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/

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Summary	This deliverable presents a complete replicability assessment of the four core innovations developed under LIFE ClimaMED: the LIDAR–LoRa–CMM real-time GHG monitoring system, the crop-specific agronomic mitigation guidelines, the Low-GHG Certification system, and the experimental SOC-change estimation methodology. Using a structured WHAT–WHERE–WHO–WHEN–HOW framework, it evaluates their technological maturity, institutional readiness, scientific requirements and operational scaling pathways across different groups of European countries. The document provides a consolidated roadmap explaining how each innovation can transition from pilot-level development to national deployment and, ultimately, to alignment with emerging EU climate and soil-governance frameworks.

Contents[1]

[1] **Although the project proposal foresees the preparation of a combined Transferability and Replicability Plan, due to the thematic overlap with the dedicated deliverable of Action C5 "Roadmap for the implementation of innovative technologies to measure and monitor GHG emissions and SOC stock changes in different productive European sectors", the transferability analysis is included within that Roadmap.**

Abbreviations

AEZ – Agro-Ecological Zone
AGRI – Directorate-General for Agriculture and Rural Development (DG AGRI)
BENAKI / BPI – Benaki Phytopathological Institute
CAP – Common Agricultural Policy
CCM – Climate Change Mitigation
CE – Conformité Européenne (European Conformity)
CMM – Climate Monitoring Mechanism (project platform)
CNR – Consiglio Nazionale delle Ricerche (Italy)
COM – European Commission Communications
CRCF – Carbon Removal Certification Framework
CREA – Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (Italy)
DESI – Digital Economy and Society Index
DG – Directorate-General
DOI – Digital Object Identifier
EC – European Commission
EEA – European Environment Agency
EIP-SC – European Innovation Partnership – Service Contractor
EPA – Environmental Protection Agency
EU – European Union
FAO – Food and Agriculture Organization of the United Nations
GHG – Greenhouse Gas
GIS – Geographic Information System
ICT – Information and Communication Technologies
IPCC – Intergovernmental Panel on Climate Change
ISO – International Organization for Standardization
ITC – Information Technology and Communication
JRC – Joint Research Centre
KPI – Key Performance Indicator
LPIS – Land Parcel Identification System
LoRa – Long Range (wireless communication protocol)
LULUCF – Land Use, Land Use Change and Forestry
MINAGRIC – (Greek) Ministry of Rural Development and Food
MRV – Monitoring, Reporting and Verification
NUTS – Nomenclature of Territorial Units for Statistics
OECD – Organisation for Economic Co-operation and Development
R&I – Research & Innovation
RDP – Rural Development Programme
SOC – Soil Organic Carbon
TRL – Technology Readiness Level
UAV – Unmanned Aerial Vehicle
WMS – Web Map Service

1. Introduction

Agricultural greenhouse-gas (GHG) monitoring is entering a decisive phase in Europe, driven by new regulatory expectations, the emergence of measurement-based approaches, and the need to align national systems with evolving EU frameworks such as the CAP Strategic Plans, the Soil Monitoring Law, the Governance Regulation and the Union Certification Framework for Carbon Removals (CRCF). Mediterranean countries face an even sharper imperative: highly variable climatic conditions, fragmented landscapes, intensive management cycles and strong seasonal pulses make their farming systems both vulnerable to climate change and significant contributors to land-based GHG emissions. Under these conditions, model-driven or low-resolution monitoring approaches are insufficient; credible mitigation requires real measurements, empirical evidence and methodologies that can be reliably reproduced across regions and Member States.

The LIFE ClimaMED project responds to this need by developing a suite of interoperable innovations, each addressing a specific part of the agricultural Monitoring-Reporting-Verification (MRV) chain.
The first is the *LIDAR–LoRa–CMM system*, a Tier-3-ready, high-frequency monitoring infrastructure capable of capturing real-time GHG fluxes at field scale, representing one of the first attempts in Europe to integrate laser-based atmospheric sensing, low-power telemetry and digital farm registries into a unified agricultural MRV architecture.
The second is an experimental *Soil Organic Carbon (SOC) methodology*, designed as a modular, technology-light empirical framework to support countries wishing to generate rapid SOC-change estimates for soil-health monitoring, carbon-farming initiatives or long-term LULUCF reporting.
In addition, the project developed a *replicable agronomic guideline package* consisting of crop-specific manuals for olives, vineyards, pistachios, cereals and vegetable systems, complemented by a cross-cutting synthesis of mitigation practices and evidence-based policy proposals for Greek Ministry of Rural Development and Food MINAGRIC. These guidelines integrate LiDAR-based GHG measurements, management data collected via the project's GIS application, interviews with farmers, soil and meteorological datasets, and continuous advisory engagement. They provide quantified emission drivers, validated mitigation practices, and implementation pathways for advisory systems and CAP eco-schemes, forming a practical, technology-independent component of the innovation suite with high replication potential in Mediterranean agricultural regions.
Finally, the project established an innovative *Low-GHG Certification System*, conceptually linked to the LIDAR–LoRa–CMM infrastructure and designed to enable measurement-based differentiation of agricultural practices once national authorities validate and host the relevant monitoring components.

Although these innovations share the common objective of enabling measurement-based, parcel-level and policy-aligned monitoring of agricultural GHG emissions and SOC dynamics, they differ substantially in technological maturity, institutional anchoring and replication requirements. The LIDAR–LoRa–CMM system has reached near-operational readiness and has already been legally adopted by Greece as a national mechanism for agricultural GHG monitoring, *an exceptional level of institutional maturity for a LIFE-developed technology*.

By contrast, the SOC methodology remains at TRL 3–4 (as foreseen in the LIFE ClimaMED proposal), requiring extensive future experimentation, multi-site calibration and scientific validation before it can support operational monitoring or contribute to national soil-governance structures. The third innovation, the agronomic mitigation-guideline package, is conceptually mature and grounded in real measurement evidence, and its replication depends on agro-ecological similarity, local management conditions and the capacity of advisory services to integrate the recommendations into national CAP frameworks. Finally, the Low-GHG Certification System, is fully designed and internally coherent, while is structurally dependent on the national deployment of the LIDAR–LoRa–CMM infrastructure, since certification cannot operate without validated, high-frequency measurement data and an administratively hosted MRV architecture.

These differences directly determine the replication pathways, adopter categories and enabling conditions required for each innovation. For this reason, the present deliverable provides a structured framework for assessing and planning the replicability of all ClimaMED innovations, following the analytical logic: WHAT (definition of the innovation), WHERE (geographical applicability and enabling conditions), WHO (adoption actors and sequencing), WHEN (sequenced scaling timeline), and HOW (operational mechanism for real-world uptake). For each component, the deliverable evaluates institutional readiness, scientific requirements, policy alignment, stakeholder engagement and digital-administrative capacities across different groups of countries

2. Replicability

2.1 Scope

The replicability dimension of LIFE ClimaMED refers to the capacity of the project's tools, methodologies and governance outputs to be re-applied in similar agricultural environments across the Mediterranean region and the EU.

Given that the full demonstration took place in five representative Mediterranean cultivations in Greece, the replicability potential concerns *agricultural systems with comparable climatic, soil and management characteristics.*

The methodologies, protocols and system architecture were fully developed, validated in Greece, and are technically ready to be replicated in other Mediterranean or semi-arid agricultural regions.

2.2 Replicability outputs produced by LIFE ClimaMED

2.2.1The LIDAR–LoRa–CMM Monitoring System

The project developed and demonstrated a complete, field-ready system composed of:

- LIDAR GHG monitoring device,
- LoRa-based telemetry communication, and
- the Center for GHG Monitoring & Management (CMM), a GIS-based decision-support platform adopted by the Greek Ministry of Rural Development and Food (MINAGRIC).

This integrated system constitutes the core technological package of ClimaMED and is immediately replicable in:

- other farms of similar crop types,
- regional monitoring networks,
- national GHG accounting frameworks.

Its replicability is further strengthened by:

- the direct participation and endorsement of the Greek Ministry of Rural Development and Food (MINAGRIC),
- the positive response and cooperation of farmers in all pilot sites.
- the proactive engagement of regional authorities and technical partners in Italy, Spain and Cyprus, who provided strong institutional support during the preparation of the legislative drafts and confirmed their willingness to adopt the system in the future.

2.2.2 Guidelines and good practice recommendations for five Mediterranean crops

Replicable outputs covering olive orchards, vineyards, vegetable crops, cereals, pistachios. include:

- GHG mitigation and Soil Organic Matter (SOC) increase guidelines,
- best-practice recommendations,
- evidence-based proposals submitted to MINAGRIC,

These guidelines can be directly replicated in regions with similar crop systems and management intensities, facilitating farmer advisory systems, regional climate plans, and CAP eco-schemes.

2.2.3 Certification scheme for "Low-GHG" agricultural products

The project proposes a certification framework for farmers who install the monitoring system and adopt specific mitigation practices.
This framework includes:

- footprint-based product differentiation (olives, grapes, cereals, vegetables, pistachios),
- guidelines for certification bodies,
- criteria linked to measured emissions and soil carbon trends.

Although the certification model was developed and demonstrated on five Mediterranean crop systems, its applicability is not crop-restricted. The methodology can be extended to any agricultural crop, provided that two conditions are met:

1. the monitoring device is installed sufficiently in advance to establish a robust baseline of GHG emissions; and
2. subsequent measurements continue over time to quantify the real mitigation effect attributable to changes in management practices.

For this reason, the certification concept is replicable across a wide range of Mediterranean farming systems and can be further expanded by national authorities or accreditation bodies to additional crops and production contexts.

2.2.4. SOC Stock-change methodology

The project developed, modelled, tested and documented a methodology for SOC change estimation using multispectral sensors. Given its lower TRL, this result has long-term replicability potential but requires further validation beyond the project. It is included in the replicability section as a future-ready tool, supporting research institutions and policy bodies aiming to improve national soil carbon monitoring systems.

2.3 Overall replication potential

Based on the project outputs, replicability is strongest in farming systems and stakeholder environments that share structural similarities with the ClimaMED pilots. In terms of production systems, the highest potential is observed for:

- Mediterranean perennial crops such as olives, grapes and pistachios, where agro-ecological conditions and management practices closely match those tested in the project
- Annual crops cultivated under semi-arid conditions, including cereals and vegetables, where emission dynamics are comparable and the monitoring protocols can be applied with minimal adaptation.

Regarding stakeholder groups and governance contexts, replicability is highest for:

- National authorities seeking to modernize agricultural GHG monitoring through Tier-3 methods and digital reporting structures
- Regional administrations implementing CAP-aligned mitigation strategies, particularly those integrating climate-smart agriculture into their regional plans
- Advisory systems and farmer networks adopting digital climate tools, which can directly support the deployment and operationalization of the ClimaMED system
- Individual farmers, especially those engaged in high-value or export-oriented crops, who can benefit from product differentiation, improved farm management and access to certification schemes.

The combination of a functional technological system, mature good-practice guidelines, a certification scheme and ready-to-adapt legislative templates provides a complete and replicable package for scaling the ClimaMED approach in other regions.

3. Methodology for LIFE ClimaMED replicability

This chapter presents the methodological framework that will guide the replication of LIFE ClimaMED outputs across regions, sectors and institutional environments. Its purpose is to explain the analytical approach, criteria, structures and processes through which replication will be planned, assessed and enabled. The methodology follows internationally recognised scaling frameworks, including the FAO Scaling Framework (FAO 2013; FAO 2021), the WHO ExpandNet model (WHO/ExpandNet 2010; Simmons et al., 2007) and the GIZ and OECD innovation-scaling guidelines (GIZ 2017; OECD 2019). These frameworks are adapted to the technological, legislative and institutional nature of the LIFE ClimaMED outputs, ensuring that replication planning is systematic, evidence-based and aligned with global best practice.

3.1 Defining the replicable package (What)

The first methodological step is to identify *what exactly is replicable*. The LIFE ClimaMED replicable package consists of five integrated components:

1. the LIDAR–LoRa–CMM monitoring system
2. crop-specific GHG mitigation guidelines
3. the low-GHG certification scheme
4. the legislative framework developed for four countries
5. the SOC stock-change methodology.

Each component represents a different type of innovation, technological, governance, advisory or research-driven, and therefore requires a differentiated methodological approach, consistent with the “innovation deconstruction” logic described in FAO (2013) and GIZ (2017).

To operationalize this step, the methodology applies three analytical processes:

1. Innovation deconstruction, which breaks each component into functional units that can be transferred or adapted (FAO 2021; WHO/ExpandNet 2010)
2. Readiness assessment, using both Technology Readiness Levels (TRL) and Governance Readiness Levels (GRL) to determine maturity and scalability, in line with OECD systems-change frameworks (OECD 2019).
3. Standardization analysis, which identifies where protocols, specifications, templates or guidelines are required to ensure consistent replication across countries, an approach directly supported by FAO scaling guidance (FAO 2013) and MRV standardization logic used by the European Environment Agency (EEA 2023).

By applying these processes, each output is treated not as a narrative result but as a structured and transferable replication package, ready for adoption by national authorities, operational actors and end-users.

3.2 Identifying replication environments (Where)

Identifying where replication can occur requires a structured assessment of geographical, agro-ecological, institutional and policy environments. The methodology employs a *Replication Feasibility Index (RFI)* based on a hybrid framework combining the scaling principles of FAO (FAO 2013; FAO 2021), institutional-readiness criteria from OECD systems-change guidance (OECD 2019), and MRV-readiness indicators used by the European Environment Agency (EEA 2023).

According to this hybrid model, the RFI evaluates five dimensions:

- Agro-ecological similarity (FAO agro-zoning),
- Policy readiness (OECD governance criteria),
- Institutional capacity (WHO ExpandNet; GIZ 2017),
- Digital infrastructure (EEA MRV indicators; EU DESI Index), and
- National climate priorities (CRCF and CAP Strategic Plans).

Each area of potential replication is scored across these dimensions and classified into Immediate (Tier A), Medium-term (Tier B) or Long-term (Tier C) replication potential (Simmons et al., 2007; WHO/ExpandNet 2010). This classification enables the project team and national authorities to priorities regions using objective, reproducible criteria.

Methodologically, the RFI is operationalized through structured datasets, including LPIS geospatial layers, CAP Strategic Plans (DG AGRI 2023), national MRV assessments, LoRa coverage and spectrum availability maps, and FAO agro-climatic classifications. This ensures that geographical targeting is evidence-based and measurable rather than subjective. The same structure supports the design of tier-specific replication pathways, whereby Tier A regions receive immediate piloting, Tier B regions undergo preparatory alignment actions, and Tier C regions are scheduled for long-term capacity-building.
All datasets referenced in this methodology are pre-existing public information sources and do not require new data production. For each category, the required information is accessed as follows:

- LPIS geospatial layers are publicly available through the national Paying Agencies (e.g. OPEKEPE in Greece) and the EU INSPIRE-linked WMS/WFS services. These datasets are used as indicators of digital agricultural readiness.
- CAP Strategic Plans (DG AGRI 2023) are published openly by the EC. Replication scoring uses their stated eco-scheme structures and mitigation priorities, without any additional modelling.
- National MRV readiness assessments are obtained from the European Environment Agency (EEA), which publishes comparative indicators on QA/QC systems, digital

reporting capability and methodological tier levels. The RFI uses these indicators directly, as provided.

- LoRa coverage and spectrum availability maps are taken from publicly accessible sources such as The Things Network, the LoRa Alliance country database and national telecom regulators. These maps are used to determine whether basic LoRaWAN infrastructure exists in each country.
- FAO agro-climatic classifications derive from global AEZ datasets (Agro-Ecological Zones), which are publicly available.

3.3 Target adopters and adoption depth (Who)

The methodology distinguishes three adopter categories following the diffusion and institutionalization principles outlined by Rogers (2003), WHO ExpandNet (2010) and FAO (2021):

1. Institutional adopters, including ministries, CAP authorities and regional administrations
2. Operational adopters, such as cooperatives, advisory services and digital-farming providers; and
3. End-users, including farmers, producer groups and networks.

Each category exhibits different motivations, capabilities and regulatory responsibilities, and therefore the replication pathway must be tailored. Adoption depth is assessed using the classical diffusion pathway (awareness, interest, trial, partial adoption and full institutionalization) consistent with Rogers (2003) and ExpandNet (2010).

For institutional adopters, *adoption depth* is measured through legislative advancement, budget allocation and the establishment of regulatory mandates, all of which can be traced through official government documents and CAP implementation structures. For operational adopters, such as cooperatives, advisory services and digital farming providers, progress is assessed not through permanent system deployment but through their engagement in pilot demonstrations, their participation in co-design processes and their expressed willingness to integrate the system into advisory workflows once national adoption begins.

For farmers, *adoption depth* cannot yet be evaluated through device installation, as no permanent deployments have taken place. Instead, it is measured through participation in pilot measurements, cooperation in providing field access, trial-based uptake of recommended mitigation practices, engagement in workshops and training sessions, and interest in participating in future certification schemes. These indicators reflect the pre-adoption stages described in the diffusion and scaling frameworks of Rogers (2003), WHO ExpandNet (2010) and FAO (2021), which emphasize awareness, engagement and trial as necessary precursors to full adoption.

3.4 Scaling timeline (When)

The methodological approach structures replication along a three-phase timeline, in accordance with FAO "sequenced scaling" guidance (FAO 2013) and OECD adaptive-scaling principles (OECD 2019):

- Phase 1 (2025–2027): Institutional anchoring, enabling-conditions building and alignment with national and CAP frameworks. The phase rrelies on a desk-based readiness appraisal using existing sources such as CAP Strategic Plans, national MRV reports, FAO agro-ecological classifications and digital-governance indicators. The purpose of this phase is analytical: to assess whether the institutional environment, data systems and policy frameworks of a given country are sufficiently aligned to host the LIDAR–LoRa–CMM system. Actions in this phase consist of clarifying regulatory pathways, identifying data-integration points and determining whether enabling conditions, such as a competent authority and a digital registry, already exist.
- Phase 2 (2027–2030): Regional expansion, integration with CAP eco-schemes, advisory-system embedding and early certification uptake. It corresponds to the stage in which a country or region, having reached sufficient readiness, can plan the initial embedding of the system into advisory and CAP-related structures. In methodological terms, this involves defining technical and administrative milestones (e.g. site selection, communication infrastructure availability, governance responsibilities). This phase follows FAO "sequenced scaling" guidance by specifying the order in which enabling steps should logically occur before any real deployment (FAO 2013). Early certification uptake is positioned here conceptually, to indicate when farmers would begin to benefit from measurement-based differentiation once a country formalizes the relevant procedures
- Phase 3 (2030–2035): Systemic multi-country uptake, full institutionalization and harmonization with Carbon Removal Certification Framework (CRCF) and EU MRV evolution. The phase represents the long-term institutionalization stage, consistent with OECD adaptive-scaling principles. It describes the point at which countries integrating the system can align it fully with EU-level frameworks such as the Carbon Removal Certification Framework (CRCF) and future MRV updates. This phase is an analytical depiction of how full integration would occur once a Member State decides to adopt the system formally.

3.5 Operational mechanism for replication (How)

The replication approach of LIFE ClimaMED is built on a phased, country-specific operational methodology that translates the maturity conditions identified in WHO and the sequencing logic of WHEN into a concrete, practical implementation pathway. The replication mechanism provides a step-by-step operational blueprint tailored to each adopting country.

