ClimaMED

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Summary	This deliverable presents the Transferability Plan and Roadmap for scaling the two LIFE ClimaMED innovations—the LIDAR–LoRa–CMM system and the SOC stock-change methodology—across productive sectors and European regions. It defines the technical, agronomic and institutional conditions required for reliable deployment, together with phased steps, regional pathways, actors, risks and resource needs. The document provides a practical blueprint for moving from pilot-level demonstrations to broad operational adoption between 2025 and 2035.

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 the Roadmap.**

Abbreviations

AKIS – Agricultural Knowledge and Innovation System
CAP – Common Agricultural Policy
CAT – Catalytic Converter Testing
CCM – Climate Change Mitigation
CMM – Climate Monitoring Mechanism (project platform)
DIAL – Differential Absorption LIDAR
EC – European Commission
EU – European Union
FAO – Food and Agriculture Organization of the United Nations
GHG – Greenhouse Gas
GIS – Geographic Information System
GPP – Gross Primary Production
IPCC – Intergovernmental Panel on Climate Change
JRC – Joint Research Centre
KPI – Key Performance Indicator
LoRa – Long Range (wireless communication protocol)
LULUCF – Land Use, Land Use Change and Forestry
MRV – Monitoring, Reporting and Verification
NDVI – Normalized Difference Vegetation Index
NBS – Nature-Based Solutions
NOAA – National Oceanic and Atmospheric Administration
QA – Quality Assurance
QC – Quality Control
RE – Ecosystem Respiration (used in SOC modelling)
SNR – Signal-to-Noise Ratio
SOC – Soil Organic Carbon
SOP – Standard Operating Procedure
TRL – Technology Readiness Level
UA – Urban Areas
WRF – Weather Research and Forecasting Model

1. Introduction

The transition toward measurement-based agricultural climate governance is accelerating across Europe, driven by the combined pressure of the CAP Strategic Plans, the Soil Monitoring Law, the Governance Regulation, and the new Carbon Removal Certification Framework (CRCF). These frameworks increasingly emphasize empirical, high-frequency and spatially explicit GHG and Soil Organic Carbon (SOC) information, moving beyond conventional model-based estimates and toward operational Monitoring-Reporting-Verification (MRV) systems capable of supporting eco-schemes, carbon-farming mechanisms and national inventory refinement. Mediterranean countries face acute challenges due to their strong climatic seasonality, fragmented farm structures and high management frequency, all of which amplify short-term GHG flux variability and the need for real measurements that can capture rapid system responses.

The LIFE ClimaMED project responds directly to these challenges by developing an interoperable suite of innovations aimed at enabling parcel-scale, measurement-informed, policy-aligned monitoring of agricultural GHG emissions and SOC stock changes. The LIDAR–LoRa–CMM[2] system constitutes a near-operational Tier-3-ready monitoring infrastructure, legally adopted by the Greek State, and represents one of the first integrated optical-telemetry–GIS MRV platforms for land-based GHG emissions in Europe. In parallel, the SOC stock-change methodology establishes a scientifically coherent, modular, hybrid empirical framework that provides a future-ready pathway toward real-time SOC estimation in Mediterranean agroecosystems.

Complementary innovations, such as the crop-specific mitigation guidelines and the Low-GHG Certification System, complete the ClimaMED methodological architecture by translating measurement results into actionable mitigation recommendations, farmer-oriented advisory material and certification rules aligned with national and EU policy frameworks.

These innovations differ substantially in technological maturity, calibration requirements, institutional anchoring, and replication prerequisites, and therefore follow different transferability trajectories.

Part A of this deliverable evaluated these differences in detail by analyzing (i) sectoral suitability, (ii) environmental and operational constraints, (iii) cross-country transferability across Mediterranean and non-Mediterranean regions, and (iv) the calibration, adaptation and quality-assurance conditions necessary for reliable deployment.

