClimaMED contributes directly to the Ministry's emerging national framework for agricultural emissions monitoring and mitigation. The proposals outlined aimed at aligning farm practices, advisory services and institutional mechanisms, offer a blueprint for future policy development and CAP implementation. Together, these elements enable Greece to move towards a low-emission agricultural model that safeguards productivity, supports farmer resilience and strengthens national capacity to meet EU climate obligations.

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ANNEX – Practical advice

1. Precision Fertilization Based on Crop Needs and Soil Testing

- **Soil Testing and Nutrient Mapping**: Conduct soil testing annually to assess baseline nutrient levels and soil organic matter status. This enables accurate identification of nutrient deficiencies and avoids over-application, which leads to excess nitrogen and phosphorus in the soil, accelerating SOC loss.
- **Variable Rate Application**: Implement precision fertilization that tailors application rates to soil zones within the field, based on the variability in soil nutrient levels and crop needs. This reduces the risk of nutrient leaching and emissions by applying nutrients where they are most needed. In Mediterranean soils, which often show significant variability in nutrient content across small distances, variable rate technology (VRT) can be a beneficial approach. This would be particularly effective in crops like olives, where soil conditions differ greatly across field sections.

2. Fertilization Scheduling Aligned with Crop's Biological Cycle

- **Split Applications**: Apply fertilizers in smaller, multiple doses timed to critical growth stages, rather than a single heavy application. This method aligns with the crop's nutrient uptake curve, allowing plants to absorb more nutrients while minimizing nitrogen losses to the atmosphere as N_2O. For vegetable and other annual crops, split applications can reduce N_2O emissions by lowering nitrogen exposure at any one time. For the cereal fields, an initial application at planting and a smaller dose during peak growth could optimize nitrogen usage.
- **Use of Slow-Release or Stabilized Fertilizers**: Using slow-release fertilizers or inhibitors (e.g., nitrification inhibitors) can prevent rapid nutrient release and keep nitrogen available longer in the soil. This approach limits microbial activity that depletes SOC and reduces N_2O emissions by keeping nitrogen in more stable forms. In pistachio and olive orchards where synthetic nitrogen use is prevalent, stabilizing agents could be introduced to prolong nitrogen availability, reducing both emissions and nutrient runoff risks.

3. Reducing and Offsetting Fertilizer-Related Emissions

- **Carbon Credit Programs for Reduced Nitrogen Use**: Participate in carbon credit or offset programs that incentivize reduced nitrogen use. By quantifying emissions reductions from optimized fertilizer management, farmers can generate income while enhancing SOC and reducing GHGs.
- **Fertilization Alternatives**: Consider biochar or zeolite amendments, which can absorb excess nitrogen, reduce leaching, and stabilize nutrients. This allows soils to retain nutrients longer, benefiting SOC and reducing emissions. Biochar, in particular, could

be introduced in high-intensity fields, where high synthetic fertilizer usage has increased emissions. Biochar has the added benefit of directly increasing SOC while supporting long-term nutrient retention.

4.Soil Management Practices: Reduced Tillage, Green Manure, and Crop Residue Integration

Soil disturbance, such as conventional tillage, can accelerate SOC decomposition by exposing organic matter to oxygen. Reduced tillage and soil conservation practices preserve SOC by protecting soil structure, minimizing erosion, and allowing organic matter to accumulate over time.

- **Reduced or No-Till Practices**: Adopting reduced tillage or no-till practices limits soil disturbance, protecting SOC and reducing CO_2 emissions from soil organic matter breakdown. Reduced tillage also promotes microbial diversity and supports long-term SOC sequestration. For annual crops, adopt minimum tillage practices using direct seeding methods, which avoid extensive soil disruption. In perennial systems, eliminate mechanical tillage altogether and rely on mulching or other methods for weed control.

- **Green Manuring with Legumes**: Green manures, especially legumes, add nitrogen and organic matter to the soil while reducing the need for synthetic fertilizers. When incorporated into the soil, green manures decompose slowly, supplying organic carbon that contributes to SOC. Rotate leguminous cover crops with primary crops, allowing legumes to mature before tilling them under, which optimizes nitrogen fixation and organic matter input.

- **Residue Integration for SOC Enhancement**: Integrating crop residues back into the soil rather than removing them provides a consistent carbon source, maintaining SOC and preventing soil degradation. This approach also improves water retention and reduces erosion, further supporting SOC. Instead of removing crop residues after harvest, spread them evenly over the field or incorporate them with shallow tillage. In orchards, spread prunings within rows as organic mulch, which will decompose over time.

5 Alternative Energy Use: Renewable Energy Solutions for Irrigation and Field Operations

Replacing fossil-fuel-powered equipment with renewable energy sources reduces GHG emissions from farming operations, particularly in energy-intensive activities like irrigation and tillage. Solar and biofuel solutions provide sustainable alternatives that align with both GHG reduction and operational cost savings.

- **Solar-Powered Irrigation Systems**: Solar energy can replace diesel or electric pumps, reducing emissions associated with irrigation. Solar-powered pumps are especially viable in Mediterranean climates, where sunlight is abundant. Install photovoltaic (PV) panels to power irrigation pumps. For large fields, use PV systems with storage to ensure continuous irrigation during peak demands. Drip irrigation, combined with solar pumps, minimizes both water and energy use.

- **Biofuels for Farm Machinery**: Biodiesel and other bio-based fuels offer a renewable energy source for tractors and other farm machinery. Using biofuels reduces GHG emissions by displacing fossil fuels and supports the use of renewable, biodegradable energy sources. Convert existing machinery to operate on biofuels, or lease machinery that supports alternative fuels. For long-term solutions, invest in or transition to electric machinery that can be charged using on-farm solar systems.
- **Wind and Hybrid Renewable Systems**: In areas with sufficient wind, hybrid systems combining solar and wind power can meet energy demands more consistently, ensuring a reliable power supply for irrigation, heating, and cooling in agricultural buildings. Integrate small-scale wind turbines with solar panels to provide stable energy to remote agricultural operations. Hybrid systems are ideal for areas with variable weather, providing energy for essential tasks like irrigation and lighting.