The methodology rests on three core principles:

1. Phased operational progression (Phase 1 → Phase 2 → Phase 3)
Countries advance through a structured sequence of operational steps that correspond to the three phases of the scaling timeline. For each phase, the methodology defines what institutions must do, how they must do it, which actors are responsible, and what technical processes are required (installation, calibration, digital integration, advisory workflows, certification preparation). This ensures that adoption proceeds only when the underlying institutional, technical and digital conditions are sufficiently developed.

2. Country-specific adaptation, not uniform deployment
The HOW methodology does not assume equal readiness across Member States. Instead, it differentiates four country groups (Greece; Italy–Spain–Cyprus; other Mediterranean countries; non-Mediterranean EU countries) and assigns distinct operational steps for each group. These steps reflect:

- their current level of institutional anchoring,
- their scientific and technical familiarity with the system,
- their digital infrastructure,
- and their agro-ecological relevance to LIDAR-based GHG flux monitoring.

Each country group therefore receives a bespoke operational pathway, structured around progressively more advanced activities:
from assessment → to calibration pilots → to installation → to advisory integration → to full institutionalization.

3. Operational pillars: legal, technical, digital and advisory integration
The methodology defines a comprehensive set of operational domains which must be activated in the correct order within each phase:

- Legal activation: adoption or adaptation of legislative templates, designation of a competent national authority, creation of an Operational Centre, and establishment of data-governance protocols.
- Technical deployment: selection of installation sites, LoRa coverage mapping, execution of calibration campaigns, application of QA/QC protocols, and integration of devices into national monitoring routines.
- Digital integration: onboarding to the CMM, interoperability with LPIS/GIS systems, secure cloud hosting, and development of dashboards and advisory interfaces.
- Advisory-system integration: training of advisory bodies, cooperatives and regional authorities; embedding measured fluxes into farm advisory workflows; and preparing the basis for CRCF-aligned certification.

These pillars form the operational backbone of the replication mechanism and ensure that each phase builds on verified technical and administrative capacity.

In support of this methodology, LIFE ClimaMED has already produced all necessary technical, scientific and institutional materials required for cross-country transfer. These include installation and calibration protocols, operational manuals, CMM onboarding documentation, interoperability guidelines, draft legislative frameworks, advisory templates and certification logic. Together, these resources provide the full theoretical foundation and practical toolkit needed for Member States to replicate and institutionalize the LIDAR–LoRa–CMM system.

4. Replication of LIDAR-LoRa-CMM system

4.1. The replicable package (What)

The technological core of LIFE ClimaMED constitutes the most mature and directly replicable component of the project. It is composed of a fully integrated field-to-platform system that combines:

1. the LiDAR-based GHG monitoring device installed on agricultural land (Photo 1),
2. the long-range telemetry network (LoRa) enabling continuous wireless data transmission, and
3. the Center for GHG Monitoring and Management (CMM), an advanced cloud–GIS platform that receives, processes, validates, maps and archives all emissions data.

Together, these elements form a complete technological package that can be transferred and deployed in other agricultural regions with minimal adaptation.

System architecture and functional components

The LiDAR device, developed and validated on five crop systems and an animal farm, measures concentration gradients of CO_2, CH_4 and N_2O. The device integrates optical, mechanical and electronic subsystems and performs automatic atmospheric corrections. The LoRa gateway provides secure long-range transmission of raw measurements to the cloud. The CMM platform, already adopted by the Greek Ministry of Rural Development and Food, functions as the central processing environment where emissions are calculated at parcel scale, mapped, stored and made available to users and authorities.

The technological package is defined not merely by hardware and software, but by the full operational workflow described in the project's measurement protocols: device installation standards, calibration routines, quality-assurance procedures, data-conversion equations, uncertainty thresholds, reporting formats and mapping procedures. These protocols ensure standardization, which is essential for replication.

Replicable elements requiring no adaptation

Several components can be replicated as-is across EU regions, including the LiDAR specifications, LoRaWAN telemetry architecture, the CMM cloud infrastructure, automated processing workflows, GIS tools, certificate-generation modules, and the entire set of technical protocols. These form the "fixed core" of the replication package.

Photo 1. The LIDAR system installed at field.

Replicable elements requiring contextual adaptation

Certain elements necessarily require adaptation to local conditions, such as power-supply configurations, LoRa network density, the integration of local meteorological inputs, alignment of parcel-identification systems with national LPIS frameworks, and national regulatory integration. These adjustments do not alter the technological core but ensure effective local operation.

Role of the CMM as a replication enabler

The CMM is the backbone of scalability. It supports multi-region deployments, real-time monitoring, parcel-level reporting, certificate issuance and integration with national registries and Paying Agencies. The Greek legislation (Law A' 34/2025) legally adopts the CMM as the national platform for agricultural GHG monitoring, significantly reinforcing its replicability.

Boundary definition of the replicable technological package

The replicable unit consists of:

- a hardware unit (LiDAR device, mounting, power supply, LoRa gateway)
- a software unit (ingestion, processing, GIS modules, dashboards, certification engine)
- a protocol unit (measurement, calibration, QA/QC, mapping, uncertainty)
- a complete workflow (installation → measurement → transmission → processing → reporting → certification).

Deployment and operation of the system

The deployment of the LiDAR–LoRa–CMM system was successfully completed across Greek pilot sites, covering olive orchards, vineyards, cereals, vegetables, pistachios and a cattle farm. The system operated on an automated twice-daily measurement schedule, with additional continuous sessions activated manually by farmers during field operations such as tillage, fertilization, irrigation or harvesting.

As reported in Deliverable "Report on GHG Emissions from the Pilot Fields", the system generated thousands of valid measurement sequences over the project period, enabling detailed mapping of diurnal and seasonal emission patterns. Measurements were consistently transmitted through the LoRa network to the CMM, which ingested, filtered, processed and archived the data following standardized workflows.

The LoRa telemetry network performed reliably, with only minor interruptions due to local power fluctuations or gateway resets. The CMM platform delivered stable performance, with continuous processing of incoming streams, generation of time-series datasets and production of parcel-level emission estimates. These datasets supported the development of agronomic guidelines, certification rules and national-level proposals.

Based on the quality of field measurements, continuity of telemetry, robustness of automated processing and the legal adoption of the system in Greece, the technological chain reached a consolidated TRL of 7–8 by the end of the project (EC, 2020).

Operational challenges and lessons learned

Although the LIDAR–LoRa–CMM system demonstrated stable and efficient operation during the Greek pilot installations, several categories of challenges were identified that must be taken into account when planning replication in new environments. These challenges are not country-specific, but relate to micro-environmental conditions, field-level infrastructure, regulatory constraints and long-term operational risks.

A major set of challenges arises from micro-topographic and agro-ecological variability. The accuracy and stability of the LiDAR beam depend on line-of-sight conditions, vegetation height, tree density, slope heterogeneity and the presence of obstacles that may cause partial scattering or attenuation. In orchards with tall or densely structured canopies, adjustments to the mounting height, beam orientation and device calibration are required to ensure consistent optical performance. Dust accumulation, morning dew, coastal humidity and temperature inversions also affect signal stability and necessitate periodic maintenance and routine system checks.

Meteorological dependency represents another critical factor. Flux-calculation accuracy relies on the availability and quality of local meteorological measurements (temperature, humidity, wind field). When on-site sensors malfunction or when fallback datasets (e.g. regional weather stations) must be used, uncertainty increases and may require additional

quality-control filtering. For replication, this implies that the presence, or installation, of reliable meteorological instrumentation is a prerequisite.
Challenges also relate to field infrastructure and security. Because many agricultural areas lack stable access to the electricity grid, external power supply becomes essential. The system can operate with photovoltaic modules, but solar power introduces risks such as battery degradation, irregular charging during winter and vulnerability to theft of panels, cables or energy-storage units. In some regions, theft and vandalism have been repeatedly reported for agricultural equipment, implying that device security, fencing or remote alarms may be necessary.

In areas with complex terrain or dense vegetation, telemetry performance may require careful placement of LoRa gateways or the use of alternative communication pathways. Limited coverage or interference can reduce data transmission frequency and lead to temporary data gaps.

A separate category of challenges concerns institutional and regulatory readiness. Planned deployments outside Greece may require import licensing, customs clearance, installation permissions, and coordination with regional agricultural authorities. Although countries may choose to import the system or manufacture it locally under authorized licensing by the developing institutions, both pathways require clear legal frameworks and administrative clarity during the preparatory stage.

Finally, regulatory compliance through CE certification remains a key requirement for large-scale diffusion of the system. Full CE conformity documentation, including safety, electromagnetic compatibility and environmental-resilience testing, is mandatory in many Member States before equipment can be installed on agricultural land or formally adopted by public authorities. Importantly, the certification challenge does not stem from any absence of compliant components. The project carried out a CE conformity study and verified that all individual components of the LiDAR unit, the electronic subsystems and the LoRa communication infrastructure already hold their respective CE certificates. What remains for large-scale replication is the formal CE certification of the integrated system as a single assembled device, a standard regulatory step for complex instruments that combine multiple certified elements. This final conformity procedure can be completed during the replication stage through targeted CE assessment, using the extensive technical documentation and component-level certifications already developed within the project. In this way, CE compliance becomes an achievable and well-prepared next step rather than a barrier to adoption.

These challenges do not limit the replicability of the system; rather, they clarify the enabling conditions that countries must consider before adoption. It is important to note that the LiDAR–LoRa–CMM system represents a completely new measurement technology and operational methodology, developed and field-tested for the first time within the LIFE

ClimaMED project. The challenges encountered during the pilot phase are therefore expected and fully consistent with the TRL (7-8) of an innovative environmental-monitoring system being deployed under real agricultural conditions.

Strategic assessment of technological replicability

The technological replicability of the LIFE ClimaMED system is assessed through a structured evaluation matrix that synthesizes the operational performance, standardization level and contextual dependencies of each subsystem. The aim is to provide a clear, decision-oriented overview of which components are immediately transferable and which require contextual adaptation during replication.

Therefore, the matrix presented below (Table 1) summarizes the readiness of each technological element, hardware, telemetry, software, protocols, data pipelines and user interfaces, and highlights the enabling conditions that national authorities or implementing institutions should secure before adoption. Together, these parameters offer an integrated understanding of the system's replication potential across Mediterranean agro-ecosystems and, with appropriate calibration, in other European regions.

Table 1. Technology replication readiness matrix.

Technological parameter	Status in ClimaMED	Replicability	TRL	Notes/conditions
LiDAR hardware performance	Stable across demo sites	High	8	Requires maintenance, height calibration
LoRa telemetry	Reliable with minor adjustments	Medium–High	7	Terrain-dependent; requires gateway optimisation
CMM cloud processing	Fully operational, validated by MINAGRIC	Very High	8–9	Needs national hosting agreements
Data ingestion pipeline	Standardised, automated	Very High	8	Replicable as-is
GHG calculation algorithms	Validated	High	7	Meteorological inputs essential
Measurement protocols	Complete, field-tested	Very High	8	Zero adaptation needed
Maintenance and calibration routines	Partially automated	Medium	6–7	Requires technician training
Power supply (grid/solar)	Variable by site	Medium	6	Context-dependent
User interface and dashboards	Operational, scalable	Very High	8	Multi-country capable
Overall technological replicability		High	7–8	Ready for Mediterranean scaling

The matrix indicates that the LIFE ClimaMED technological package has *high overall replicability,* with several components ready for direct transfer without modification. Elements that require contextual adaptation, such as LoRa gateway placement, power-supply configuration or technician training, do not undermine replicability but define the enabling conditions necessary for optimal performance. With a consolidated TRL of *7–8,* the system is technically mature and ready for scaling in Mediterranean environments, while remaining adaptable for deployment in other European regions through calibration and localized integration.

4.2. Replication environments (Where)

Identifying where the LIDAR–LoRa–CMM system can be replicated requires a structured assessment of geographical, agro-ecological, institutional and policy environments. For this purpose, the methodology employs a *Replication Feasibility Index (RFI)* based on a hybrid framework that combines:

- the scaling principles of the FAO Scaling Framework (FAO 2013; FAO 2021),
- institutional-readiness criteria from OECD systems-change guidance (OECD 2019), and
- MRV-readiness indicators used by the European Environment Agency (EEA 2023).

According to this hybrid model, the RFI evaluates five dimensions relevant to the successful deployment of real-time agricultural GHG measurement technologies:

1. *Agro-ecological similarity*, based on FAO agro-ecological zoning and the presence of Mediterranean or semi-arid cropping systems comparable to the Greek pilots.
2. *Policy readiness*, reflecting the existence and strength of CAP eco-schemes, climate strategies and agricultural-environmental policy instruments, as documented in the 28 approved CAP Strategic Plans.
3. *Institutional capacity*, including clear mandates for agricultural and climate authorities and the ability to host and manage national monitoring systems, consistent with WHO ExpandNet (WHO/ExpandNet, 2010) and GIZ (2017) scaling guidelines .
4. *Digital infrastructure*, assessed through the maturity of LPIS systems, GIS services and e-government performance as reflected in EU Digital Decade / DESI reporting.
5. *National climate priorities*, including commitments in CAP Strategic Plans, national climate laws and emerging EU frameworks such as the Carbon Removal Certification Framework and the enhanced MRV obligations under the Governance Regulation.

Each country (or group of countries) is scored on a 1–5 scale for each dimension and classified into Immediate (Tier A), Medium-term (Tier B) or Long-term (Tier C) replication potential, in line with the categorization logic proposed by Simmons et al. (2007) and WHO/ExpandNet (2010).

Data sources used for the RFI
All information for the estimation of the RFI is drawn from existing, public datasets and official documents:

- Agro-ecological similarity is derived from FAO and IIASA (2022) Global Agro-Ecological Zones (GAEZ) and FAO ecological zones, which clearly identify the Mediterranean climatic band and its extension into Southern Europe.
- CAP and policy readiness are assessed using the European Commission's CAP Strategic Plans "CAP in my country" and "at a glance" factsheets for each Member State (EC, 2023).
- Institutional capacity and MRV readiness are inferred from the EU greenhouse gas inventory documentation and EEA reports (EEA, 2023) on the EU MRV system and national inventory arrangements, which describe robust, standardized reporting structures across Member States.
- Digital infrastructure is evaluated through the EU Digital Decade / DESI country reports (EC, 2023), which highlight the progression of Member States in digital public services and data systems, and show overall high digital performance of the Member States.
- LoRaWAN and IoT connectivity are assessed based on publicly available maps and operator information (e.g. The Things Network frequency-by-country list and LoRaWAN operators such as Netmore) (LoRa Alliance, 2023; The Things network, 2024).

Greece – Priority Tier A (Immediate replication)

Greece is the primary replication environment and the only country where the LIDAR–LoRa–CMM system has already been legally anchored as a national mechanism for agricultural GHG monitoring. The adopted law (Articles 30–33 of Law A' 34/2025) formally establishes the Operational Centre and the use of ClimaMED devices on agricultural land, assigning responsibility to the Ministry of Rural Development and Food. This places Greece at very high policy readiness and institutional capacity, with a clear mandate, defined governance structure and an explicit national objective to integrate real-time GHG monitoring into agricultural policy.

Agro-ecologically, Greece is fully representative of the Mediterranean climatic zone and cropping systems (olive, grape, pistachio, cereals, vegetables), matching the pilot conditions of ClimaMED. The Greek CAP Strategic Plan reinforces this context by emphasizing green and digital agriculture, climate action and advisory services, providing a natural policy home for the LIDAR–LoRa–CMM system.

Digital infrastructure has improved significantly in recent years: DESI assessments show Greece among the countries with the fastest relative improvement in digital performance, especially in e-government and digital public services, although starting from below-EU-average levels. LoRaWAN connectivity is expanding through national IoT operators and pan-European networks, enabling cost-effective deployment of gateways and devices in many agricultural regions.

Given these conditions, Greece achieves *RFI scores close to the maximum* in agro-ecological similarity, policy readiness and institutional capacity, with moderately high scores in digital/LoRa infrastructure and climate priorities. It is therefore classified as *Tier A –*

Immediate replication, with direct large-scale rollout possible as soon as implementation decisions are taken by the Ministry.

Italy, Spain and Cyprus – Project countries with high replication potential
Italy, Spain and Cyprus participated directly in LIFE ClimaMED and already have draft legislative frameworks prepared under the project, which incorporate the LIDAR–LoRa–CMM system into their national or regional governance structures. This substantially raises their policy and institutional readiness relative to other Member States.

All three countries possess extensive Mediterranean or semi-arid agricultural zones with perennial crops (olive, grape, citrus) and annual field crops under water stress, closely matching the agro-ecological conditions where the system was piloted. Their CAP Strategic Plans, approved by the European Commission, emphasize climate action, sustainable resource management and, particularly in Italy and Spain, strong mitigation and adaptation objectives.

Digital infrastructure and LPIS systems are well established in these countries, and DESI/Digital Decade assessments classify Italy and Spain as mid-range to improving performers, with Cyprus slightly below the EU average but progressing. LoRaWAN coverage is already available in Spain and Italy through operators such as Netmore and other LPWAN providers and can be extended to rural regions in a targeted way.

Overall, Italy, Spain and Cyprus achieve *high RFI scores* across all five dimensions. Their classification is:

- Italy: Tier A/B – ready for early large-scale pilots linked with regional agencies and CAP eco-schemes.
- Spain: Tier A/B – strong regional governance and CAP alignment support rapid regional replication, especially in Mediterranean regions.
- Cyprus: Tier A/B – small but highly relevant system where replication can be implemented at national scale with relatively low deployment effort.

Other Mediterranean EU countries
Beyond the project countries, several additional EU Member States combine Mediterranean or sub-Mediterranean agro-ecological conditions with relatively strong policy and digital readiness:

- France and Portugal include extensive Mediterranean or Atlantic-Mediterranean zones with vineyards, olives and irrigated horticulture that face similar climate and emission challenges. FAO ecological zoning and MedECC assessments both describe Southern France and coastal Portugal as part of the broader Mediterranean climatic influence. Their CAP Strategic Plans and national climate policies place strong emphasis on GHG mitigation, sustainable water management and digitalization of advisory services. DESI and Digital Decade reporting show high or above-average digital performance, including advanced e-government and data

infrastructures. LoRaWAN networks are already well developed in both countries through operators such as Netmore and national telecoms.
- Malta, Croatia and Slovenia have smaller Mediterranean or sub-Mediterranean agricultural areas but still host high-value perennial crops (vineyards, olives, horticulture) exposed to climate risk. Their CAP Strategic Plans follow the same EU-wide framework and include climate and digitalization measures, though institutional capacity for large-scale Tier-3 monitoring may be more limited and would require targeted capacity building and partnerships.

For this group, agro-ecological similarity and policy alignment with climate-smart agriculture are generally high, digital infrastructure is medium to high, and MRV capacity is robust at national GHG inventory level. The main constraints are institutional prioritization and the need to embed a new monitoring system into existing advisory, certification and paying-agency structures. These countries are therefore classified overall as *Tier B – Medium-term replication*, with *France and Portugal towards the upper end of Tier B* and *Malta/Croatia/Slovenia at the lower end*, where preparatory work (pilot deployments, institutional agreements, technician training) will be essential.

Non-Mediterranean EU Member States

For non-Mediterranean Member States (Central, Northern and parts of Eastern Europe), the RFI profile is more heterogeneous:

- Agro-ecological similarity is generally low, as temperate, continental and boreal agro-systems differ substantially from the semi-arid and Mediterranean conditions under which ClimaMED was piloted.
- Policy readiness, MRV capacity and digital infrastructure, however, are often very high: the EU-wide MRV system is fully operational, DESI scores for many countries (e.g. the Netherlands, Denmark, Sweden, Estonia) are among the best in the Union, and CAP Strategic Plans contain strong climate, environmental and digitalization components.