Part B builds on this analytical foundation by translating it into a coherent, phased Roadmap for transferability. It identifies the sequential steps, enabling conditions, institutional responsibilities, timelines, risks and resource requirements necessary to scale the ClimaMED innovations from pilot-level demonstration to broad EU-wide deployment between 2025

[2] CMM: Central Monitoring and Management platform of the LIFE ClimaMED project

and 2035, consistent with the horizons defined in the Replicability Plan and the operational constraints observed during the project. Through this Roadmap, the deliverable provides a practical, evidence-based blueprint for Member States, regional authorities, paying agencies, advisory bodies and private-sector actors wishing to adopt measurement-based GHG and SOC monitoring tools within agricultural, restoration and wider land-management sectors.

Part A – Transferability Plan

2.Overview of the LIFE ClimaMED transferable innovations

2.1 Lidar-LoRa-CMM monitoring system

The technological core of LIFE ClimaMED constitutes the most mature and potential transferable 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 potentially transferred and deployed in other European productive sectors.

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 and transfer.

Boundary definition of the transferable technological package

The transferable unit consists of:

- a hardware unit (LiDAR device, mounting, power supply, LoRa gateway)
- a software unit (ingestion, processing, GIS modules, dashboards, certification engine)

- 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.

Photo 1. The LIDAR system installed at field.

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).

2.2 Soil Organic Matter estimation methodology

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.

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 transferability potential because it is technology-light and does not require specialized atmospheric instrumentation. 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.

3.Transferability across sectors: LIDAR-LoRa-CMM technology

The LIDAR–LoRa–CMM system constitutes a highly mature, integrated technological chain capable of producing real-time, high-frequency measurements of CO_2, CH_4 and N_2O fluxes at field scale. Its design, which combines a field-deployed DIAL instrument, long-range telemetry and the cloud-GIS CMM platform, provides an unprecedented measurement-based Monitoring-Reporting-Verification (MRV) architecture that extends far beyond traditional agricultural applications.
For this reason, assessing its transferability across productive European sectors requires a careful analysis of the environmental geometry, emission characteristics, atmospheric behavior, operational routines and institutional prerequisites of each sector (Wang et al., 2022).

The following subsections present a detailed sector-specific analysis, explaining why the technology is suitable, what value it can provide, what the current limitations are, and to what extent each sector constitutes an appropriate environment for transfer.

3.1 Livestock systems

Livestock systems represent one of the most naturally compatible domains for the transfer of the LIDAR–LoRa–CMM technology. During the LIFE ClimaMED project, the system was successfully deployed in an open-air cattle farm, providing valuable evidence on its capacity to detect and quantify both CH_4 and CO_2 emissions from enteric fermentation and manure handling, animal concentration and movement patterns, respectively.

Livestock farms typically display open, obstacle-free geometries (yards, feeding alleys, manure strips, movement corridors) allowing the laser beam to propagate without interference while enabling robust dispersion modelling. These conditions are substantially more favorable than in many horticultural systems, where tall vegetation or dense canopy can partially obstruct the beam.
In operational terms, livestock units generate highly dynamic and easily detectable emission plumes. Peaks in CH_4 emissions can be correlated with feeding cycles, rumination periods and temperature-driven physiological responses, while CO_2 fluxes to both animal density and manure management operations (scraping, removal, agitation). These well-defined patterns could provide strong signals for the LIDAR system to capture.

The technology therefore offers livestock systems the capacity to obtain real-time, empirical and sector-specific emission curves, which can directly support national GHG inventories, refinement of Tier-2 emission factors and transition to Tier-3-ready accounting.

A critical consideration in evaluating the applicability of the LIDAR–DIAL system in livestock environments is whether typical emission concentrations exceed the instrument's minimum detection thresholds. According to the ClimaMED operational protocol, reliable retrieval requires atmospheric concentrations above **5 ppmv for CO_2**, **50 ppbv for CH_4**, and **3 ppmv for N_2O**. Empirical evidence from livestock studies consistently shows that actual emission levels from enteric fermentation, manure decomposition and slurry management exceed these thresholds by one to three orders of magnitude, ensuring robust detectability under all meaningful operational conditions. In specific:

- For CO_2, the background atmospheric level (~420 ppmv) already surpasses the instrument limit. In dairy and beef operations, animal respiration typically elevates CO_2 concentrations to 600–1,200 ppmv in open barns and feeding alleys, with peaks reaching 1,500–2,000 ppmv during high-density animal congregation or manure removal (Ngwabie et al., 2011; Kinsman et al., 1998). These concentrations exceed the detection threshold by factors of 100–400.
- For CH_4, the minimum detectable concentration is approximately 0.050 ppmv. Enteric fermentation produces plume concentrations of 3–10 ppmv in open-air beef and dairy operations (Hristov et al., 2015; Todd et al., 2014), 10–30+ ppmv in semi-enclosed barns (Prairie et al., 2008), and 40–100 ppmv near slurry stores or during manure agitation (Sommer et al., 2004). These values exceed the threshold by factors of 60 to >2,000, confirming that all significant CH_4 plumes fall well within the system's reliable measurement range.
- For N_2O, while background concentrations (~0.33 ppmv) fall below the detection limit, major livestock-related emission events consistently exceed it. During slurry agitation, barn-floor denitrification episodes, or manure spreading, N_2O concentrations typically reach 3–10 ppmv, with peaks of 10–30 ppmv reported in dairy systems following wetting or high-temperature periods (Luo et al., 2018; Amon et al., 2001). These values surpass the ClimaMED detection threshold of 3 ppmv, ensuring that all meaningful biological and management-driven N_2O peaks are detectable, even though diffuse background N_2O cannot be resolved.

Thus, the instrument reliably captures the full range of significant CH_4, CO_2 and N_2O flux events in livestock farming. This makes open-air livestock systems one of the most technically favorable environments for LIDAR-based GHG monitoring within Europe.

Enclosed or partially enclosed livestock barns, especially those relying on mechanical ventilation, internal partitions, roof structures or irregular airflow channels, present inherent limitations for optical plume reconstruction. In these environments, the natural formation of CH_4, CO_2 and N_2O plumes is fragmented: air is mechanically redirected through fans or chutes, creating turbulent recirculation zones, non-linear pressure gradients and highly non-

Gaussian dispersion patterns. Under such conditions, the assumptions required for the Gaussian line-source inversion model are not fulfilled, as the plumes do not propagate in a stable, downwind trajectory. Only barns with large openings, clear cross-ventilation and unobstructed outflow paths allow partially interpretable plume structures.

A methodological constraint concerns the scale of retrieval. The LIDAR measures path-integrated atmospheric concentrations and therefore quantifies aggregated area-level fluxes, rather than emissions attributable to individual animals or pens. This limitation is intrinsic to all remote optical sensing systems operating across open paths and does not stem from the instrument's performance, but from the physics of integrated-beam measurement.

Outdoor or semi-open Mediterranean livestock units provide clear optical geometry, consistent wind fields and strong emission signals, typically exceeding detection thresholds by one to three orders of magnitude, allowing highly reliable plume detection and flux estimation. Consequently, transferability potential is very high across Southern European livestock systems and moderate, yet feasible, in northern enclosed housing systems, provided that installations target open yards, manure-handling areas or outdoor emission sources where plume dynamics remain physically interpretable.

Technical transferability for livestock systems requires installation of the LIDAR device at 3–4 m height with a clear line-of-sight across animal zones, stable telemetry connectivity, and continuous wind monitoring. Calibration routines are similar to crop systems, although dust and particulate matter require more frequent maintenance.

3.2 Agroforestry systems

Agroforestry environments, such as olive groves, pistachio orchards and vineyards combined with grazing or intercrops, constitute a second highly compatible category for the LIDAR–LoRa–CMM system. This conclusion is grounded in the extensive ClimaMED field evidence: the system was successfully deployed in five Mediterranean perennial crop systems, demonstrating its ability to detect GHG emissions associated with agricultural practices and biological processes.

Agroforestry systems typically combine medium-height perennial vegetation (1.5–3.5 m) with open inter-row spaces. These inter-row corridors are advantageous for LIDAR deployment, as they allow the laser path to traverse air masses that represent the integrated emissions of the system. When alignment follows row orientation, canopy obstruction is minimal and plume dispersion remains interpretable.

In these settings, the LIDAR system can monitor both temporal emission patterns (e.g., increased GHG during tillage or pruning waste decomposition) and management-driven pulses (fertilization, manure addition). Since agroforestry systems are key contributors to land-based GHG emissions in southern Europe, real measurements can substantially improve national inventories, CAP eco-scheme verification and advisory recommendations.