For these countries, the technical replicability of the LIDAR–LoRa–CMM system is not constrained by governance or digital factors, but by the need for new calibration work and agro-ecological adaptation: dispersion dynamics, background concentrations and management practices differ, and additional validation would be required before using the system directly for national GHG accounting.

As a result, non-Mediterranean EU countries are classified mostly as *Tier B/C:* promising environments for targeted pilots, research collaborations and future adaptation, rather than immediate large-scale deployment for agricultural mitigation policy.

Replication Feasibility Index (RFI)

Table 2 below summarizes the RFI assessment across the five dimensions and provides an overall replication classification. Scores are on a 1–5 scale (1 = very low, 5 = very high). Values are indicative and based on the structured evidence described above.

Table 2. Replication Feasibility Index (RFI) for the LIDAR–LoRa–CMM system

RFI Dimension	Greece	Italy	Spain	Cyprus	France	Portugal	Malta	Croatia	Slovenia	Non Med EU
Agro-ecological similarity	5	5	5	5	4	4	3	3	3	1–2
Policy readiness	5	4	4	4	4	4	3	3	3	4–5
Institutional capacity	5	4	4	4	4	4	3	2–3	2–3	4–5
Digital infrastructure	4	4	4	3	5	5	3	3	3	4–5
National climate priorities	5	4	4	4	4	4	3	3	3	4–5
Overall RFI Score	**4.8**	**4.2**	**4.2**	**4.0**	**4.2**	**4.2**	**3.2**	**2.8–3.0**	**2.8–3.0**	**3.0–4.0**
Replication Tier	**A**	**A/B**	**A/B**	**A/B**	**B**	**B**	**B-/C+**	**B-/C**	**B-/C**	**B/C**

4.3 Target adopters and adoption depth (Who)

The adoption strategy for the LIDAR–LoRa–CMM system follows the diffusion and institutionalization principles outlined by Rogers (2003), the WHO ExpandNet model (WHO/ExpandNet, 2010) and FAO scaling guidance (FAO 2013; FAO 2021). In line with this framework, three main adopter categories are distinguished:

1. Institutional adopters, including national ministries, CAP authorities, paying agencies and regional administrations.
2. Operational adopters, such as cooperatives, producer organizations, advisory services, digital-farming providers and technical agencies.
3. End-users, including individual farmers, producer groups and local farmer associations.

Each category has different mandates, incentives and constraints, so the replication pathway and the assessment of adoption depth must be tailored accordingly. Adoption depth is conceptualized along a classical diffusion sequence (awareness, interest, trial, partial adoption and full institutionalization), as described by Rogers (2003) and WHO/ExpandNet (2010).

In the context of LIFE ClimaMED, adoption depth is not yet measured through permanent device installation outside the Greek pilots, but through *legal commitments, formal roles in governance, and documented behavioral commitments* (participation in pilots, round tables, memorandum of understanding, willingness to adopt). This section describes how these indicators are applied in Greece, in the three project countries (Italy, Spain, Cyprus), in other Mediterranean Member States and, finally, in non-Mediterranean EU countries.

Core adopter groups created by LIFE ClimaMED

LIFE ClimaMED has already established a *multi-layer core of potential adopters* in the four project countries:

- At institutional level, the coordinating and associated beneficiaries include:

  - Benaki Phytopathological Institute (coordinator), FORTH, Technical University of Crete, the Greek Ministry of Rural Development and Food (MINAGRIC) in Greece, and Green Projects SA (IT developer)
  - ENVITECH (Cyprus), University Miguel Hernández (Spain) and CeRSAA (Italy).

  These institutions collectively cover research, technology development, policy integration and digital infrastructure.
- At operational level, ClimaMED has formalized collaboration with regional authorities in the four countries (Region of Crete, Region of Ionian Islands, Region of Sterea Ellada / Agrifood Business of Sterea Ellada, Region of Valencia-Spain, Region of Liguria-Italy, Municipality of Sotira-Cyprus, Commissioner for the Environment of Cyprus).
- At end-user / farmer level, a network of associations and cooperatives has been mobilized: pistachio, olive and vegetable cooperatives and farmer associations in Aegina, Fthiotida, Kefalonia–Ithaca and Peloponnese (Greece); multiple farmer associations and cooperatives in Liguria (Italy); and irrigator communities and farmer organizations in the Valencian region (Spain).

The *Memorandum of Understanding on the dissemination and use of the project results*, signed between key partners and stakeholder organizations, formalizes the intention to continue collaboration beyond the project period and to promote the deployment of the LIDAR–LoRa–CMM system as a reference technology for agricultural GHG monitoring.
In addition*, training/demonstration activities and six round table events* organized in Greece, Cyprus, Italy and Spain brought together ministries, regional authorities, cooperatives, advisory services and farmer organizations, documenting their interest, questions and perceived benefits of the system and the associated certification framework. These events provide a qualitative baseline of adoption depth: *awareness and interest have been clearly established in all four project countries, while trial and partial adoption have started in Greece through the legal anchoring of the system*.

Greece – From trial to early institutionalization
In Greece, the main institutional adopter is the Ministry of Rural Development and Food (MINAGRIC), which has taken a central role in ClimaMED as both a project beneficiary and the future owner of the Operational Centre. The adoption depth for institutional actors in Greece is already at the "*early institutionalization*" stage:

- The Greek Parliament has adopted Articles 30–33 of Law A' 34/2025, legally integrating the ClimaMED system into the national agricultural GHG monitoring framework and assigning responsibility to MINAGRIC.
- The law mandates the operation and future transfer of the Operational Centre, providing a clear long-term governance structure and budgetary obligations.
- The Ministry is explicitly tasked with coordinating the extension of the system across the territory and with designing incentives for farmers to adopt the technology (e.g. through CAP eco-schemes or national measures).

These elements correspond to legislative advancement, budget allocation and the establishment of regulatory mandates, which are the core indicators of institutional adoption depth in the methodology.

At operational level, Greek actors such as BPI, FORTH, TUC, Green Projects and regional authorities (Crete, Ionian Islands, Sterea Ellada) have progressed to an advanced "*trial / partial adoption*" stage:

- The research and ICT partners have already implemented pilot deployments, refined protocols and integrated the CMM into operational workflows.
- Regional authorities have participated in the stakeholder network as formal stakeholders, expressed interest in using the system for regional climate strategies and participated in round tables and consultation events.

At farmer and cooperative level, Greek end-users are at the "*interest / trial*" stage:

- Cooperatives of pistachio, olives, vegetables and arable crops have participated in round tables where the technology, the CMM and the low-GHG certification concept were presented.
- Farmers have engaged in pilot measurements, provided field access, tested mitigation recommendations derived from the measured fluxes and expressed interest in future participation in the certification scheme.

For Greece, therefore, the LIDAR–LoRa–CMM system has moved beyond mere awareness and is entering <u>*early institutionalization*</u> at ministerial level, with strong trial engagement among operational actors and farmer organizations.

Italy, Spain and Cyprus – High readiness, advanced "interest / trial" stage

In Italy, Spain and Cyprus, the system has not yet been legally adopted, but the project has created a mature pre-adoption environment across all three adopter categories.

At institutional level:

- Draft legislative frameworks have been prepared in each country, defining how the system would be integrated into national or regional governance (competent authorities, operational centres, data flows, certification logic and incentive schemes).
- Regional and local public bodies such as the Region of Liguria, Region of Valencia, Municipality of Sotira and the Commissioner for the Environment of Cyprus are formally listed as authorities–stakeholders of the project, signaling institutional awareness and willingness to explore adoption.

These elements correspond to an "*advanced interest / early trial*" stage of institutional adoption: legal texts exist, roles are defined and political actors have publicly associated with the project, even though formal parliamentary adoption has not yet occurred.

At operational level:

- Technical partners - CeRSAA (Italy), ENVITECH (Cyprus) and UMH (Spain) - have acted as operational hubs, contributing to the design of deployment protocols, organising national meetings and preparing national dissemination materials.

- Farmers' associations and cooperatives in Liguria and within the Valencian irrigation communities (Riegos de Levante, Carrizales, La Unió de Llauradors i Ramaders) have been formally recognized as stakeholders and participated in demonstrations and training activities. Although the LiDAR system was not deployed in their countries, they observed the system during visits to Greece, received training on the CMM and provided feedback on operational feasibility and user requirements.
  These actors have reached an "*engagement / familiarization*" depth of adoption: they have been exposed to the technology, interacted with the advisory outputs and contributed to the identification of institutional and operational requirements for future scale-up, but did not host on-site trials.

- At farmer level, individual producers participated in field visits, round tables and awareness activities. Their involvement places them at an "*interest/early engagement*" stage.

Other Mediterranean EU countries – Potential adopter profiles
For other Mediterranean or sub-Mediterranean EU Member States (France, Portugal, Malta, Croatia, Slovenia), the methodology does not yet identify named stakeholders but instead defines target profiles for each adopter category, consistent with FAO and GIZ guidance on scaling agricultural innovations (FAO 2021; GIZ 2017):

- *Institutional adopters* would typically include ministries of agriculture and environment, national CAP managing authorities, paying agencies and regional governments in Mediterranean regions. These institutions already oversee CAP eco-schemes, climate-adaptation policies and digital farm registries, making them natural future hosts for the LIDAR–LoRa–CMM system.
- *Operational adopters* would comprise chamber-of-agriculture networks, regional research institutes, irrigation consortia, producer organisations and digital-farming companies, who could host pilots or integrate real-time GHG monitoring into advisory services.
- *End-users* would mainly be cooperatives and producer groups in perennial crops (vineyards, olives, citrus) and irrigated horticulture, where GHG mitigation and water efficiency are high priorities.

To date, these actors have not been directly involved in the project. Their exposure has been limited to indirect channels, including online dissemination materials, participation in a Mediterranean conference, and presentations delivered through other EU projects in which partners from these countries are involved. As a result, adoption depth remains at a *generic "awareness"* level rather than interest or engagement.
The replication plan therefore foresees targeted future outreach to these adopter profiles, through EU-level platforms (ENRD, CAP networks, Copa–Cogeca), regional Mediterranean initiatives and forthcoming LIFE/Horizon proposals, in order to move them progressively from awareness to interest and eventually to trial adoption.

Non-Mediterranean EU countries – Collective pre-adoption environment

In non-Mediterranean EU Member States (Central, Northern and parts of Eastern Europe), no direct stakeholder engagement has yet taken place under ClimaMED. Exposure to the LIDAR–LoRa–CMM system has been limited to indirect channels, such as online dissemination materials, conference presentations and references within other EU-funded projects in which ClimaMED partners participate.

Given this context, the analysis focuses on potential adopter profiles, consistent with EU and FAO scaling frameworks:

- *Institutional adopters* would include ministries of agriculture and environment, CAP managing authorities and paying agencies. These institutions operate within advanced MRV and digital governance systems, but agro-ecological conditions differ clearly from the Mediterranean calibration domain of ClimaMED.
- *Operational adopters* would include research institutes, advisory services and digital agriculture platforms. These actors possess strong technical capacity and could, in principle, implement pilots, but substantial recalibration of measurement protocols would be required to reflect temperate or continental emission patterns.
- *End-users* (farmers and cooperatives) could adopt future adapted versions of the system, particularly in intensive livestock, horticulture or high-input arable farming.

For these countries, adoption depth is classified as "*minimal awareness*": stakeholders have only indirect exposure and no operational involvement. They represent potential future collaborators for joint calibration studies, proof-of-concept pilots and cross-regional methodological adaptation, rather than immediate candidates for deployment of the Mediterranean-calibrated system.

Adoption-depth summary by adopter category and region

Table 3 below summarizes the current adoption depth of the LIDAR–LoRa–CMM system across institutional adopters, operational adopters and end-users in four geographic groups, based on levels of awareness, engagement, trial involvement and institutional commitment.

Table 3. Stakeholder adoption readiness matrix for the LIDAR–LoRa–CMM system

Region / Country group	Institutional adopters	Operational adopters	End-users
Greece	Early institutionalisation	Trial / partial adoption	Interest / trial
Italy, Spain, Cyprus	Advanced interest / early trial	Engagement / familiarisation	Interest / early engagement
Other Med EU countries	Awareness / interest	Awareness / early interest	Awareness
Non-Med EU countries	Minimal awareness	Minimal awareness	Not yet targeted

4.4 Scaling timeline (When)

In line with FAO "sequenced scaling" guidance (FAO 2013; FAO 2021) and OECD adaptive-scaling principles (OECD 2019), the timeline follows a phased logic where countries move forward only when their institutional and technical environment is sufficiently mature.
Rather than proposing abstract forecasting, the implementation plan focuses on real conditions already established by the project: the presence of national legislation in Greece, draft laws and institutional partners in Italy–Spain–Cyprus, and varying levels of readiness across the wider Mediterranean and EU.

Phase 1 (2025–2027): Early institutional anchoring and initial deployments

- Greece (Immediate Phase 1–Phase 2 transition)
  Greece is the only Member State where the LIDAR–LoRa–CMM system is already legally institutionalized. The next critical step is the publication of the Joint Ministerial Decision (KYA) defining installation standards, responsibilities, and operational parameters of the national system. Once the KYA is enacted, an initial implementation period of approximately 12 months will be required to:
  - deploy the first wave of devices in selected regions,
  - establish operational routines between MINAGRIC, benediciaries and regional authorities,
  - align the CMM with national registries (LPIS, GIS, advisory networks),
  - prepare the technical-administrative conditions for national expansion.

  This first year functions as a commissioning phase: fine-tuning workflows, validating telemetry coverage, and training operational personnel.

- Italy, Spain, Cyprus (Advanced pre-adoption phase)
  These countries have draft legislative frameworks, developed under LIFE ClimaMED, and a trained group of beneficiary institutions familiar with the technology. During Phase 1 they must:
  - initiate formal consultation processes for legislative adoption,
  - identify the competent authority and hosting institution for the Operational Centre,
  - conduct preliminary alignment with CAP eco-schemes and digital registries,
  - select candidate pilot regions through regional agencies and cooperatives,
  - establish financing options (CAP funds, digitalization budgets).

  The absence of an enacted law means that the earliest realistic deployment horizon is late Phase 2, but groundwork and institutional anchoring already begin here.

- Other Mediterranean countries
  Phase 1 actions consist mainly of awareness-building and feasibility preparation, including:

- assessment of national CAP structures for compatibility,
- evaluation of LoRa and digital infrastructure,
- identification of host institutions (paying agencies, advisory institutes),
- early scientific exchanges or MoUs.

No deployments occur here yet; activities remain analytical and preparatory.

- <u>Non-Mediterranean EU countries</u>
  Phase 1 is limited to awareness, research dialogue and calibration study planning, because agro-ecological divergence requires future adaptation of dispersion models and calibration routines.

Phase 2 (2027–2030): Regional expansion, advisory-system integration and early certification potential

- <u>Greece (Full Phase 2 implementation)</u>
  After the first year of installation, Greece will enter accelerated regional expansion. With a fully operational CMM and a functioning legal framework, Phase 2 includes:
  - extending installations to additional regions based on national priorities,
  - embedding the system into regional advisory structures and CAP eco-schemes,
  - first interactions with farmers on mitigation advice and data-driven decision making,
  - optional first trials for early product differentiation and preparatory steps for certification.

  Given institutional backing and stakeholder familiarity (through round tables and farmer participation in pilots), a national system expansion period of ~5 years is realistic. This means that by *2030*, Greece could reach near-full national coverage.
- <u>Italy, Spain, Cyprus (Transition into operational adoption)</u>
  Once legislative procedures advance (expected earliest around 2027–2028), these countries can:
  - establish a national or regional Operational Centre,
  - run initial deployments in selected agricultural zones,
  - integrate telemetry and CMM connections with national LPIS/GIS systems,
  - engage cooperatives and advisory bodies trained during the project,
  - prepare certification integration for specific crops.

  This phase enables real deployments, not yet at national scale but at regional pilot-to-pre-commercial scale, with Cyprus having the fastest adoption potential due to its small territory.
- <u>Other Mediterranean countries</u>
  For these Member States, Phase 2 corresponds to:
  - conducting first calibration/pilot deployments (1–2 regions),
  - forming partnerships with research institutions or advisory services,
  - evaluating administrative pathways for future legislative adoption.

Full operation is not expected before Phase 3.

- Non-Mediterranean EU countries
  Phase 2 consists primarily of R&D partnerships, calibration studies, and targeted pilots under EU innovation frameworks (Horizon, LIFE, CAP innovation actions), preparing the ground for long-term adaptation of the system.

Phase 3 (2030–2035): Systemic uptake, institutionalization and EU-level harmonization

- Greece (Phase 3 completed earlier)
  By this stage, Greece is expected to have:
  - fully institutionalised the system,
  - transferred the Operational Centre to MINAGRIC (as mandated by law for 2029),
  - integrated real-time GHG monitoring with CAP payments, eco-schemes and national registers,
  - activated certification pathways for low-GHG products.

  Greece becomes a *reference case* for other Mediterranean Member States.
- Italy, Spain, Cyprus (Acceleration to national-scale adoption)
  With operational pilots completed during Phase 2 and institutional structures in place, Phase 3 involves:
  - scaling from regional deployments to national registries,
  - formal incorporation of LIDAR-based monitoring into CAP instruments,
  - alignment with the EU Carbon Removal Certification Framework (CRCF),
  - expansion of device installations across representative agro-ecosystems.
- Other Mediterranean countries
  For this group, Phase 3 is the earliest realistic moment for:
  - legislative integration,
  - expanded pilot deployments,
  - establishment of CMM-compatible national structures,
  - technical certification steps for full adoption.
- Non-Mediterranean EU countries
  These countries may engage in long-term integration for:
  - calibration-based adoption of the LIDAR system,
  - MRV alignment under CRCF and post-2030 EU climate governance,
  - targeted use for research, advisory tasks, or carbon-farming schemes.

Table 4. Consolidated timeline summary

Region/ Country Group	Phase 1 (2025–27)	Phase 2 (2027–30)	Phase 3 (2030–35)
Greece	Legal framework finalization, first installations	Regional expansion, advisory integration, pre-certification	National coverage, full institutionalization
Italy, Spain, Cyprus	Legislative preparation, stakeholder mobilization	Pilot deployments, early integration	Large-scale adoption and CRCF alignment
Other Med EU	Feasibility + awareness	Calibration pilots	Legislative uptake + system scaling
Non-Med EU	Awareness + research dialogue	Targeted pilots	Long-term adaptation + possible adoption

Concluding, the overall scaling horizon for the LIDAR–LoRa–CMM system across the EU is:

- Greece: Full adoption by 2030
- Italy–Spain–Cyprus: First national adoptions by 2031–2033
- Other Mediterranean countries: Legislative + system integration by 2033–2035
- Non-Mediterranean EU: Long-term calibrated adoption beyond 2035

This timeline is aligned with the project's stakeholder base, the legal environment, the RFI analysis, and the observed technological readiness of the system.

4.5 Operational mechanism for replication (How)

Replication of the LIDAR–LoRa–CMM system is not a diffusion exercise but an institutional transformation that must be grounded in the governance, economic, scientific and digital capacity of each adopting country. Replication of the LIDAR–LoRa–CMM system requires a structured sequence of legal, technical, digital and advisory steps that correspond to the phases described in the timeline (Tables 5, 6, 7).
For each country or country group, the HOW describes the concrete operational actions, the responsible actors, the procedural sequence, and the technical tasks required for moving from preparation to installation, and from installation to institutionalization.

LIFE ClimaMED has already produced all technical, scientific and institutional materials required for transferring the system to other EU Member States.
These include:

- full installation and calibration protocols,
- device operation and maintenance manuals,
- digital and CMM onboarding documentation,
- data-governance and interoperability guidelines,
- draft legislative frameworks ready for national adaptation,
- advisory templates and certification process drafts,
- complete scientific background for cross-country calibration and modelling.

- Training material for CMM

As a result, the project has already generated the complete technical foundation, legal templates, and scientific know-how necessary for replication and institutional adoption in additional countries.

Table 5. Operational replication steps for Greece (Phases 1-3)

Greece	Phase 1(2025–2027): Legal activation, technical setup and first deployments				
Regulatory activation	**Institutional coordination**	**Technical preparation of pilot regions**	**Installation & calibration**	**Digital integration**	**Capacity building**
• Drafting, inter-ministerial consultation and publication of the Joint Ministerial Decision (KYA). • Specification of installation standards (height, orientation, safety requirements, QA/QC). • Definition of responsible entities for installation, monitoring, maintenance, and data validation.	• Establishment of a permanent coordination committee (MINAGRIC–Operational Centre–FORTH–BPI). • Allocation of responsibilities for: o device procurement, o installation contracting, o LoRaWAN network planning, o regional liaison, advisory-system integration	• LoRa coverage maps, signal validation and gateway reinforcement where needed. • Field surveys identifying suitable installation points (terrain, wind, obstacles, access). • Environmental safety checks and risk assessments.	• Deployment of the first wave of devices under full installation protocol. • Execution of the multi-step calibration sequence: o zero/span checks, o background correction, o range validation, o atmospheric stability classification. • Validation of first measurement cycles by FORTH and the Operational Centre.	• Connection of the CMM to MINAGRIC's national cloud. • Interoperability testing with LPIS, meteorological services, advisory apps. • Generation of validation and monitoring dashboards.	• Training of: o MINAGRIC Monitoring Division, o Operational Centre staff, o regional agronomists, o installation contractors. • Development of technical manuals for daily operations and troubleshooting.

Phase 2 (2027–2030): Regional expansion and integration into advisory services			
Scaling installations	**Advisory-system integration**	**Data-flow routine establishment**	**Pre-certification pilots**
• Expansion to additional regions based on agro-ecological relevance. • Deployment planning using national priority maps for GHG mitigation.	• Direct incorporation of flux-based recommendations into farm advisory visits. • Workshops with cooperatives (pistachio, olive, vegetables, grains) to interpret flux patterns. • Integration with CAP eco-schemes: o activity logs, o mitigation reporting, o conditionalities.	• Continuous monitoring of device performance through the CMM. • Automatic anomaly detection and remote troubleshooting. • Standardized weekly advisory reports per region.	• Selection of crops and cooperatives for low-emission product development. • Measurement-based demonstration of mitigation effects (tillage adjustment, irrigation optimisation, organic amendments).

Phase 3 (2030–2035): Full institutionalization and national system completion			
Transfer of the Operational Centre	**National MRV integration**	**Certification activation**	**Long-term sustainability**
• Formal handover of managerial authority from project partners to MINAGRIC. • Establishment of permanent staffing positions.	• Binding integration of LIDAR–LoRa–CMM measurements into the national agricultural GHG inventory. • Automated data flows for policy reporting	• Use of flux validation for product differentiation (CRCF-aligned). • Development of national verification guidelines	• Annual budget line under MINAGRIC and CAP. • National maintenance and upgrade programme

Table 6. Operational replication steps for Spain, Italy and Cyprus (Phases 1-3)

Spain-Italy-Cyprus	Phase 1(2025–2027): Institutional preparation & foundational alignment				
Legislative preparation	**Institutional configuration**	**Technical groundwork**	**Installation & calibration**	**Financial planning**	**Capacity building**
• Formal consultation on draft national frameworks developed by ClimaMED. • Alignment with internal legal structures (agricultural MRV, digital governance, CAP authorities).	• Designation of the national authority responsible for hosting the system. • Design of an Operational Centre (staffing, workflows, hosting infrastructure).	• Mapping of candidate pilot regions (Liguria, Valencia, Sotira + others). • Assessment of: o LoRaWAN coverage, o LPIS compatibility, o digital registries, o CAP ecosystem requirements.	• Deployment of the first wave of devices under full installation protocol. • Execution of the multi-step calibration sequence zero/span checks, background correction, range validation, atmospheric stability classification. • Validation of first measurement cycles by FORTH and the Operational Centre.	• Identification of funding instruments (CAP 2027–2030, digitalisation funds). • Development of a costed deployment plan.	• Training workshops based on experience gained in Greece. • Technical transfer of: o calibration procedures, o installation protocols, o CMM management routines.

Phase 2 (2027–2030): Pilot deployments and operational testing			
Establishment of Operational Centre	**Pilot installations**	**Integration with advisory structures**	**Digital connections**
• Hosting on a national or regional institution (e.g., UMH, CeRSAA, ENVITECH in support). • Deployment of full data workflows (collection, validation, advisory).	• Installation of devices in selected agricultural zones. • Local calibration campaigns with support from Greek scientific teams.	• Adoption of LIDAR-based GHG advice by regional cooperatives. • Field demonstrations for farmers based on initial measurement results.	• Linking the CMM with national LPIS/GIS and meteorological systems. • Dashboard development for policy and advisory monitoring.

Phase 3 (2030–2035): National expansion and institutionalization
Operational actions
• Extension of installations to additional regions. • Embedding of the system into CAP eco-schemes, national MRV frameworks, advisory networks. • Development of certification pathways (CRCF integration). • Establishment of permanent funding and staffing at national level.

Table 7. Operational replication steps for other Med and Non-Med countries (Phases 1-3)

Other Med countries	**Phase 1(2025–2027): Readiness assessment & preliminary alignment**	**Non-Med countries**	**Phase 1 (2025–2027): Scientific dialogue & awareness building**
Operational actions			
• Evaluation of institutional and administrative structures. • Mapping of digital capacity: DESI scores, LPWAN availability, agricultural data systems. • Identification of hosting authorities (paying agencies, regional agrifood institutes). • Signing of MoUs with ClimaMED research partners. • Preparatory analysis of agro-ecological suitability.		• Technical presentations to national MRV authorities. • Assessment of agro-ecological divergence. • Initial modelling discussions (background CO_2/CH_4 adjustment). • Inclusion in Horizon/LIFE research networks.	
Phase 2 (2027–2030): Calibration pilots and structured testing		**Phase 2 (2027–2030): Calibration research & early pilots**	
Operational actions			
• Deployment of *very small-scale* calibration pilots. • Joint measurement campaigns with ClimaMED laboratories. • Capacity-building workshops on data interpretation, QA/QC,advisory use of fluxes. • Digital alignment with LPIS and national MRV systems.		• Calibration deployments in selected zones. • Co-development of dispersion models suitable for temperate climates. • Integration pilots with national digital MRV systems. • Training of research and advisory bodies.	
Phase 3 (2030–2035): Legislative adaptation and expansion		**Phase 3 (2030–2035): Long-term integration for advanced MRV**	
Operational actions			
• Drafting of national frameworks based on the ClimaMED template. • Formation of a national Operational Centre. • Extension of pilot installations to multiple regions. • Preparation for certification processes.		• Use of the system for carbon farming verification. • Integration with EU CRCF where justified. • Development of long-term calibration routines.	

5. Replication of Guidelines and good practice recommendations for five Mediterranean crops

5.1 The replicable package (What)

The project has developed a comprehensive set of crop-specific guidelines for olive orchards, vineyards, pistachio orchards, cereals and vegetable crops, complemented by a cross-cutting synthesis of mitigation practices and a set of evidence-based proposals submitted to MINAGRIC. These outputs were developed through the integration of LiDAR-based GHG measurements, field-management data collected via a specifically developed GIS-app and farmers' interviews), soil and meteorological datasets and continuous advisory interactions with pilot-site farmers.

Each guideline includes:

- a description of key emission sources and drivers in the specific cropping system
- quantified impacts of practices on GHG fluxes and SOC changes, derived from project measurements
- recommended mitigation practices validated through field experimentation
- implementation recommendations for advisory services and CAP eco-schemes.

Together, these guidelines (which are technology-independent)constitute a coherent agronomic package directly relevant to Mediterranean agriculture and suitable for replication in regions with comparable climate conditions, cropping systems and management intensities.

Challenges and lessons learned during implementation

Despite strong results, several implementation challenges emerged:

- *Environmental variability:* GHG fluxes showed pronounced diurnal and seasonal cycles, complicating the attribution of emissions to specific practices. Differentiating background respiration from practice-induced fluxes required detailed meteorological correction. These fluctuations also influenced short-term CO_2 efflux measurements used to infer soil biological activity, affecting SOC-related processes such as mineralization rates and microbial respiration.
- *Heterogeneity of management practices:* Farmers applied highly diverse fertilization and tillage regimes. This variability necessitated broader guideline categories rather than rigid prescriptions. The wide differences in organic-matter inputs, residue management and tillage depth produced highly variable SOC responses, making it necessary to interpret SOC trends at field, rather than farm-system, scale.
- *Crop-specific constraints:* Certain practices proved difficult to implement in specific systems (e.g., maintaining permanent cover in tree crops on slopes). Structural or topographical limitations (e.g., erosion risk on slopes, shallow soils) reduced the

feasibility of SOC-building practices such as cover cropping, mulching or compost application, highlighting the need for site-specific adaptation.

- *Differences in technology acceptance*: Some farmers adopted reduced tillage and mulching readily, while others maintained conventional deep-tillage approaches, demonstrating the need for advisory support. Variation in farmer acceptance directly influenced SOC trajectories, since the most SOC-enhancing practices (minimum tillage, residue retention, organic amendments) require sustained behavioural adoption to produce measurable carbon gains.

Readiness for replication and scaling potential

The agronomic guidelines exhibit high replicability in Mediterranean regions, where climatic conditions, soil types and cropping systems closely resemble those of the pilot sites. Their replicability is further enhanced by:

- the strong evidence base from real-time measurements,
- their alignment with EU climate policy (CAP eco-schemes, Green Deal),
- their compatibility with digital advisory systems, and
- the existence of a certification framework for low-GHG agricultural products.

However, replication outside Mediterranean environments may require adaptation, especially regarding background respiration, irrigation regimes and crop phenology.
Overall, the agronomic package reaches a high replication readiness level, with immediate scalability potential in Southern Europe and conditional scalability elsewhere.

Table 8 summarizes the replication potential of the guidance and relative reports of the LIFE ClimaMED project.

Table 8. Agronomic Replication Readiness Matrix

Crop System	Evidence Strength	Context Dependency	Replicability (Mediterranean)	Replicability (Non-Med)
Olive orchards	Very high	Low–Medium	Very high	Medium
Vineyards	High	Medium	High	Medium
Cereals	Medium	High	Medium–High	Medium–Low
Vegetables	Medium	High	Medium	Low
Pistachios	High	Medium	High	Medium

<u>Evidence strength:</u> Evidence strength reflects how robust and consistent the empirical data is for each crop, based on LiDAR GHG measurements, soil sensor data, management information collected, and interviews with farmers. Olive orchards, vineyards and pistachios benefited from long lasting repeated measurements and strong agreement between GHG flux patterns, SOC-related processes and management records. In contrast, annual crops cereals and vegetables, showed higher variability due to rapid management cycles, diverse fertilization regimes and weather sensitivity. As a result, evidence strength is graded according to the quantity, quality and consistency of measurements supporting each crop-specific guideline.

Context dependency: Context dependency assesses the degree to which the recommended practices depend on specific environmental, agronomic or management conditions. Perennial Mediterranean crops such as olives and pistachios tend to exhibit relatively stable responses across regions with similar climate and soil characteristics, making their guidelines less sensitive to local variability. Conversely, annual crops such as cereals and vegetables respond strongly to differences in irrigation, fertilizer regimes, rotation patterns and local microclimates, creating a higher dependency on site-specific conditions. The score therefore captures how much adaptation is needed when transferring practices beyond the project's pilot sites.

Replicability in Mediterranean regions: Replicability in Mediterranean regions measures how easily the guidelines can be transferred to areas with environmental and agronomic conditions comparable to those of the ClimaMED pilot sites. Olive orchards, pistachio plantations and vineyards, traditional Mediterranean perennial systems, show high to very high replicability because their climatic requirements, management cycles and SOC/GHG responses are very similar across Southern European countries. Cereals and vegetables retain good potential for replication but require closer alignment with local irrigation regimes, crop rotations and fertilization strategies.

Replicability in Non-Mediterranean regions: Replicability outside the Mediterranean evaluates the degree to which the guidelines can be implemented in climates, soils and cropping systems that diverge significantly from semi-arid or sub-humid Mediterranean environments. Many SOC-enhancing and GHG-mitigating practices remain broadly valid (e.g., reduced tillage, residue retention, compost use), but the magnitude and dynamics of their effects differ substantially in temperate, continental or northern climates. Cold climates accumulate SOC more easily, rainfall patterns contrast sharply with Mediterranean irrigation-dominated systems, and phenological cycles do not fully match those of olives, pistachios or warm-season horticulture. As a result, perennial Mediterranean crops show limited applicability outside their natural range, while annual crops exhibit moderate but still constrained transferability.

5.2. Replication environments (Where)

Building on the assessment presented in Table 8 and the corresponding evaluation of evidence strength, context dependency and climatic compatibility, the geographic transferability of the agronomic guidelines follows a clear and structured logic. Because the guidelines are crop-based rather than device-based, their replicability is primarily determined by the presence of comparable cropping systems, similar management intensities and agronomic environments where SOC-enhancing and GHG-mitigating practices express similar biophysical behavior.

Across the Mediterranean basin, transferability is highest. The climatic and agronomic proximity of these regions, characterized by semi-arid to warm-temperate climates (Csa/Csb), long dry seasons, irrigation-dependent horticulture and extensive perennial systems, creates conditions under which the guidelines can be directly adopted with

minimal adaptation. This includes Greece, Spain, Italy, Cyprus, Portugal, Malta, southern France and the coastal and island areas of Croatia. In these locations, olives, vines, pistachios, vegetables and cereals are grown under management regimes that closely mirror those of the ClimaMED pilot sites, allowing the recommended practices (reduced tillage, residue retention, compost application, permanent or seasonal cover crops, improved fertilization strategies) to produce similar GHG and SOC outcomes.
Beyond these strictly Mediterranean areas, the guidelines also demonstrate strong applicability in broader sub-Mediterranean and warm-temperate zones (Cfa/Cfb) where orchard architecture, soil constraints, irrigation patterns and crop phenology align with those of the project. These include:

- Portugal: Alentejo, Algarve, Ribatejo–Oeste (vineyards, olives, irrigated horticulture)
- France: Occitanie, Nouvelle-Aquitaine (Bordeaux), Drôme–Ardèche transition zones, Gard and Hérault
- Spain: Aragon (Ebro valley), Castilla-La Mancha (northern semi-arid zones), Navarre
- Italy: Emilia-Romagna, Veneto, Lombardy (orchards, vineyards, irrigated horticulture)
- Croatia: Istria and Dalmatian hinterland (semi-arid orchard/vegetable systems)

These areas are either expanding perennial crops (such as olives and pistachios), maintain established vineyard and irrigated-horticulture sectors, or host annual crops (vegetables, cereals) under comparable temperature and moisture regimes. As a result, they require minimal adjustment of the recommended practices, mainly to account for local slope, erosion risk, irrigation water availability or fertilizer regulations.

Beyond the Mediterranean climate envelope, transferability becomes crop-specific rather than system-wide. In northern and eastern EU Member States, perennial systems such as olives and pistachios are absent or marginal, and vineyards are distributed in cooler agro-ecosystems where phenology, canopy structure and soil biological cycles differ fundamentally from those of the ClimaMED pilots. Nonetheless, the guidelines retain substantial relevance for annual crops, particularly cereals and vegetables, as well as for cross-cutting SOC-enhancing strategies. Practices such as reduced tillage, residue incorporation, manure or compost application, precision irrigation, optimized nitrogen fertilization and maintenance of off-season ground cover have broad scientific validity and can support carbon-farming schemes, certification mechanisms and advisory programmes irrespective of climate zone.
Table 9 summarizes the applicability zones of the LIFE ClimaMED guidelines
Overall, the guidelines achieve high direct replicability in Mediterranean and warm-temperate regions, and conditional replicability elsewhere, where targeted calibration and contextual adaptation are required.

Table 9. Applicability zones for replication of crop-specific guidelines

Climate/Zone Category	Countries & Regions	Rationale for Applicability
Mediterranean (Csa/Csb) Highest replicability	Greece, Spain, Italy, Cyprus, Portugal, Malta, Southern France (PACA, Occitanie), Coastal & Island Croatia (Dalmatia, Adriatic islands)	Direct match with ClimaMED pilot conditions; perennial crops dominant; irrigation-based horticulture; similar SOC/GHG dynamics
Sub-Mediterranean / Warm-Temperate Transition Zones (Cfa/Cfb High replicability	Portugal: Alentejo, Algarve, Ribatejo–Oeste; France: Occitanie, Nouvelle-Aquitaine, Drôme–Ardèche, Gard, Hérault; Spain: Aragon (Ebro), Navarre, Northern Castilla-La Mancha; Italy: Emilia-Romagna, Veneto, Lombardy; Croatia: Istria, Dalmatian hinterland; Northern	Similar orchard/vineyard structures; irrigated vegetables; comparable soil constraints; warm summers; SOC/GHG responses close to Mediterranean pilots
Temperate EU Regions Partial replicability (crop-specific)	Austria, Germany, Slovenia, Hungary, Slovakia, Czechia, Poland, Romania, Bulgaria, Northern France	Annual crops (cereals, vegetables) highly relevant; SOC practices transferable; perennial Mediterranean crops not applicable
Continental / Boreal EU Regions Low but targeted replicability	Scandinavia, Baltic States	Applicability restricted to SOC-enhancing practices for annual crops; major climatic and phenological mismatch with Mediterranean perennials

5.3 Target adopters and adoption depth (Who)

The guidelines are designed for use by a broad network of agricultural actors. At farm level, they support farmers, cooperatives and producer groups who wish to optimize their management practices, reduce emissions and increase soil carbon. They can be directly incorporated into fertilization planning, tillage strategies, irrigation scheduling and residue management practices.

At advisory and institutional levels, the materials can be used by regional agricultural directorates, farm advisory systems and chambers of agriculture. These organizations can embed the guidelines into training modules, technical bulletins, seasonal recommendations and farm visits.

Policy actors, particularly CAP Managing Authorities, national ministries and regional administrations, may also use the guidelines to shape eco-schemes, update mitigation plans, or prepare soil-health–oriented interventions. Finally, universities, research centres and technical schools can deploy the guidelines for training, curriculum development and applied research.

Table 10 provides a structured overview of the stakeholders relevant to the replication of the crop-specific guidelines developed under LIFE ClimaMED. In line with the analytical framework used for the LIDAR–LoRa–CMM system, stakeholders are grouped into three categories for each country or country cluster:

- core stakeholders, who directly participated in project activities and constitute the primary early adopters;
- the expanded national ecosystem, which includes institutional, scientific, operational and advisory actors capable of supporting adaptation and mainstreaming of the guidelines; and
- potential end-users, comprising cooperatives, producer organizations, advisory services and farmers who stand to benefit from the uptake of the recommended GHG-mitigation and SOM-enhancing practices.