Despite the generally favorable geometry of Mediterranean orchard-type agroforestry systems, several methodological constraints must be acknowledged when deploying the LIDAR–DIAL system in multi-layered perennial environments. First, dense or tall canopies, particularly those exceeding an effective height of approximately 3 m, attenuate or partially occlude the optical beam, reducing the contrast between on-line and off-line wavelengths and thereby limiting the precision of the retrieved concentration gradients (Manolis et al., 2019). Multilayered structures, such as alley systems combining trees with shrubs or understory crops, introduce additional complexity, as overlapping vegetation layers generate turbulent, non-linear plume pathways that deviate from the assumptions of a horizontally homogeneous Gaussian line-source model (Baldocchi, 2014). For this reason, agroforestry transferability is strongest in Mediterranean orchard systems with well-spaced rows and open inter-row corridors, whereas it is substantially more challenging in Northern European silvopastoral systems or intensive fruit-tree plantations with closed canopies.

A second limitation relates to source attribution. Because the LIDAR retrieves path-integrated concentrations across a full optical transect, the system quantifies aggregate, whole-area emissions rather than crop-specific fluxes. It is therefore not possible to disaggregate emissions to individual agroforestry components (e.g. olive vs. pasture, trees vs. intercrops), nor to derive product-based indicators such as kg gas per kg or lt product. The system can only provide estimates expressed per unit area (e.g. kg gas per hectare per year), which is appropriate for land-based GHG accounting but less compatible with yield-normalized metrics.

Furthermore, the ClimaMED demonstration activities showed that N_2O emissions in Mediterranean agroforestry systems are extremely low, typically manifesting only as diffuse background concentrations and rarely exceeding the system's operational detection threshold of 3 ppmv. While N_2O is indeed present and biologically produced, through nitrification and denitrification processes, the low intensity and high spatial heterogeneity of these fluxes mean that the DIAL retrieval does not consistently detect them. This is precisely why the Certification System developed under the project specifies that N_2O can only be accepted as a measurable component *if* the retrieved concentration surpasses the verified threshold; otherwise, it must be treated as "below detection" and excluded from area-level calculations.

Therefore, although highly promising, in order to extend the transferability of the technology to more complex or denser agroforestry systems, targeted experimentation and methodological refinement will be required. A key priority is to explore the performance of the LIDAR at higher installation heights, for example 5–6 m, allowing the optical path to clear upper canopy layers and sample less obstructed airstreams. Such modifications will necessitate the development of new operational protocols, including revised procedures for alignment, calibration, and quality control. Likewise, new agroforestry-specific σy and σz dispersion parameter sets will need to be derived, as the annual least-squares fitting used in open cropland may not adequately describe plume behavior in multi-layered vegetation

structures. Dedicated trials should also be conducted to characterize stability-class transitions within heterogeneous canopies, adapt baseline filtering for shade-induced temperature inversions, and test alternative baseline correction methods that account for canopy-driven microclimatic stratification.
Only after these refinements, higher mounting geometries, new dispersion coefficients, dedicated canopy, aware QC routines and agroforestry-specific calibration datasets—will the system reach full transferability potential in complex agroforestry landscapes across Europe.

3.3 Protected agriculture (greenhouses and tunnels)

The applicability of the LIDAR–LoRa–CMM system in protected agriculture is more constrained due to the physical characteristics of greenhouses and tunnels. These structures fundamentally alter natural airflow, create artificial microclimates, and impose physical barriers that disrupt the laser beam. For these reasons, the LIDAR cannot be installed or operated inside closed greenhouses or plastic tunnels, as the beam is reflected or absorbed by plastic films, metallic arches and internal equipment.
However, protected agriculture environments remain partially compatible through external perimeter monitoring. Emissions associated with compost incorporation, soil preparation, diesel-powered machinery, or waste handling near greenhouse perimeters can be reliably measured. Furthermore, the system can capture CH_4 and CO_2 fluxes from adjacent open fields that form part of integrated greenhouse production systems.
While this offers value for whole-farm emission accounting, the technology cannot quantify internal greenhouse emissions, ventilation-related fluxes or CO_2 enrichment events, all of which are relevant for greenhouse climate management. Transferability to this sector is therefore partial, with meaningful but limited benefits.

From a technical standpoint, transferability in protected agriculture requires placement of the LIDAR device outside the greenhouse envelope, with the beam aligned parallel to the greenhouse walls to avoid reflective artefacts. Frequent quality-control checks are required due to increased optical noise.

3.4 Composting units and waste-valorization facilities

Composting facilities represent one of the most favorable environments for transferring the LIDAR–LoRa–CMM technology. Open composting yards produce strong, easily detectable plumes of CO_2 and CH_4 during biological decomposition, particularly during turning, aeration and maturation stages. These emissions will display well-structured temporal patterns, morning peaks, turning-induced bursts, temperature-linked daily cycles, which the LIDAR can capture.
Because compost piles are typically organized in windrows with open spaces between them, the optical beam can traverse the emission field without major obstruction. This geometry is ideal for dispersion modelling and provides a unique opportunity to assess

emission dynamics from circular-economy operations, municipal organic-waste treatment plants and farm-scale composting units.

Limitations arise mainly when windrows exceed approximately 3 m in height or when machinery generates excessive dust that interferes with optical propagation. Subsurface anaerobic pockets within very deep piles may also release CH_4 too diffusely to be captured effectively at beam height. Despite these constraints, composting facilities remain one of the strongest candidates for transfer due to their open structure, strong emission signals and high policy relevance.

To enable reliable transfer of the LIDAR–LoRa–CMM system to composting and waste-valorization facilities across Europe, targeted experimentation and methodological refinement will be essential. Although composting sites offer favorable geometries, open windrows, unobstructed corridors and strong CH_4 and CO_2 emissions, each facility presents unique operational conditions, thermal gradients, surface heterogeneity and disturbance patterns that must be empirically characterized before full-scale deployment.

A critical requirement is the development of compost-specific dispersion modelling parameters. The Gaussian σy–σz coefficients calibrated for croplands during LIFE ClimaMED project are not fully adequate in composting facilities, where heat release from piles generates strong buoyant updrafts, vertical turbulence and thermally driven microplumes. These processes alter the effective plume height and shape, meaning that the standard agricultural stability-class calibrations (A–F) should be supplemented with new coefficients derived directly from compost-yard microenvironments. This will require dedicated pilot trials at representative composting units (municipal, farm-scale, mechanical-biological treatment plants), during which full daily plume profiles are recorded under different turning, aeration and humidity conditions.

A second experimental priority concerns beam–pile interaction. As windrow heights vary seasonally (e.g., during pile build-up or after turning), the beam height may partially intersect upper pile layers, especially in windrows exceeding 3 m. To address this, the system must be tested under different installation heights, including elevated mounting at 4–6 m, to ensure that the beam consistently passes above peak pile elevations. These trials will inform the development of new installation protocols specifying minimum beam heights, optimal baseline lengths and alignment strategies to prevent optical clipping and reduce temperature-induced beam distortion.

Furthermore, composting systems often produce episodic high-emission events (turning bursts, anaerobic pocket releases, rewetting shocks after rainfall) which require the LIDAR's quality-control algorithms to be adapted (Hellebrand and Kalk, 2015; Spokas, 2013). New event-detection rules and anomaly-handling subroutines must be developed, allowing the system to distinguish between genuine flux surges and operational artefacts caused by machinery, dust plumes or sudden thermal discontinuities. For this purpose, cross-validation measurements should be carried out using portable FTIR systems or static chamber reference measurements, enabling the refinement of QC thresholds and the validation of new compost-specific filtering criteria.

Dust is another significant factor affecting optical propagation. Many composting facilities generate substantial particulate matter during turning and loading. To ensure robust operation, enhanced lens protection, periodic cleaning protocols, and potentially laser-housing modifications (e.g., dust-resistant casings, improved air-intake filters) must be evaluated experimentally. These modifications will inform updated maintenance guidelines and the definition of site-specific operational limits (e.g., minimum wind speeds to dissipate dust, maximum distances from turning equipment).