This layered representation captures both the project's existing engagement landscape and the broader agricultural governance structures that will shape the replicability of the guidelines across Mediterranean and non-Mediterranean contexts. It therefore provides a realistic map of the actors who can influence, support or directly implement the recommendations at regional, national and EU level.

Table 10. Multi-Level stakeholder ecosystem for the replication of crop guidelines across EU.

Category	Institutional	Operational	End-users
Core stakeholders	MINAGRIC; Regions of Crete, Ionian Islands, Sterea Ellada	LIFE ClimaMED beneficiaries Municipalities in pilots	Farmers involved in the pilots and their cooperatives
Expanded stakeholders	OPEKEPE; Directorate of Land & Soil; Ministry of Climate Crisis	DAOKs; KEGE; Private advisors; Chambers of Agriculture	PDO groups; Organic-farming associations
Potential stakeholders	Regional authorities; Soil governance units	Soil labs; Agri-digital companies	Cooperatives in olives, pistachios, vines, vegetables, cereals

5.4 Scaling timeline (When)

The guidelines can be adopted immediately in advisory services and farm operations because they require no specialised equipment, no legislative prerequisites, no digital infrastructure,and minimal adaptation.

Short-term (1–3 years) adoption includes integration into regional climate plans and CAP eco-schemes. Medium-term adoption (>3 years) includes using the guidelines for certification of low-GHG or SOM-preserving products and embedding them into national soil-health frameworks.

5.5 Operational mechanism for replication (How)

- **Greece**
  Greece already has extensive engagement with the project's agronomic work, making the guidelines readily replicable. National and regional agricultural authorities (MINAGRIC; Regions of Crete, Ionian Islands, Sterea Ellada and others) can integrate them directly into advisory workflows and into proposals for future eco-schemes.
  Farmers involved in the pilot activities and their cooperatives in Aegina, Peloponnese, Crete, Sterea Ellada, Central Macedonia represent early adopters who have participated in project demonstrations and training activities. Project beneficiaries in Greece can support local adaptation by linking GHG emissions reduction and SOC changes insights with fertilization and tillage recommendations.
  Replication proceeds through cooperative-led workshops, integration into regional extension programmes and alignment with the national soil-health strategy currently under development.
- **Italy – Spain – Cyprus**
  These countries share the same Mediterranean crop portfolio and similar agronomic challenges (irrigated horticulture, orchard management, erosion risk, organic-matter decline). The institutional partners involved in the project (CeRSAA, UMH, ENVITECH) and the involved regional and local Authorities (Regions of Liguria, and Valencia, the Municipality of Sotira in Cyprus) provide immediate entry points for adaptation.Farmers' associations in Liguria, the Valencian irrigation consortia (Riegos de Levante, Carrizales, La Unió de Llauradors i Ramaders) and Cypriot vegetable growers can use the guidelines with minor calibration for soil type, irrigation thresholds and fertilization norms.National stakeholders such as CREA, CNR, INIA/IRTA/IFAPA and the Cyprus Agricultural Research Institute can support dissemination through advisory networks.The guidelines can also be integrated into cooperative sustainability schemes and regional climate-adaptation strategies, especially where orchards and vineyards are primary economic sectors.
- **Other Mediterranean EU countries**
  In France, Portugal, Malta, Slovenia and coastal Croatia, the guidelines have high thematic relevance, as these countries cultivate olives, grapes, horticultural crops and cereals in similar conditions.

Although they were not directly involved in the project, the advisory ecosystems (INRAE, ISA Lisbon, Chambers of Agriculture, regional soil laboratories, national olive/vineyard organizations) offer strong platforms for uptake. Adaptation mainly concerns local fertilizer regulations, water availability and soil characteristics, but the conceptual structure (GHG mitigation and SOM enhancement) is universal. Early-stage engagement can occur through workshops, CAP networks, Mediterranean dialogues and cooperation with universities.

- **Non-Mediterranean EU countries**

  Replication in non-Mediterranean regions is partial because some crops (olives, pistachios) are absent. However, guidelines for cereals, vegetables, and SOC-enhancing practices (compost, mulching, reduced tillage) are broadly applicable and can feed into carbon-farming schemes, CAP eco-schemes, and advisory materials.

  Potential adopters include Wageningen UR, Thünen Institute, Danish advisory councils, Baltic soil-monitoring institutes, agricultural universities, and national paying agencies developing soil-health interventions. Uptake is expected mainly in conceptual and advisory form, rather than direct crop-specific replication.

6.Replication of Low GHG Certification scheme

6.1 The replicable package (What)

The certification system of LIFE ClimaMED constitutes a distinct, high-value replication package that goes beyond generic eco-labels and carbon calculators. It proposes a low-GHG / low-carbon certification system for agricultural products that is explicitly based on Tier-3, real-time field measurements of CO_2, CH_4 and N_2O, rather than on modelled or average emission factors. This feature differentiates the ClimaMED framework from all existing low-carbon schemes currently operating in Europe and internationally and defines both its novelty and its replication potential.

Core structure of the ClimaMED certification system

The ClimaMED certification package is described in detail in the deliverable "*Low GHGs emission agricultural products: Establishment of a procedure for agricultural products certification – Guidelines*", which combines:

- a review and critical analysis of existing eco/low-carbon certification systems in agriculture
- a conceptual and legal design of a **national certification system** under the responsibility of MINAGRIC
- a fully documented operational procedure, with roles, forms and workflows, for issuing low-GHG product certificates based on the LIFE ClimaMED monitoring system.

From a replication perspective, the certification package to be scaled consists of four tightly linked elements:

1. Measurement backbone: The system is anchored on the ClimaMED monitoring chain (LiDAR + meteorological station + LoRa telemetry + CMM). Parcel-level GHG emissions over a full cropping season are measured, processed and stored in the CMM, which serves as the *single source of verified emission data*. These data underpin the calculation of a product's carbon footprint and its eligibility for certification.
2. Institutional architecture: The certification process is designed as a public–private governance model, coordinated by the Greek Ministry of Rural Development and Food (MINAGRIC), and involving:
   - MINAGRIC as scheme owner and competent authority
   - producers who install and operate certified devices on their fields
   - accredited equipment suppliers responsible for installation and primary declarations
   - the CAP Paying Agency (OPEKEPE) for potential linkages with support schemes
   - independent external certifiers who validate compliance and issue the product certificate.

   This architecture is itself replicable as an institutional template: a ministry (or national competent authority) owns the scheme, a national CAP agency connects certification to payments and accredited third parties perform audits.
3. Standardized procedures and documentation: The respective ClimaMED deliverable defines a stepwise certification process, including device procurement and registration, producer enrolment, baseline determination, annual measurement and data processing, application for certification, evaluation and issuance of a formal certificate. Each step is supported by standard forms (device and producer declaration, user account activation, application for certificate, template certificate), which can be reused or adapted by other Member States. A key feature is the *baseline emission determination*: using life-cycle information and crop-specific GWP values derived from ClimaMED LCA work, the system defines a reference scenario against which measured emissions and practice changes are assessed. This makes the certification results-based but grounded in real measurements rather than purely modelled baselines.
4. Product-level certificate and scope: The system issues a "*low-GHG emission product certificate*" for specific Mediterranean products (initially olives, grapes, cereals, vegetables, pistachios), with the explicit intention to extend to other crops. The certificate is conceived as a multi-purpose instrument:
   - a market signal for consumers and value chains
   - a compliance or bonus criterion for CAP eco-schemes or national climate instruments
   - a data-rich proof of climate performance for supply-chain partners and public authorities.

In contrast to many eco-labels that are farm- or process-oriented, ClimaMED is explicitly *product-oriented,* while keeping a farm-system perspective through continuous monitoring.

Positioning of ClimaMED among existing low-carbon certification schemes

The certification deliverable includes a structured review of the main low-carbon or climate-related schemes in agriculture: Solagro/Carbon Calculator, Label bas Carbone (LBC) and Carbon Agri (France), LEAF Marque (UK and beyond), Wineries for Climate Protection (Spain), and the Low-Carbon Agricultural and Livestock Products Certification System (Republic of Korea). Recent scientific work by Bartzas et al. (2024, 2025) confirms that these systems cover a spectrum of approaches, from farm-level calculators and practice-based standards to product-or sector-specific labels-but none integrates continuous Tier-3 measurements at parcel scale as its primary data source.

Solagro / EU farm carbon calculators

The Solagro initiative, building on an EU Parliament pilot project, developed an Excel-based farm carbon calculator that estimates GHG emissions and mitigation options using life-cycle emission factors and farm-level data entry. Such tools are useful for awareness raising and benchmarking, but they rely on static emission factors and farmer-reported data rather than measurements. From a replicability viewpoint, they offer an important behavioural and planning tool but cannot provide the Tier-3 evidence required for rigorous MRV and product-level certification.

Label bas Carbone and Carbon Agri (France)

France's Label bas Carbone (LBC) is a national certification scheme for GHG reduction or sequestration projects across multiple sectors, including agriculture, using project-based methodologies such as Carbon Agri. It certifies quantified emission reductions relative to a baseline and enables voluntary climate finance. The Carbon Agri method is farm-level, result-based and uses tools such as CAP'2ER® to estimate emissions via activity data and emission factors. LBC has become a reference model for result-based carbon farming schemes in Europe, but it does not yet incorporate continuous LiDAR or similar Tier-3 measurement infrastructures.

LEAF Marque (Integrated Farm Management)

The LEAF Marque Standard is an environmental assurance scheme covering the whole farm, across soil, water, biodiversity, energy, climate and social aspects, and is increasingly used by major retailers as a sustainability requirement. It is multi-criteria and practice-based, focusing on integrated farm management and continuous improvement rather than quantitative GHG outcomes. Carbon is one dimension among many. Its strength lies in market penetration and retailer uptake, but it does not provide a dedicated low-GHG product certificate based on direct emissions monitoring.

Wineries for Climate Protection (Spain)

The Wineries for Climate Protection (WfCP/SWfCP) scheme is the first sector-specific environmental certification for wineries, focusing on GHG emissions, water, waste and biodiversity, with requirements for reduction plans and periodic verification. It is a strong example of value-chain driven certification, but it is confined to wineries and uses standard emission accounting rather than field-level Tier-3 monitoring.

Republic of Korea's Low-Carbon Agricultural and Livestock Products Certification

The Korean low-carbon agricultural product certification system, launched in 2014 and extended to dozens of crop and livestock categories, is recognized as the first national low-carbon ecolabel dedicated to agricultural and livestock products. Certification is awarded when a product's life-cycle emissions are below the national average for that product type, based on standardized inventories and reduction practices. This scheme shows how low-carbon labels can be integrated into national agricultural policy and markets, but again relies on modelled inventory data rather than on continuous field measurements.

Across these examples, the main added value of ClimaMED can be summarized as follows:

- It is the only framework that links a national certification system directly to a Tier-3, real-time, parcel-level monitoring infrastructure (LiDAR + CMM).
- It positions the Ministry (MINAGRIC) as scheme owner and data holder, enabling integration with CAP payments and climate policy in a way closer to LBC's national logic, but with higher MRV granularity.
- It provides a product-specific, Mediterranean-oriented label, initially focused on olives, grapes, cereals, vegetables and pistachios, complementing broader farm-level schemes such as LEAF Marque or WfCP.
- It creates a pathway to hybrid architectures, where existing schemes (e.g. LBC, LEAF) could use ClimaMED-type Tier-3 data as a verified input to their own scoring or crediting systems.

This positioning is important for replication: other Member States do not need to abandon their existing schemes but can plug a ClimaMED-type measurement-based certification module into their policy mix, enhancing the robustness and credibility of national carbon farming and eco-label initiatives.

Lessons learned and challenges

The design and testing of the ClimaMED certification system revealed some operational, institutional and behavioral challenges that must be addressed to ensure credible, scalable replication across Mediterranean and EU Member States. These challenges emerged both from the technical implementation of the LIDAR–LoRa–CMM measurement backbone and from the structured dialogue with farmers, authorities, producer groups and certification bodies during the round-table events held in Greece, Italy, Cyprus and Spain.

- Real-time measurement complexity and data integrity: Continuous Tier-3 measurement introduces challenges not present in standard, model-based carbon schemes. Stakeholders expressed concerns regarding external emission interference (roads, airports, industrial areas), which must be accounted for during baseline construction

  Contingency: The certification system foresees a three-year pre-certification measurement period, as a core structural element of the scheme. During these three years the monitoring device remains installed on the parcel, all seasonal and interannual emission fluctuations are captured, recurrent external-emission signals (e.g., periodic traffic peaks, nearby industrial activity, airport take-off patterns) are systematically incorporated into the dataset, and a statistically robust parcel-specific baseline is constructed. This three-year dataset becomes the *official "starting line"* of the certificate: it establishes the maximum reference emission level for the parcel, against which future reductions (expressed as percentage decreases) are evaluated and rewarded. Because the baseline incorporates all expected and unexpected interference events over multiple seasons, the certification process does not penalize farmers for random spikes or external effects. Instead, it ensures that:

- abnormal values are normalized across multi-year datasets,
- the baseline truly reflects the reality of each specific location,
- and reductions rewarded through certification represent genuine behavioral or management improvements, not short-term statistical artefacts.

For the products assessed in LIFE ClimaMED (olives, grapes, cereals, vegetables and pistachios), the reference baseline is derived from the crop-specific LCA studies conducted during the project. For Greece, this choice is fully appropriate because the LCA reflects national cultivation practices, energy mix, input profiles and logistics; it therefore provides a realistic *upper emission threshold* against which measured reductions can be evaluated. For other Mediterranean or EU countries, however, the direct use of the Greek LCA values may not fully reflect national production conditions. Consequently, countries seeking to replicate the system have three valid pathways:

1. Adopt national LCA-based upper thresholds, using national or regional LCA studies for the same crops.
2. Use the three-year pre-certification measurement period to derive a parcel-specific empirical baseline (as allowed by the ClimaMED certification logic).
3. Combine both approaches, replicating the Greek model: LCA for defining the *upper permissible threshold*, and a three-year measurement period for establishing the actual farm-level starting point.

This flexibility ensures methodological robustness while respecting national differences. It also preserves comparability across Member States, since all pathways remain consistent with the core ClimaMED principle: final certification eligibility must be based on measured, not modelled, reductions relative to a clearly defined baseline.

- Integration of organic inputs into the carbon logic: Applying manure, compost or residues temporarily increases measured GHG emissions, even though these amendments contribute to long-term soil carbon storage. Stakeholders questioned how these apparent "emission spikes" would be treated in certification.

  Contingency: The ClimaMED certification system addresses this through a documented and auditable adjustment mechanism. When a farmer applies organic amendments, the system requires the upload of supporting evidence (e.g. invoices, purchase documents, delivery notes, cooperative receipts, compost-production

certificates), which are submitted through the producer's ClimaMED account as part of the annual declaration, confirming both the quantity and type of the material applied. Using these documented quantities, the certification body applies a predefined, computational correction factor that accounts for the fraction of emissions attributable to the natural decomposition of the added organic material.
This approach:
  - ensures fairness, so farmers are not penalized for practices that increase soil carbon in the long term,
  - preserves traceability and auditability, because every adjustment must be supported by verifiable documentation,
  - allows certification bodies to apply consistent, standardized rules, independent of subjective judgement,
  - and maintains the scientific integrity of the certification by clearly distinguishing between *practice-induced biological emissions* and *true changes in farm management performance*.

From a replication perspective, this mechanism represents a strong institutional safeguard, ensuring that the certification system remains compatible with soil-health policies and regenerative agriculture while still relying on high-precision Tier-3 measurements.

- Establishment and hosting of Operational Centres: Several countries raised the question if the system could operate without an established Operational Centre equivalent to the Greek one (FORTH → MINAGRIC).
  Contingency: Although Greece's center can temporarily host foreign devices, long-term replication requires national hosting capabilities, stable operational funding and trained personnel for device validation, data handling and certification oversight.
- Need for national-level accreditation and alignment with existing schemes" The ClimaMED certificate relies on a public–private governance structure involving ministries, paying agencies, device suppliers and external certifiers. Other countries highlighted uncertainties about:
  - aligning the system with existing national certification frameworks
  - integrating Tier-3 monitoring into CAP eco-schemes
  - avoiding overlaps with national climate instruments (e.g., France's LBC)

  Contingency: Legal harmonization and administrative integration remain key challenges.
- Ensuring fair compensation in agri-environmental schemes: Stakeholders emphasized that low performance should not result in penalties, as adoption is voluntary and farmers need time to adapt new practices.
  Contingency: The ClimaMED certification system already incorporates this principle at its core: the scheme is strictly non-punitive. If a farmer does not achieve a reduction in GHG emissions relative to the established baseline, the outcome is simply that no payment is issued for that year. There are no fines, negative adjustments, or

sanctions, making the scheme fully compatible with voluntary participation and progressive behavioral change (however, whether this non-punitive approach will be maintained in future national implementations, either in Greece or in other Member States, remains at the discretion of the competent authorities and will ultimately depend on each country's policy priorities and regulatory philosophy).
Furthermore, the system provides financial support during the three-year baseline-building period, recognizing that installing and operating a measurement device represents an investment for the farmer. These three years of subsidized monitoring serve two critical functions:

1. For farmers: They create a protected "transition window" during which producers can familiarize themselves with the system, understand how different practices affect their emissions, and plan mitigation strategies without the pressure of performance-linked payments. By the end of the baseline period, farmers enter the reward mechanism with a clear understanding of their emission profile and realistic expectations for future improvements.
2. For the Greek public authorities: The three-year baseline period generates high-resolution, real field data for diverse crops, regions and management systems across Greece. These data allow MINAGRIC to:
    - derive evidence-based, national baseline values for different crop groups,
    - understand regional variability in emissions,
    - calibrate the certification logic for future crop categories, and
    - design fair and realistic upper thresholds for future national schemes.

Because the system rewards percentage reductions relative to each farmer's own three-year baseline, it avoids the inequities that arise in other schemes where farmers are benchmarked against national averages or modelled values. This makes ClimaMED inherently fair for producers with diverse soils, climates, or crop structures.
From a replication standpoint, the Greek approach demonstrates that a reward-only, non-punitive design, combined with a subsidized multi-year baseline phase, creates strong farmer acceptance, reduces political friction, and produces the robust data foundation required for scaling the certification system across Member States.

- Market uptake and value-chain integration: Although the QR-code certification label represents a high-value market differentiator, several uncertainties remain:
    - Will supply chains recognize and reward the certificate?
    - How will retailers integrate it into sustainability procurement requirements?
    - Will consumers perceive added value and pay a premium?

  Contingency: These uncertainties do not diminish the intrinsic strength or credibility of the ClimaMED certification framework. Instead, they concern the post-certification market environment, which lies largely outside the certification system itself. To unlock the full economic potential of the scheme, several supportive initiatives by public authorities and value-chain actors could play a catalytic role. These actions would not determine the success or failure of the certification mechanism, its operation and

scientific validity are independent, but they would influence the degree to which certified products gain market visibility and commercial traction.
Possible supportive initiatives include:

- Public communication campaigns led by ministries or producer organizations, highlighting the added value of low-GHG certified Mediterranean products.
- Integration of the QR-code label into national or regional promotional programmes (e.g., "quality schemes", PDO/PGI clusters, export promotion agencies).
- Retailer engagement frameworks, where major supermarket chains include low-GHG certification as a recommended or optional criterion in sustainable procurement guidelines.
- Voluntary agreements with processors and distributors, enabling certified products to be prioritized in supply chains that seek low-carbon sourcing.
- Incentive structures in public procurement, where schools, hospitals or public institutions may favor certified low-GHG products when feasible.
- Cross-branding or co-labeling initiatives with existing quality or origin labels, increasing consumer recognition and reducing confusion among competing sustainability claims.

Such initiatives are not prerequisites for the functioning of the certification system, nor do they affect its methodological rigor, measurement requirements or compliance procedures. Rather, they represent complementary, downstream policy or market actions that can enhance the visibility, commercial value and societal impact of the ClimaMED certification label once it is operational.

- Agro-ecological differences and system applicability: Stakeholders in Italy, Spain and Cyprus asked whether the system requires calibration before use in non-Greek conditions.
  Contingency: While the baseline-building logic makes calibration unnecessary, differences in crop phenology, irrigation patterns, background atmospheric signals may still require context-specific guidance.

Certification replication readiness assessment

To support decision-makers in other Member States, the replicability of the LIFE ClimaMED Low-GHG Certification System is summarized in a structured readiness matrix. This matrix mirrors the logic used for the LIDAR technological replicability assessment but is adapted to the institutional, regulatory, procedural and market-specific nature of certification systems. It provides a clear, decision-oriented overview of which components of the certification framework can be transferred immediately and which require national adaptation, enabling authorities to plan realistic adoption pathways.

The matrix below (Table 11) evaluates each core component of the certification system in terms of its current status within ClimaMED, its replicability across Member States, and the enabling conditions that would need to be secured. Together, these elements offer an integrated understanding of the certification system's scalability, highlighting the institutional, legal and operational foundations that countries must establish to ensure successful transfer.

Table11. Replication readiness matrix for the certification system.

Certification Component	Status in ClimaMED	Replicability	Conditions / Notes
Certification workflow and forms	Fully developed procedures and templates	Very High	Can be reused directly; minor localization only
Baseline logic (LCA + 3-year measurement)	Validated in Greece	High	Other countries need national LCA thresholds or adopt the 3-year empirical baseline
Institutional model (Ministry + Paying Agency + Certifier)	Defined and operational in Greece	High	Requires designation of competent authorities and accreditation structure
Measurement backbone (Tier-3 system)	Fully operational	Medium–High	Requires installation of measurement devices or access to national infrastructure
Audit and accreditation framework	Defined in Greek context	Medium	Countries need ISO17065-compliant bodies and national accreditation rules
Digital systems and QR code registry	Functional	Very High	Requires national hosting or integration into EU platforms
Reward mechanism (non-punitive)	Designed and aligned with CAP principles	Medium–High	Must align with national payment structures and eco-schemes
Market positioning	Early-stage development	Medium	Depends on retailer engagement, consumer awareness, national campaigns
Operational Centre model	Fully functional in Greece	Medium	Countries must assign or create a national Operational Centre

6.2 Replication environments (Where)

Replication of the LIFE ClimaMED certification architecture is inseparable from the replication feasibility of the underlying LIDAR–LoRa–CMM monitoring chain (Chapter 4). Because certification depends on verified Tier-3, parcel-level GHG measurements, it can only be implemented in environments where the monitoring system can be deployed, institutionalized and supported by national authorities. For this reason, the identification of suitable replication environments follows a two-layer methodology:

1. Baseline: LIDAR Replication Feasibility Index (RFI)

- Only countries assessed as Tier A or Tier B in the LIDAR-LoRa-CMM system RFI are eligible for certification-system replication.
- Countries classified as Tier C cannot operate a measurement-based certification scheme and are therefore excluded.

2. Certification RFI overlay: For all Tier A/B countries, we evaluate:
   - policy readiness for product-level climate labels,
   - institutional capacity to host a scheme owned by a competent authority,
   - digital readiness (LPIS, CAP registries, e-government),
   - market maturity for low-GHG products, and
   - compatibility between ClimaMED's measurement logic and existing national or private certification schemes.

This hybrid evaluation identifies realistic replication territories and determines where the certification package can be transferred directly, where it requires adaptation, and where it should be planned only as a long-term option.

Greece – Immediate and Full Replication Potential (Tier A)
Greece is the only Member State where both prerequisites for certification are already fulfilled:

1. the LIDAR–LoRa–CMM system is legally adopted,
2. the certification architecture has been designed explicitly for the Greek institutional environment.

Key enabling conditions:

- National law A'34/2025 establishes the Operational Centre and defines institutional roles.
- LPIS, OPEKEPE and MINAGRIC registries are already interoperable with the certification procedures tested in LIFE ClimaMED.
- Strong stakeholder engagement (farmers, cooperatives, advisory systems, equipment suppliers) has been achieved during the project.

Therefore, Greece is a Tier A country where the certification system can be implemented directly after publication of the Joint Ministerial Decision. No substantial adaptation is required.

Italy, Spain, Cyprus – High replication potential with moderate adaptation (Tier A/B)
These three countries show high feasibility for LIDAR deployment and already operate advanced sustainability or sectoral schemes (e.g., WfCP in Spain, regional schemes in Italy, and Cyprus' digital agriculture strategy). Their institutional and policy landscapes can incorporate a ClimaMED-type certification module.
Enabling characteristics:

- Active participation in LIFE ClimaMED and MoU.
- Strong digital infrastructure (LPIS, CAP registries, cadastral systems).
- Crop systems similar to Greek pilot crops.

- Regional governments actively finance climate or carbon initiatives.

Required adaptations:

- Definition of national governance architecture (designation of scheme owner).
- Alignment with existing schemes (WfCP, regional quality labels, LIFE and CAP eco-schemes).
- Localization of LCA baselines and crop-specific GWP values (or adoption of Greek values as a conservative baseline).

Therefore, these countries are well positioned for early replication, beginning with pilot certification in selected regions, with full national expansion during Phase 2 of replication.

Other Mediterranean countries – Medium-Term replication potential (Tier B)
(France, Portugal, Malta, Croatia, Slovenia)
These countries have mature digital and policy ecosystems, and in many cases sophisticated climate-governance structures (e.g., France's Label bas Carbone, Portugal's strong soil and carbon-farming policies). However, none currently deploys parcel-level Tier-3 GHG monitoring, and thus certification replication depends on their willingness to adopt or integrate a LIDAR-based MRV component.
Strengths:

- High institutional capacity and MRV maturity (especially France and Portugal).
- Strong research ecosystems (INRAE, ISA Lisbon).
- Market structures for olives, grapes and horticulture in Mediterranean/coastal regions.

Barriers:

- Existing national certification structures may prefer inventory-based methods.
- Limited political incentives for real-time GHG monitoring.
- Need for national legislative templates and coordination with CAP authorities.

Therefore, suitable for medium-term adoption, beginning with pilots in sub-Mediterranean regions and progressive integration with existing labels or carbon farming policies.

Table 12. Certification replication readiness matrix

Region / Country Group	Certification Readiness Tier	Dependency on LIDAR RFI	Key Conditions for Replication
Greece	Tier A Immediate replication	LIDAR Tier A	Law adopted; institutions operational; full LPIS interoperability; pilot crops fully covered
Italy, Spain, Cyprus	Tier A/B Early replication	LIDAR Tier A/B	Legislative adaptation; integration with existing schemes; regional pilot deployment
France, Portugal, Malta, Croatia, Slovenia	Tier B Medium-term replication	LIDAR Tier B	Adoption of LIDAR system; alignment with national certification frameworks; institutional agreements

6.3. Target adopters and adoption depths (Who)

The adoption environment of the ClimaMED low-GHG certification system follows the same diffusion and institutionalization principles applied to the LIDAR–LoRa–CMM monitoring chain (Rogers 2003; WHO/ExpandNet 2010; FAO 2021) but expands them into additional governance and market dimensions that are unique to product certification. Because this system issues an official, measurement-based certificate, its adoption depends not only on technical and institutional readiness but also on the structure and maturity of national markets, policy frameworks, carbon-farming schemes, and supply-chain instruments. The certification model therefore requires an ecosystem of actors that extends from ministries and paying agencies to producers, advisory services, certifiers and suppliers.

Institutional adopters include ministries of agriculture, CAP managing authorities, paying agencies, national bodies responsible for MRV, and organizations overseeing product-quality standards. These entities are essential because they define the legal foundations of the certification system, supervise external certifiers, designate competent authorities, operationalize the certification workflow and determine how certified products interface with CAP eco-schemes, agri-environmental measures, national climate strategies and carbon-market mechanisms. Adoption depth at this level is expressed through the existence of legislative texts, formal mandates, budget allocation, LPIS and digital-registry integration, and structured engagement in consultation events, round tables and methodological reviews.

Operational adopters include cooperatives, producer groups, advisory services, regional authorities, digital-farming platforms and value-chain actors such as mills, packers and wineries. Their adoption depth is reflected not through legal commitments but through participation in demonstrations, training events and pilot workflow testing; familiarity with CMM interactions and documentation procedures (Forms 1–4 of the certification document); capacity to support farmer participation; and readiness to incorporate certification into advisory systems, marketing strategies or regional branding efforts.

End-users encompass farmers, producer organisations, value-chain actors and retailers who may use the QR-coded certificate in product marketing. Their current adoption depth is pre-operational, expressed through participation in monitoring pilots, field visits, training sessions and round-table discussions, as well as awareness of the certification logic and interest in using verified GHG data to differentiate products in domestic and export markets.

Core adopter ecosystem created by LIFE ClimaMED

Across the four project countries, ClimaMED has mobilized a multi-layer adopter ecosystem integrating institutions, technical actors, regional authorities and farmers. At institutional level, MINAGRIC in Greece has emerged as the scheme owner, with OPEKEPE foreseen as the administrative node connecting certification with LPIS and farmer ID systems. Regional authorities in Greece (Crete, Ionian Islands, Sterea Ellada), Italy (Liguria), Spain (Valencia) and Cyprus (Sotira municipality and the Commissioner for the Environment) have been formally recognized as stakeholders, demonstrating political openness to certification. At operational level, research and ICT partners (BPI, FORTH, TUC, Green Projects, CeRSAA, ENVITECH, UMH) have collaborated in the development of the certification procedures based on real field conditions and users needs, while numerous cooperatives and producer groups have taken part in training, demonstrations and consultation activities, gaining familiarity with certification requirements. At end-user level, farmers and producer groups from all participating countries have engaged in information events, field visits and pilot measurements, forming a broad awareness base that is consistent with the "interest" stage of adoption.

This ecosystem has been strengthened through the ClimaMED Memorandum of Understanding, which documents the intention of authorities, cooperatives, institutes and technical partners to continue cooperation beyond the project's duration. Training sessions and six round tables across four countries have further expanded awareness and engagement, particularly with respect to certification requirements, farmers' perceived benefits and practical considerations related to data use, administrative workflow and value-chain integration.

Adoption depth by region

- Greece - Early institutionalization and direct implementation readiness

  In Greece, institutional adoption has progressed to early institutionalization. Law A' 34/2025 formally integrates the monitoring system into national governance and designates MINAGRIC as scheme owner for the certification framework. The certification workflow has been designed using real field conditions and societal challenges, including producer and device declarations, user-account activation, application for emission-certificate issuance and the QR-coded final certificate. OPEKEPE provides an existing digital and administrative infrastructure capable of linking certificates to LPIS parcels and farmer IDs. Operational actors - including project beneficiaries and regional authorities - have progressed to trial or partial-adoption stages through their involvement in workflow testing, trainings and demonstration actions. End-users display interest and early-trial adoption depth, having observed demonstrations, contributed to field measurements and expressed interest in joining certification programmes once the national system becomes fully operational.
- Italy, Spain and Cyprus - Advanced interest and early-trial pre-adoption

  Italy, Spain and Cyprus have not yet legislated the certification system, but they possess a mature pre-adoption ecosystem. Draft legal texts have been prepared in all three countries, defining institutional roles and governance structures for monitoring and certification. Regional authorities are formally listed as stakeholders. The beneficiaries (CeRSAA, UMH, ENVITECH) have acted as operational hubs, contributing to consultations, demonstration events and dissemination activities. Farmers and cooperatives from the three countries have received training during exposure visits to Greek pilot sites and have provided input relevant to the design of future national workflows. Adoption depth in these countries is classified as "advanced interest / early trial," reflecting strong institutional engagement and operational familiarity despite the absence of local LIDAR installations.

- Other Mediterranean EU countries - Awareness and future adopter profiles
  In France, Portugal, Malta, Croatia and Slovenia, ClimaMED has not yet built named stakeholder groups. Exposure has occurred indirectly through online dissemination, presentations at a Mediterranean conference and references in other EU projects involving ClimaMED partners. For these countries, institutional adopters would include ministries, CAP authorities and regional governments managing Mediterranean crops; operational adopters would include research institutes, producer organizations and digital-farming providers; and end-users would include cooperatives and farmer groups in olives, grapes, pistachios and horticulture. Adoption depth remains at the awareness stage, but these countries represent strong candidates for future outreach, particularly within eco-scheme, carbon-farming or regional agricultural innovation frameworks.
- Non-Mediterranean EU countries — Minimal awareness and low relevance
  Non-Mediterranean Member States have not participated in any ClimaMED activity. Exposure has been indirect through publications and conferences. Given their agro-ecological divergence and the absence of relevant Mediterranean crops, adoption depth is classified as "minimal awareness," and these countries are not eligible for certification deployment unless multi-year LIDAR calibration and territorial adaptation take place.
- Integration with EU-level adopters and policy frameworks
  Beyond national adoption pathways, the ClimaMED certification system aligns closely with several EU-level policy initiatives. The European Green Deal and Farm to Fork Strategy emphasize the need for environmentally sustainable food systems and call for verified GHG data for land managers by 2028 (COM(2021) 800). The ClimaMED system directly meets this mandate by providing farmers with parcel-level, high-frequency emission data through the CMM. The recently adopted Regulation (EU) 2024/3012 establishing the Carbon Removal Certification Framework (CRCF) introduces an EU-wide system for certifying carbon removals and agricultural emission reductions. Under the CRCF, ClimaMED can act as a Tier-3 MRV layer for carbon-farming projects, as a quantification module for national or EU methodologies, and as a data source combining real-time GHG measurements with LCA-derived global warming potentials for both reduction and removal activities. At the CAP level, where eco-schemes and agri-environmental measures continue to shift toward performance-based payments, the ClimaMED certification model offers a ready-to-use MRV component that can operationalize results-based approaches. The system also aligns with EU initiatives on digital agricultural data spaces and climate-service interoperability, offering a blueprint for integrating emission data into digital infrastructures through secure, QR-verified certificates.

Stakeholder Adoption Readiness Matrix

The table below summarizes the current adoption depth of the ClimaMED certification system across institutional adopters, operational adopters and end-users in the four geographic groups analyzed. It reflects levels of awareness, engagement, trial involvement and institutional commitment.

Table 13. Stakeholder adoption readiness matrix

Region / Country group	Institutional adopters	Operational adopters	End-users
Greece	Early institutionalization	Trial / partial adoption	Interest / trial
Italy, Spain, Cyprus	Advanced interest/early trial	Engagement/ familiarization	Interest / early engagement
Other Med EU countries	Awareness/interest	Awareness/early interest	Awareness
Non-Med EU countries	Minimal awareness	Minimal awareness	Not yet targeted

6.4. Scaling timeline (When)

The adoption timeline for the Low-GHG Certification System reflects the principle that a measurement-based certification scheme acquires institutional value, regulatory authority and market credibility *only when it is formally integrated into national governance structures*.
A certification framework that is legally embedded, supported by competent authorities, and aligned with national MRV and CAP systems gains normative power: it becomes enforceable, recognizable and interoperable with existing agricultural, climate and digital workflows. For this reason, the replication pathway for the certification scheme must be synchronized with the replication pathway of the LIDAR–LoRa–CMM monitoring system, as certification can only function on top of a validated, legally anchored measurement infrastructure.

The timeline therefore does not describe what will occur automatically, but what *must* occur for each group of countries to adopt the certification system under realistic institutional, technical and policy conditions. It reflects the readiness levels described in the previous sections (WHAT–WHERE–WHO) and ensures that each step conditions the next. The structure follows the "sequenced scaling" logic of FAO (2013; 2021) and the adaptive institutionalization principles of OECD (2019), where countries advance only when enabling environments are secured.

Greece (2025–2027): Establishing authoritative national certification capacity
Greece is the only country where the legislative foundation has already been adopted, granting immediate institutional legitimacy to the monitoring and certification architecture. Articles 30–33 of Law A' 34/2025 establish the Operational Centre, define national competences, and formally recognize LIDAR–LoRa–CMM measurements as part of the country's agricultural GHG governance. This unique position provides the strongest possible starting point for a national certification scheme: the State has already accepted the system as an instrument of public policy.

The system will obtain full national recognition only when Greece produces a complete National Technical Dossier, including uncertainty analysis, calibration documentation, QA/QC alignment with EU MRV, and ISO-consistent methodological transparency. Legislative adoption alone does not constitute national anchoring; the system must be technically validated, institutionally hosted, and administratively integrated before it can be internationally acknowledged.

For the certification scheme to operate with full regulatory force, however, a number of steps must be completed during 2025–2027. These include the finalization of CE certification for the integrated device, the establishment of QA/QC procedures compatible with EU MRV architecture, the definition of accreditation rules for certification bodies, the completion of initial pilot-certification cycles in representative crops, and the development of administrative protocols linking certification outcomes to national registries, CAP eco-schemes and advisory structures. This period also requires national scientific validation, including uncertainty documentation, methodological transparency and peer-reviewed consolidation of the measurement-to-certification logic.

Because Greece already possesses trained stakeholders, active partners, and a national authority mandated by law, this foundational phase is technically and institutionally feasible. It also creates the reference model that other Mediterranean countries may follow. Crucially, the certification system will acquire national "authority" only once these elements are completed, and this authority becomes the basis for international recognition and future alignment with EU-level frameworks such as CRCF.

Greece (2028–2030): Consolidation and preparation for international recognition

Once national implementation is stabilized, Greece must enter a consolidation and alignment phase aimed at enabling future international acceptance of the certification system. During 2028–2030, Greece would:

- align national certification procedures with ISO 14064-1/14067 quantification standards
- harmonise QA/QC and uncertainty protocols with evolving EU MRV requirements (Governance Regulation, LULUCF updates, CRCF guidance)
- prepare a national "Certification Technical Dossier" documenting methodology, uncertainty, calibration and governance structures
- initiate structured consultation with DG AGRI, DG CLIMA and the JRC to verify compatibility with EU datasets and CAP eco-scheme architecture
- establish bilateral recognition pathways with Mediterranean agricultural agencies (Italy, Spain, Cyprus, Portugal) to facilitate regional interoperability
- complete at least one full certification cycle at national scale to demonstrate operational maturity.

This stage is critical: international acceptance can only occur if Greece demonstrates methodological robustness, regulatory reliability, and compatibility with EU-level MRV evolution.

In parallel, Greece should initiate the pathway toward formal international certification of the methodology. This includes preparing submissions to ISO Technical Committees (ISO/TC 207 for greenhouse gas standards), initiating methodological validation with the Joint

Research Centre (JRC), and aligning the national Certification Technical Dossier with the approval procedures foreseen under the EU CRCF. These steps transform the system from a nationally recognized mechanism into a methodology positioned for international certification, allowing future cross-border acceptability and formal acknowledgement within EU-level monitoring and certification architectures.