Finally, transferability requires the creation of new operational manuals and training modules specific to composting environments. These should include: (a) safety guidelines for installation near heavy machinery, (b) procedures for synchronizing LIDAR measurements with turning schedules, (c) protocols for logging moisture, temperature and aeration frequency, all of which affect plume dynamics. The successful adoption of the system will therefore depend not only on hardware deployment but on an integrated process of experimentation, calibration, protocol revision and capacity building among facility operators and regional environmental authorities.

Through these targeted refinements (new dispersion coefficients, higher mounting configurations, compost-specific QC modules, dust-resilient protective systems, and expanded technical protocols) the LIDAR–LoRa–CMM system can be fully adapted and validated for use in the waste-valorization and composting sector.

3.5 Land management sectors (degraded lands, restoration sites, ex-quarries, semi-closed landfills)

Land management sectors include a wide range of environments (mine rehabilitation zones, ex-quarry restoration areas, semi-covered landfill sections, degraded soils undergoing ecological restoration and brownfield conversion projects). All these landscapes involve biophysical processes that generate GHG emissions which can be spatially heterogeneous but detectable when the surface behaves as a diffuse source.

The LIDAR system is particularly valuable in restoration and reclamation contexts because the objective is often to identify emission hotspots, track seasonal flux changes, or verify the climate benefits of nature-based restoration activities. In semi-open landfill settings, the system can detect episodic CH_4 leakage, providing actionable MRV information to authorities and operators.

In land-management and restoration sites, the key considerations for transferability relate primarily to calibration and protocol adaptation. Because these environments evolve over time, through soil replacement, vegetation establishment, capping works or landfill-gas operations, the LIDAR system requires site-specific calibration periods, regular background checks, and periodic updates of dispersion parameters (σy, σz) to reflect changing microclimatic and surface conditions.

A major practical limitation in these environments is dust generation, especially during earth-moving, cover-placement, grading, or waste-handling activities. High particulate loads can attenuate or scatter the optical beam, reduce signal-to-noise ratio and create short-term data gaps. For this reason, deployment in these sectors requires enhanced optical protection, clear scheduling of measurements outside heavy-machinery operations, and periodic lens-cleaning or automated dust-shielding systems.

Reliable operation also depends on clear optical-path planning to avoid infrastructure obstacles (e.g. gas-collection pipes, fences, temporary covers) and continuous wind monitoring to support accurate plume modelling. To ensure consistency along the restoration trajectory, new operational protocols should be developed for logging restoration interventions, coordinating measurements with landfill-gas management activities, and validating LIDAR outputs with occasional reference measurements during the initial deployment phase.
With these targeted adaptations (site-specific baselining, periodic recalibration, dust-management measures and updated operational protocols) the LIDAR–LoRa–CMM system can be robustly applied to land-management, rehabilitation and waste-recovery landscapes.

To support these adaptations, a dedicated experimental programme will be required before large-scale deployment in land-management sectors. Pilot campaigns should be implemented in a small number of representative sites (e.g. one ex-quarry under restoration, one semi-closed landfill cell, one degraded soil rehabilitation project), where the LIDAR–LoRa–CMM system is operated continuously over at least one full seasonal cycle. Additional short-term experiments should focus on (i) controlled dust-generation events, to test the effectiveness of different optical protections and cleaning schedules, (ii) coordinated measurements during landfill-gas management operations or cover-placement works, to characterize the signature of operational emission peaks, and (iii) repeated baselining campaigns as vegetation cover and soil structure change over time.
The results of these experiments will feed directly into the revision of operational protocols, the refinement of dispersion and QC parameters for land-management sites, and the formalization of a transferable "LIDAR deployment package" tailored to rehabilitation and waste-recovery landscapes

3.6 Other sectors (campuses, industrial low-height zones, harbors)

The LIDAR–LoRa–CMM system also exhibits potential for deployment in several non-agricultural productive environments, particularly those characterized by open spaces and low vegetation (< 2m heigh).
University and research campuses often include extensive open areas, sports fields, botanical gardens and peripheral green spaces, providing suitable geometry for real-time GHG monitoring. Here, the technology can support climate-neutral campus initiatives, quantify emissions from maintenance activities, and create educational datasets.