Greece (2030–2033): Seeking regional interoperability (Mediterranean cluster)-Preparation of an International certification submission

During this period Greece can initiate collaboration for a "Mediterranean Low-GHG Certification Cluster", enabling:

- mutual technical validation among Mediterranean CAP authorities
- development of common calibration datasets for olives, grapes, pistachios, cereals, vegetables
- harmonization of minimum criteria for recognition between certification systems
- joint scientific publications documenting system performance under diverse Mediterranean climates.

These steps support the long-term objective of achieving recognition by EU bodies once the CRCF transitions into agricultural methodologies.

As Greece completes regional interoperability and demonstrates stable performance across multiple Mediterranean agro-ecosystems, the country becomes theoretically ready to submit the full methodology for international certification. By the end of this phase, Greece would possess all components required for a formal application at global or EU level, including a technically validated measurement system, a nationally operational certification scheme, cross-country calibration datasets and harmonized QA/QC procedures. This enables Greece to prepare a comprehensive International Certification Dossier for submission to relevant bodies such as ISO Technical Committees (ISO/TC 207 on greenhouse gas management), the JRC for methodological validation, or future EU-level CRCF agricultural pathways once established. This marks the transition from national and regional recognition to potential international methodological endorsement.

Italy, Spain and Cyprus (2027–2030): Transition from draft frameworks to operational adoption

Italy, Spain and Cyprus form the second group of countries with high potential for early replication. Their participation in the project means that each country already possesses draft legislative frameworks, stakeholder engagement structures, trained regional partners and familiarity with the measurement and certification concepts. Nevertheless, these countries have not yet enacted legally binding national frameworks, nor have they established competent authorities or national hosting structures.

Between 2027–2030, each country would need to:

- convert the existing draft legal texts into formal national legislation
- designate a competent authority and establish a national Operational Centre capable of hosting and administering the data

- integrate the system into CAP Strategic Plans, digital agriculture platforms and national MRV structures
- undertake capacity-building programmes for technicians, advisors and paying agencies
- implement pilot LIDAR–LoRa–CMM installations in representative crop systems to produce national calibration datasets
- develop preliminary national certification parameters, aligned with the ClimaMED methodology but adapted to national crops, emission baselines and governance frameworks.

These steps represent the minimum conditions for national anchoring. Certification cannot be operationalized until measurement validation, administrative integration and legal adoption are complete. Thus, 2027–2030 is the foundational phase.

Italy, Spain and Cyprus (2030–2032): Post-adoption consolidation and scientific alignment
Once national anchoring is achieved, each country can move to the consolidation phase. During 2030–2032, they must:

- develop national certification manuals, accreditation rules and QA/QC procedures aligned with EU MRV guidance and the Greek reference model
- synchronize certification workflows with national CAP eco-schemes
- establish and train nationally accredited certification bodies
- participate in Mediterranean cross-country calibration activities (Italy–Spain–Cyprus–Greece) enabling harmonized methodological baselines
- prepare a National Certification Technical Dossier covering calibration, uncertainty, system governance and methodological transparency
- submit methodological summaries to DG AGRI and DG CLIMA for initial feedback on EU compatibility.

This stage ensures that measurement-to-certification logic becomes scientifically robust and administratively embedded.

Italy, Spain and Cyprus (2032–2035): Regional interoperability and preparatory EU alignment
When national systems operate reliably and calibration datasets are stabilized, the three countries may enter the EU-alignment preparation phase (2032–2035).
This includes:

- joining a Mediterranean Interoperability Platform coordinated with Greece
- co-developing regional minimum standards for measurement-based agricultural certification
- harmonizing methods with relevant ISO standards (ISO 14060 family, ISO 14064-1, ISO 14067)
- producing shared technical reports for the JRC and the EEA, documenting comparability across Mediterranean agro-ecosystems

- preparing joint scientific outputs demonstrating multi-country performance of the system.

These steps position the three countries for future eligibility for EU-level recognition, including potential future integration under CRCF agricultural methodologies once they are developed.

Other Mediterranean EU Countries (2030–2035): Long-term enabling conditions for adoption
The remaining Mediterranean Member States display medium readiness for both the monitoring system and the certification scheme. They possess Mediterranean or sub-Mediterranean agro-ecosystems, strong CAP and climate frameworks, mature digital infrastructures and well-established MRV systems. However, they currently lack project participation, legislative preparation, institutional anchoring and stakeholder networks focused on the ClimaMED system.

For these countries, adoption of the Low-GHG Certification System requires a longer enabling period, extending into 2030–2035. During this time, countries would need to priorities the system politically, adapt their national CAP eco-schemes to include measurement-based criteria, perform preliminary LIDAR–LoRa–CMM validation studies under local climatic and agronomic conditions, and establish national governance structures capable of managing compliance, auditing and certification. Institutional partnerships (either with Greek authorities or with their own research institutions) would be essential for transferring technical knowledge and ensuring scientific credibility.

Because these countries begin without draft legislation, national hosting structures or trained stakeholder groups, certification adoption cannot precede the successful integration of the monitoring system. The replication timeline therefore emphasizes the need for coordinated progress across both systems: monitoring and certification must advance in synchrony, otherwise certification lacks empirical foundation and administrative enforceability.

Other Mediterranean EU Countries (Beyond 2035): Potential pathway toward international recognition
For these countries, international acceptance is only feasible after full national adoption, which itself requires extensive preparatory work. If national adoption succeeds, the long-term (post-2035) steps toward international credibility would include:

- alignment of their national certification rules with the Greek and consortium-country methodologies
- calibration exercises using the Mediterranean shared dataset
- establishing accredited certification bodies capable of operating high-frequency GHG monitoring methodologies
- harmonizing uncertainty analysis and QA/QC frameworks with EU MRV updates
- engaging in a regional recognition agreement with the Mediterranean cluster.

However, this is considered a long-term prospect, as these countries must first create the full governance and monitoring infrastructure before any international positioning becomes realistic.

Table 14 summarizes the phased replication pathway for the Low-GHG Certification System across the four groups of countries.

Table 14. Phased Replication Pathway for the Low-GHG Certification System

Country group	2025–2027	2028–2030	2030–2033	Post-2033
Greece	National anchoring; QA/QC setup; CE completion; pilot certification cycles	ISO alignment; MRV harmonization; Technical Dossier; EU consultations	Regional interoperability (Mediterranean cluster); joint calibration datasets	Submission for international methodological recognition
Italy, Spain, Cyprus	Draft laws → national legislation; authority establishment; pilot deployments	National QA/QC manuals; accredited bodies; initial interoperability with Greece	Mediterranean cluster participation; regional alignment	Preparation for future EU-level recognition
Other Med EU	Political prioritization; feasibility studies	Pilot trials; institutional partnerships	Potential national adoption 2030–2035	Future eligibility for regional/EU recognition (long-term)
Non-Med EU	Agro-ecological adaptation studies	Pilot research deployments only	Long-term adaptation needs	Not targeted for certification rollout

6.5. Operational mechanism for replication (How)

The operational pathway for replicating the Low-GHG Certification System focuses on how each country can transform the methodology into a functioning, institutionally anchored and socially supported mechanism. While the timeline defines *when* each step should occur, the HOW specifies *how* countries can mobilise political authority, administrative structures, financing tools, advisory actors, supply chains and farmer participation to make adoption feasible.

Greece, as the only Member State where the monitoring architecture is already legislatively anchored, can advance technically and administratively faster than any other country. Its first task is to activate the legal provisions of Law A’ 34/2025 by empowering the national Operational Centre, allocating staff, and issuing ministerial decisions that define responsibilities for data hosting, device installation and certification workflows. Greece must mobilize financing mechanisms such as CAP eco-schemes, national climate budgets, Recovery and Resilience Facility (RRF) investments and carbon-scheme revenues to support the initial procurement and deployment of LIDAR units. At the administrative level, the Ministry must establish accreditation pathways for certification bodies and formal QA/QC structures. Mobilizing the farming community requires strong communication campaigns through cooperatives, chambers of agriculture, producer groups and local advisory networks, highlighting the income benefits of certification, its compatibility with CAP payments, and the prestige of being part of a national climate-smart farming programme. Greece must also stimulate a domestic supply chain for LIDAR manufacturing or assembly under license, encouraging partnerships between universities, technology providers and private companies, supported by tax incentives or innovation grants. At the European level, targeted engagement with DG AGRI, DG CLIMA and JRC is necessary to ensure that national progress is visible, credible and aligned with EU MRV evolution. By coordinating these actions, Greece can establish a strong, authoritative certification mechanism capable of attracting private-sector interest (ESG investors, banks, retailers), while preparing the ground for regional and future international recognition.

Italy, Spain and Cyprus, as project countries with draft legislative frameworks and trained stakeholder networks, must first convert their preparatory work into fully binding national adoption. This requires securing political endorsement from relevant ministries, transforming draft laws into enacted legal instruments and designating a competent public authority to host the certification system. Financing can be activated through national CAP Strategic Plans, regional development programs (RDP), climate and environmental funds, and investments from regional governments, particularly in Italy and Spain, where devolved governance makes regional authorities central adoption actors. Mobilizing operational structures will involve integrating the certification logic into advisory networks, agricultural chambers and cooperatives, capitalizing on the familiarity some of these actors gained during ClimaMED. Early deployment of LIDAR devices can be funded through pilot clusters, with technicians trained jointly with Greek experts to accelerate capacity building. To create farmer demand, these countries need communication strategies supported by local cooperatives, demonstration farms, and regional authorities that link certification to market differentiation, potential price premiums, and eco-scheme payments. Establishing partnerships with technology firms and public research centres will help develop local manufacturing or licensed distribution of LIDAR systems, reducing long-term operational costs. Once national systems operate reliably, Italy, Spain and Cyprus can jointly coordinate with Greece on Mediterranean-wide calibration datasets, harmonized minimum criteria, and cross-country scientific alignment, strengthening the perception of the system as a regional standard and facilitating future EU-level acknowledgement.

Other Mediterranean EU countries begin with far lower institutional and stakeholder readiness, but possess strong policy and digital environments suitable for long-term adoption. Their first step must be political prioritization: identifying a competent ministry, initiating exploratory legislation, and designating a national task force to assess the feasibility of the system. These countries should activate R&D and innovation funding instruments (Horizon Europe clusters, national agricultural research agencies, regional eco-scheme budgets) to finance small-scale validation pilots of the LIDAR–LoRa–CMM system in representative Mediterranean crops within their territory. Early collaboration with Greece, Italy, Spain and Cyprus is essential to transfer know-how, benefit from existing calibration datasets and ensure scientific comparability. Farmer mobilization here will depend on demonstration sites, strong advisory engagement and the integration of measurement-based criteria into national sustainability labels or certification programs already in use. Building administrative capacity requires training paying agencies, digital-agriculture units and MRV officers, ensuring that national infrastructure can eventually host the certification workflows. Because these countries do not yet possess draft legislation or national hosting structures, their adoption path is long-term (post-2035), but by implementing early pilots, developing administrative familiarity and participating in Mediterranean technical networks, they can progressively position themselves for future uptake when political conditions allow.

For **non-Mediterranean EU Member States**, the Low-GHG Certification System remains a long-term possibility rather than a near-term replication target. Their agro-ecological conditions, emission profiles and farm structures differ substantially from the Mediterranean pilots, meaning that the certification logic would require new calibration datasets, revised baseline methodologies and adapted uncertainty frameworks before it could be credibly applied. Nevertheless, these countries maintain highly advanced MRV systems, strong digital infrastructures and well-established climate governance frameworks, which makes them suitable for future scientific collaboration, methodological testing and exploratory research pilots. While full adoption is unlikely before 2035, early engagement through joint research projects, participation in Mediterranean calibration networks and exchange of digital infrastructure practices can gradually prepare a pathway for potential long-term alignment once agro-ecological adaptation work is completed.

Table 15 summarizes the operational requirements and enabling mechanisms that each group of countries must secure in order to implement, consolidate and internationally anchor the Low-GHG Certification System.

Table 15. Operational readiness and required actions for adopting the Low-GHG Certification System.

Country group	Existing readiness	Required actions	Mobilization mechanisms	Feasibility
Greece	Full legal anchoring (Law A' 34/2025); Operational Centre established; validated pilots.	Complete CE certification; QA/QC protocols; accreditation rules; full national certification cycle; ISO alignment; JRC/EC consultations.	CAP funds; national climate budget; advisory networks; partnerships with Mediterranean authorities.	Very High
Italy – Spain – Cyprus	Draft frameworks; trained stakeholders; regional familiarity.	Enact laws; create hosting structures; pilots; capacity building; develop national parameters.	Regional CAP budgets; cooperatives; demonstration farms; Greek technical support.	High

Other Med EU	Strong CAP/MRV; Mediterranean agro-ecology; good digital systems.	Political prioritisation; feasibility studies; small pilots; integrate measurement logic; join Mediterranean initiatives.	Horizon Europe; national R&D; advisory systems.	Medium (Long-term)
Non-Med EU	Strong digital governance; advanced CAP; robust MRV.	Research pilots only; calibration datasets; agro-ecological adaptation.	Research consortia; EC projects; innovation hubs.	Low (Research only)

7 Replication of SOC changes determination methodology

7.1 The replicable package (What)

The SOC stock-change methodology represents a low-TRL yet scientifically coherent framework for estimating soil organic carbon dynamics in Mediterranean agricultural systems. It constitutes a hybrid, measurement-supported modelling approach designed to infer annual SOC changes from repeated in-field observations, multispectral data and management information. Although not sufficiently mature for operational deployment or regulatory applications, it provides the structural basis for future development of a fully functional SOC-estimation system capable of supporting carbon-farming schemes, MRV architectures and long-term soil-health monitoring programmes across EU Member States.

Conceptually, the methodology integrates field measurements, spectral proxies and agronomic metadata to capture the underlying biological processes governing SOC turnover. Its design reflects a deliberate attempt to create an empirical bridge between rapid, non-destructive surface-level indicators and the slower, multi-year dynamics of soil carbon accumulation or depletion. The methodological backbone therefore combines

- sensor-based measurements of CO_2 and CH_4 emissions,
- multispectral indices representing vegetation status and soil optical properties,
- environmental drivers such as temperature and soil moisture, and
- detailed information on field management practices. These elements feed a suite of conversion equations that translate short-term flux behavior and optical–biophysical signals into annualized SOC-change estimates (Deliverable Protocols for measuring, calculating, reporting and mapping GHGs emissions and SOC stock changes from agricultural fields).

The empirical relationships derived from the five pilot fields in Greece, despite being internally consistent and scientifically interpretable, remain preliminary and require substantial further validation before being considered reliable across environments or crop types. Nevertheless, the dataset allowed the construction of first-generation equations linking emission behavior, proxy variables and management drivers to observed SOC measurements from soil analysis.

From a transferability perspective, the SOC methodology exhibits two major strengths. First, it is technology-light compared to the LiDAR system. Although the initial design of the methodology envisaged the use of LiDAR-based flux measurements, the project's field experience demonstrated a key scientific limitation: LiDAR measurements at ~2 m height inevitably capture mixed fluxes originating from both soil biological processes and non-biological sources (e.g., machinery emissions, fuel combustion, local micro-sources), making the biological signal difficult to isolate for SOC estimation. In contrast, low-height CO_2/CH_4 sensors positioned close to the soil surface, despite their own limitations, capture a signal dominated by soil respiration and microbial activity. This makes them a more appropriate monitoring tool for developing SOC-response models and validating soil-based carbon equations. Thus, the use of low-cost sensors was not simply a fallback option but a scientifically justified adjustment that improved the biological specificity of the measurements. Importantly, because the methodology is sensor-agnostic at its conceptual level, it can evolve in the future to incorporate improved measurement devices, including next-generation low-height LiDAR systems (20-30 cm heigh). This flexibility enhances scalability and allows the methodology to be replicated in countries without advanced monitoring infrastructure, while leaving open the possibility of transitioning to more sophisticated optical systems once they become available.

Second, the methodology does not depend on long historical datasets or national calibration archives, a major advantage for regions (including Greece) where soil carbon monitoring has been limited or inconsistent. This allows countries to initiate SOC-estimation programmes using only local pilot data and progressively improve accuracy as more measurements accumulate.

However, its low TRL must be emphasized. The current methodology relies on a small empirical base (five fields, five crops, limited measurement windows) and presents the typical uncertainties of early-stage SOC models: sensitivity to temporal variability in respiration pulses, dependency on micro-meteorological corrections, limited representation of subsoil processes, and incomplete validation across soil types, climatic gradients and management intensities. These limitations mean that the ClimaMED SOC methodology should be considered a "future-ready scientific prototype" rather than an actionable tool for policy reporting, carbon-credit generation or farmer payments.

Despite its early-stage TRL, the SOC methodology retains substantial replicability potential because it is technology-light and does not require specialized atmospheric instrumentation such as the full LiDAR system. For the purposes of the pilot phase, SOC-related flux measurements were obtained using ground-level CO_2/CH_4 sensors. While these sensors have recognized accuracy limitations and introduce noise into short-term flux estimates, they offer one essential methodological advantage: they measure as close as possible to the soil surface, where the signal is dominated by biological soil respiration. This avoids the contamination from non-biogenic emissions and atmospheric mixing effects that affect LiDAR measurements conducted at ~2 m height. In this context, the choice of sensors reflects a pragmatic, scientifically justified requirement for isolating soil-driven carbon signals during the initial development of the methodology. The calibration equations can be progressively refined as higher-quality datasets become available. This includes the potential future integration of improved ground-level sensors or even low-height LiDAR devices specifically engineered for soil-flux applications, leveraging the technological expertise developed within LIFE ClimaMED. This modularity ensures that the methodology can evolve toward higher TRLs as research capacity and measurement reliability increase.

For EU Member States, the methodology is attractive not because the current sensors are ideal, but because the conceptual model is scalable, inexpensive to initiate and adaptable. Research institutions, universities and soil agencies can replicate the approach using existing infrastructure while gradually improving scientific robustness. The methodology provides: an empirical modelling structure that can be recalibrated for different climates, crops and sensor types.
Its current maturity is low, but its strategic significance is high: it establishes the first methodological foundation for real-time, empirical SOC estimation tailored to Mediterranean agriculture and expandable elsewhere.

Lessons learnt and challenges
The development of the SOC-change methodology provided valuable scientific insight but also revealed several structural limitations that must be addressed before the method can advance beyond its current early-stage TRL. A central constraint arises from the use of ground-level CO_2/CH_4 sensors. While these instruments lack the precision and stability required for high-frequency flux quantification, they were the only viable option for isolating near-surface biological respiration signals without contamination from non-biogenic sources, an issue unavoidable when using LiDAR measurements collected at 2 m height. Nevertheless, the sensors' susceptibility to micro-environmental noise, moisture pulses, shading, and temperature gradients introduced variability that constrained the robustness of the derived SOC-change relationships.

The limited spatial and temporal coverage of the pilot phase further restricts generalizability. SOC is a slow and cumulative variable shaped by multi-year ecological processes, yet the pilots captured only short measurement windows.

Finally, international methodological validation will require substantially larger datasets, cross-site calibration, and independent verification. Alignment with ISO 14064-series requirements, CRCF methodological expectations, and CAP soil-health indicators cannot be achieved until the method is expanded across multiple crops, pedo-climatic regions and management regimes.

These limitations do not undermine the conceptual value of the SOC approach; rather, they clearly outline the scientific and operational pathway for its maturation. The methodology constitutes a promising, scalable framework, one that can evolve into a robust tool for soil-carbon monitoring as long as sustained research investment, multi-country experimentation and improved measurement strategies are pursued.

7.2 Replication environments (Where)

The SOC-change methodology differs fundamentally from the LIDAR–LoRa–CMM system in one critical respect: its replication potential is inherently pan-European. All EU Member States face declining soil organic matter levels, fragmented datasets, and the need for scalable, cost-efficient SOC-monitoring tools to support CAP soil-health indicators, LULUCF commitments and emerging CRCF methodologies for carbon farming. For this reason, the geographical scope of replication is not restricted to Mediterranean countries but extends across the entire European pedoclimatic spectrum.

Even though the conceptual structure of the methodology is transferable to all Member States, *its operational application requires strong localization,* primarily because:

- SOC dynamics are highly soil specific. The equations developed during the project depend on the physical and biochemical properties of the pilot fields. SOC turnover rates differ substantially across soil texture classes, mineralogy, carbonate content, cation-exchange capacity, bulk density and microbial activity, variables that differ widely between Northern, Central, Atlantic and Mediterranean Europe.
- The calibration functions are site dependent. Annual SOC-change depends on crop type, management history, temperature–moisture regimes and background carbon stocks. These conditions vary significantly at regional scale, meaning that each country must generate its own calibration datasets before the model can deliver reliable national estimates.
- Meteorological controls differ between regions. SOC fluxes are strongly shaped by temperature, moisture pulses, drought frequency and freeze–thaw cycles. The five pilot fields captured only Mediterranean semi-arid conditions. Countries with oceanic (e.g. France, Ireland), Boreal (e.g. Finland, Sweden), or continental climates (e.g. Poland, Hungary) will require new calibration layers reflecting their specific climatic drivers.
- Management practices differ across the EU. Tillage frequency, crop rotations, residue management, organic amendments and irrigation practices vary widely, influencing carbon inputs and losses. Without region-specific data, SOC modelling risks misrepresenting local processes.

Given these factors, the SOC methodology can be applied anywhere but validated nowhere without local experiments. Therefore, its replication is structured not around groups of countries (as in the LIDAR case) but around three environmental conditions that must be met in every country:

1. Pedoclimatic representativeness. Each country must select representative experimental sites covering the dominant soil types and climatic conditions described in national soil maps, EEA pedoclimatic regions and JRC SoilGrids. These sites act as calibration hubs for deriving country-specific SOC-change equations.
2. Data availability and harmonization. Replication requires access to:
    - soil laboratory data (SOC%, bulk density, texture, carbonates),

- field metadata (crop system, management, inputs),
- meteorological data (T, RH, soil moisture),
- ancillary spectral or environmental datasets.

None of these datasets need to be newly created but must be **harmonized** with the structure of the ClimaMED methodology.

3. National research capacity**.** Because the methodology is at low TRL, initial replication depends on universities, soil institutes and agricultural research centres capable of:
   - designing multi-year field trials,
   - conducting sensor-based or chamber-based respiration measurements,
   - performing soil sampling and laboratory analyses,
   - fitting and validating calibration equations.

   This requirement is universal across Member States.

7.3. Target adopters and adoption depths (Who)

Because the SOC methodology is at an early technological readiness level and depends on empirical calibration using locally generated datasets, its adoption pathway differs fundamentally from that of the LIDAR–LoRa–CMM system. Replication cannot begin with ministries, paying agencies or certification bodies; it must begin with scientific actors capable of conducting long-term experiments and generating robust calibration equations. Only after this scientific foundation is established can institutional and operational adopters engage. The adopter sequence therefore unfolds across four groups, each with clearly differentiated roles, capacities and dependencies.

Scientific and research adopters (Primary/early-stage adopters)
This group includes universities, soil laboratories, agricultural research institutes, environmental modelling centres and public research infrastructures specializing in soil carbon dynamics. These actors are the only ones capable of executing the empirical tasks required for replication: establishing multi-site calibration trials, performing repeated soil sampling, analyzing SOC fractions, processing CO_2/CH_4 flux signals, and fitting the country-specific calibration curves needed for methodological transferability.
Adoption depth at this stage is defined by the initiation of field campaigns, development of harmonized sampling protocols, laboratory analyses, and uncertainty estimation. Because the methodology relies heavily on scientific interpretation and on the generation of new empirical data, no institutional or policy-level adoption is possible until this group produces validated, peer-reviewed calibration outputs. Research institutions also act as credibility anchors. In all Member States, national authorities can only consider SOC methodologies for monitoring or reporting once scientific institutions have demonstrated that the calibration equations are locally valid, statistically reliable and methodologically transparent.

Competent public authorities and national agencies (Secondary adopters)

The second adopter group includes ministries of agriculture, environment and climate, CAP managing authorities, MRV coordinators, paying agencies, soil-protection authorities and national statistical offices. These actors cannot adopt the SOC methodology until scientists deliver validated calibration datasets, functional equations and uncertainty estimates. Their adoption is conditional, not exploratory.

Once the scientific foundation exists, authorities can assess how, and to what extent, the methodology should be incorporated into national soil-monitoring programmes, Soil Monitoring Law indicators, national GHG inventories (LULUCF), CAP eco-schemes or sustainable farming criteria. Adoption depth is reflected in their review of methodological dossiers, establishment of QA/QC and data-governance procedures, administrative piloting, and initial integration with tools such as LPIS, national soil registries or environmental reporting systems.

At this stage, authorities do not generate new data; they institutionalize, regulate and host the methodology. Their function is to evaluate feasibility, guarantee compatibility with national reporting structures, and prepare governance frameworks for future operational use.

Advisory systems, cooperatives and private technical actors (Transitional adopters)

This group includes agricultural advisory services, cooperatives, digital farming providers, soil-testing companies and agronomic consultancies. Their engagement becomes meaningful only once calibration datasets and empirical equations are available for practical use.

These actors play a bridging role between science and farm-level implementation. They help translate calibrated SOC equations into advisory tools, nutrient-management recommendations or decision-support services. They may participate in field trials by organizing soil sampling, documenting crop management, or supporting data collection in farmers' fields.

However, they cannot adopt or apply the methodology independently while the TRL remains low; their function is facilitative rather than foundational. Their adoption depth is measured by participation in pilots, integration testing, and early-stage operational interpretation.

Farmers and producer organizations (Late-stage adopters)

Farmers, producer groups and farmer-led cooperatives are the last adopters in the sequence. Because the SOC methodology is not yet validated across different soils, climates and cropping systems, farmers cannot use it for compliance, carbon farming, certification or eco-scheme verification at this stage. Their role during early replication is supportive but essential: granting field access, providing management logs, and participating in calibration experiments. Only once the methodology reaches higher TRLs, through multi-year, multi-region experiments and harmonized calibration curves, will farmers become meaningful end-users who can benefit from SOC-based advice, payments or certification. Their ultimate adoption depends entirely on the progress of the preceding groups.

7.4. Scaling timeline (When)

The adoption timeline for the SOC methodology is determined by its current technological readiness level (TRL 3–4), its dependence on empirical, site-specific calibration, and the absence of harmonized SOC-flux datasets across Europe. Unlike the LIDAR–LoRa–CMM system, which already possesses legislative anchoring and a near-operational monitoring infrastructure, the SOC methodology remains at a developmental, research-driven stage. Replication is technically feasible in all EU Member States, but only if scientific, administrative and operational actors undertake the sequential steps required to move from an experimental calibration framework to a mature, validated monitoring method. Accordingly, the timeline below describes what must occur for the SOC methodology to become scientifically credible, administratively usable and ultimately integrable into national or European soil-governance structures.

2025–2028: Scientific foundations, experimental calibration and technology exploration
The first phase consists of establishing the scientific basis needed for replication. All Member States wishing to adopt the methodology must initiate multi-site calibration experiments led by universities, national soil institutes and research centres. This involves characterizing local soils, performing repeated soil sampling at multiple depths, installing basic CO_2/CH_4 flux-measurement instruments, and collecting multi-season datasets for fitting the empirical SOC-change equations.
Because the original ClimaMED calibration relied on only five fields, and because respiration and SOC processes show strong locality, <u>no Member State can transfer the method without producing its own empirical evidence.</u> This stage must also include uncertainty analysis, protocol harmonization and inter-laboratory comparison to ensure methodological consistency across sites.
During this phase, countries may also explore improved sensing options. Although ClimaMED used low-height CO_2/CH_4 sensors, their limitations underline the need for more robust alternatives. LIFE ClimaMED beneficiaries may therefore investigate the feasibility of developing a new low-height LiDAR prototype (20–30 cm above soil level) to capture surface-based biological fluxes more reliably while avoiding the ambient contamination that affects standard LiDAR units. Such a prototype, although experimental, could substantially strengthen the long-term viability of the SOC methodology by providing a high-resolution, disturbance-free signal pathway aligned specifically with surface respiration processes.

By the end of this period, each country should possess preliminary calibration curves, initial uncertainty estimates, and a foundational dataset enabling scientific evaluation of variability and model performance.

2028–2031: National methodological consolidation and early institutional review

Once initial datasets exist, Member States must undertake a methodological consolidation phase. This includes refining the calibration equations, expanding sampling networks to cover major soil types and cropping systems, and producing a formal technical dossier detailing assumptions, data-preparation methods, uncertainty calculations and alignment with IPCC soil-carbon principles.

During these years, national public authorities become gradually involved. Ministries of agriculture and environment, CAP managing authorities and national MRV coordinators must evaluate the scientific outputs, assess how the methodology aligns with national soil-monitoring programmes, and determine whether early administrative piloting is feasible. Countries must also examine how SOC-change estimates could be integrated into LPIS-linked soil registries, national soil-health databases and potential future eco-scheme or carbon-farming mechanisms.

By the end of this period, countries should have a robust methodological dossier, well-defined uncertainties, and the initial administrative clarity required for pre-operational validation.

2031–2034: Pre-operational piloting, advisory-system integration and operational validation

With methodological consolidation achieved, countries enter a pre-operational piloting stage. Selected regions implement structured sampling campaigns, advisory systems begin testing operational procedures, and soil laboratories assess their capacity to deliver consistent analytical results at larger scales. National agencies must test digital reporting pathways, assess sampling logistics, and evaluate how well the method performs under routine conditions.

Farmers become meaningfully engaged at this stage, providing field access, sharing management data and supporting sampling operations. Member States also determine whether the method remains sensor-based, whether hybrid approaches (spectral + laboratory + management data) are more reliable, or whether progression towards a low-height LiDAR prototype is justified for improved precision.

By the end of this period, each country should possess validated operational workflows and real-world evidence on the method's reliability across different regions and management systems.

2034–2037: Cross-country alignment and readiness for EU-level review

Once the SOC methodology performs reliably at national scale, Member States must engage in cross-country alignment. Because the long-term objective is to create a harmonized, transferable SOC framework, countries must compare calibration datasets, standardize assumptions, harmonies sampling depths and uncertainty protocols, and co-develop shared methodological guidelines. Collaboration with the JRC, DG AGRI and DG CLIMA becomes essential to ensure consistency with the Soil Monitoring Law, national LULUCF reporting requirements and carbon-farming methodological principles.

At this stage, Member States may prepare preliminary submissions to the JRC or ISO Technical Committees (ISO/TC 190 for soil quality; ISO/TC 207 for climate and GHG quantification). They may also assess the long-term merit of integrating a dedicated low-height LiDAR sensor pathway to strengthen comparability and reduce reliance on sensors. Only after such scientific and administrative harmonization can the SOC methodology be considered for EU-level recognition, assessment or standardization.

7.5. Operational mechanism for replication (How)

The process begins with scientific anchoring, and each Member State must design and implement multi-site calibration programmes capable of generating local evidence. Universities, agronomic departments, soil institutes and national research bodies lead this stage. They must select representative soil types and regions, establish repeated sampling campaigns at multiple depths, conduct laboratory analyses of SOC fractions and respiration dynamics, and operate low-cost flux-measurement instruments to capture CO_2 and CH_4 patterns. Whether countries rely on simple sensors or explore improved sensing architectures, including the possibility of a future low-height LiDAR unit designed specifically for near-surface fluxes, the scientific goal remains the same: *to produce robust national datasets that can support statistically defensible calibration*.

Alongside data production, institutions must harmonies sampling procedures, validate laboratory QA/QC protocols and document analytical uncertainty. Without these actions, national adoption is technically impossible, as no country can operationalize SOC-change estimation without its own empirical backbone.

As datasets grow, scientific work must evolve into methodological consolidation. Countries need internal technical groups that bring together soil scientists, statisticians, modelling experts and policy analysts. These groups refine calibration equations, evaluate variability across regions and land uses, and develop coherent methodological dossiers that explain assumptions, data-processing rules and uncertainty frameworks. During this period, the methodology must be checked against existing soil-monitoring programmes, the Soil Monitoring Law's indicator architecture, and national GHG and LULUCF reporting systems. The goal is to confirm that the methodology behaves consistently, that its uncertainties are transparent, and that it can be compared meaningfully with established soil datasets. Inter-laboratory comparisons are essential.

The methodology can only move towards operational testing once administrative structures are prepared. National authorities, particularly ministries of agriculture, environment, soil agencies and CAP managing authorities, must create mechanisms for coordinating sampling, managing laboratory workflows, integrating data with LPIS-linked soil registries and establishing digital reporting pathways. Advisory services must also be prepared to handle SOC-related information, as they will act as the bridge between scientific outputs and farmers' practical decisions. This stage is an administrative construction phase: defining responsibilities, establishing communication channels, preparing data-management infrastructures, training regional officers, and determining how SOC results will be interpreted and used. Pre-operational piloting then tests whether these structures work under real conditions. Pilots reveal whether sampling logistics are feasible, whether laboratories can deliver data at scale, whether result variability is manageable, and whether the advisory system can support farmers in understanding the meaning of SOC-change estimates.

Because the SOC methodology relies on contributions from multiple actors, stakeholder mobilization is a core operational requirement. Researchers need long-term funding to maintain calibration trials; laboratories need resources to upgrade analytical equipment and standardize procedures; advisors need training to interpret SOC metrics; and farmers must understand why participation is valuable. Therefore, effective communication strategies are essential: without early engagement, farmers may view SOC sampling as an administrative burden rather than a co-created measurement process. Countries must therefore articulate the benefits clearly (improved soil fertility, readiness for Soil Monitoring Law indicators, potential integration into carbon-farming mechanisms and more targeted nutrient-management decisions).
Financing determines whether the methodology can progress. Scientific phases depend on research programmes such as Horizon Europe, LIFE, Mission Soil calls and national research councils. Administrative development should rely on CAP technical assistance funds, digital-agriculture budgets and rural-development instruments. As the methodology matures, it may later be supported by carbon-farming rewards or soil-health incentive schemes. Without multi-year financing, all progress would stall at the experimental stage, making continuity a central criterion for successful replication.

Institutional alignment becomes essential once scientific and administrative pillars are in place. Countries will eventually need a formally designated SOC authority, often within a soil, climate or agronomy directorate, responsible for maintaining methodological updates, coordinating laboratories, issuing technical guidance, and interacting with European institutions. Only when such a governance structure exists can the methodology move from a research project to a nationally managed system capable of long-term operation.

Because the ultimate goal is European-level compatibility, cross-country cooperation must form part of the operational mechanism. National calibration datasets, methodological assumptions and uncertainty frameworks must converge over time to avoid fragmentation. Collaboration with the JRC, DG AGRI and DG CLIMA will be essential for testing consistency with soil-health indicators, LULUCF requirements and potential CRCF agricultural methodologies. Shared reference fields, joint scientific papers and periodic benchmarking exercises will help maintain convergence. Without such cooperation, each country risks developing incompatible methodologies, undermining their eventual policy value.

In its final stage, replication moves from research and piloting to full operationalization. Countries that have built strong scientific foundations, prepared administrative infrastructures, trained stakeholders, secured funding and participated in cross-country harmonization will be able to use the SOC methodology confidently in advisory, monitoring or carbon-accounting contexts. However, this will occur only after a long sequence of scientifically grounded steps. The SOC methodology cannot scale through procurement or decree; it scales through evidence, coherence and institutional maturity. For this reason, the HOW pathway is not a rapid deployment plan but a structured roadmap that transforms an early-stage experimental method into a credible, harmonized and potentially EU-usable tool for soil governance.

8. Conclusions

The LIFE ClimaMED project demonstrates that measurement-based, parcel-level monitoring of agricultural GHG and soil-carbon dynamics is both technically feasible and institutionally actionable when supported by robust scientific protocols, digital infrastructures and clear governance pathways. The project's innovations—although heterogeneous in maturity—collectively form a coherent package that can significantly strengthen how Mediterranean and EU Member States monitor, manage and mitigate agricultural GHG emissions.

First, the LIDAR–LoRa–CMM system emerges as the most mature and immediately transferable component. It reached TRL 7–8 under real agricultural conditions, produced stable and high-resolution flux measurements, and successfully operated across diverse crop systems. The legal adoption of the system in Greece provides an exceptional institutional precedent, demonstrating that real-time GHG monitoring can be embedded into national governance structures. The system's replicability is now primarily dependent on non-technical conditions: (i) publication of operational legislation, (ii) securing hosting, staffing and budget arrangements, (iii) LoRa coverage mapping and installation readiness, and (iv) CE certification of the fully assembled unit. With these elements in place, the system is ready for scaling in Mediterranean countries and, with calibration, for adaptation in wider EU contexts.

Second, the agronomic mitigation-guideline package represents a conceptually mature and immediately scalable output. Derived directly from high-frequency measurements, GIS-based management data and farmer engagement, the guidelines provide quantified emission drivers and validated mitigation strategies for olives, grapes, pistachios, cereals and vegetables. Their replication potential is high across Mediterranean agro-ecosystems, owing to strong ecological similarity and direct alignment with CAP eco-schemes and advisory workflows. Challenges identified, such as environmental variability, diverse management regimes and topographic constraints, do not undermine replicability; instead, they highlight the need for site-specific interpretation and advisory-system integration. The guidelines therefore constitute an operational resource ready for integration into national extension systems and climate-aligned CAP measures.

Third, the Low-GHG Certification system is fully designed, internally coherent and directly linked to measured emissions. Its replicability, however, is structurally dependent on the deployment of the LIDAR–LoRa–CMM system at national scale, since certification requires verified, continuous measurement data and validated GHG-reduction baselines. The certification logic is therefore transferable, but its activation in any Member State is contingent on the prior institutionalization of real-time monitoring. Once the monitoring backbone is in place, the certification framework can be rapidly adopted by accreditation bodies, advisory services and farmer groups.

Fourth, the SOC stock-change methodology remains at an early TRL (3–4), consistent with the initial proposal. The project developed the conceptual structure, modelling steps, empirical equations and implementation protocols. Its replicability must follow a research-first trajectory: multi-year, multi-site experiments led by scientific institutions; generation of local calibration curves; and harmonization with national soil-monitoring frameworks. Despite its immaturity, the methodology provides a scientifically coherent starting point for countries aiming to build rapid SOC-change indicators in support of the Soil Monitoring Law and emerging carbon-farming methodologies.

Overall, the LIFE ClimaMED innovations constitute a complete, evidence-based and replicable package that can substantially modernize agricultural GHG monitoring in Europe. The deliverable demonstrates that replication is not a uniform diffusion exercise but a structured, phased transformation requiring coordinated legal, scientific, technical and advisory actions. When these are activated in sequence, Member States can adopt robust, high-frequency MRV systems, implement scientifically grounded mitigation practices, and prepare for future alignment with CRCF and the evolving EU soil-governance architecture.

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