Low-height industrial zones (logistics yards, warehouses, distribution centres and light-manufacturing complexes) are similarly compatible. These sites generate transport-related

CO_2 emissions and occasional CH_4 releases from waste-water systems, which the LIDAR can monitor at parcel scale. The relative absence of tall infrastructure allows the optical beam to operate effectively.

Harbors present a more complex environment: while open dockside areas are favorable for optical propagation, high humidity, sea spray, cranes, container stacks and vessel movement introduce optical and atmospheric noise. Nevertheless, the system can still quantify CO_2 plumes from auxiliary engines during docking or loading operations, offering a novel contribution to maritime-sector MRV.

Technical transferability in campuses, industrial zones and harbor environments requires a set of sector-specific adaptations to ensure robust system performance.
In maritime areas in particular, high humidity, salt spray and corrosive marine aerosols pose a major operational challenge. This was clearly demonstrated during the installation of the LIDAR system in the Italian harbor pilot, where the instrument experienced progressive degradation and ultimately malfunctioned within 1–2 months due to persistent humidity exposure and salt-induced corrosion of internal components. For this reason, deployment in coastal or port zones demands marine-grade, corrosion-resistant housings, reinforced sealing of optical compartments, desiccant-based humidity control, and periodic preventive maintenance to protect the optical path and electronics.
Moreover, industrial yards and port infrastructures often contain large metallic surfaces (cranes, warehouses, trucks, shipping containers) that can generate reflections, beam scattering or intermittent optical noise. To mitigate these effects, the LIDAR should be mounted at elevated positions and aligned to avoid reflective geometries, with additional shielding to reduce stray-light interference. In high-traffic environments, such as logistics centres or dockside loading zones, integration with local activity data (ship arrivals, cargo-handling cycles, vehicle flow schedules) is essential for interpreting emission peaks and separating operational events from background variability.
Finally, successful transferability requires the development of sector-specific operational protocols, including guidelines for humidity-risk assessment before installation, safe mounting procedures near industrial or maritime equipment, and synchronization of measurements with scheduled operations (e.g., engine idling, loading/unloading cycles, waste-water aeration). With these adaptations (corrosion-resistant protection, elevated mounting, optical-noise mitigation and activity-linked calibration) the LIDAR–LoRa–CMM system can be reliably deployed across campuses, industrial low-height zones and selected harbor environments.

Table 1 synthesizes the sector-specific transferability assessment presented in this chapter., i.e. the main advantages, limitations, operational constraints and overall suitability of each productive environment based on the ClimaMED demonstration results, the technical specifications of the DIAL instrument and the cross-sector analysis.

Table 1. Summary Evaluation Table - Transferability of the LIDAR–LoRa–CMM system.

Sector	Advantages	Limitations	Constraints / Special Conditions	Overall Suitability
Livestock systems	• Strong CO_2 -CH_4 -N_2O peaks • open geometry • clear plume behavior • excellent alignment with detection limits	• Limited applicability in enclosed barns • cannot disaggregate emissions per animal	• Requires outdoor zones • stable wind • path-aligned installation • higher maintenance in dusty yards	Very high
Agroforestry systems	• Compatible with orchards and vineyards • row geometry suits optical paths • strong management-driven emission pulses	• Dense/multilayered canopies reduce accuracy • cannot assign emissions to different crops	• Needs higher mounting in tall crops • new σy–σz calibrations • canopy-aware QC	High (very high for open orchards)
Protected agriculture	• Effective for perimeter and open-field components • supports whole-farm MRV	• Cannot operate inside greenhouses • reflections from films and metal	Requires external mounting and strict QC	Moderate
Composting and waste-valorization units	• Very strong emission signals • ideal for plume modelling • high policy relevance	• Dust interference • tall windrows may clip beam • subsurface pockets diffuse at height	• Needs dust-resistant protection, • elevation tests, • compost-specific dispersion coefficients	Excellent
Land-management sectors	• Valuable for hotspot detection • supports restoration MRV • suitable for semi-open landfill cells	• Dust loads from machinery • evolving surfaces require repeated calibration	• Needs site-specific baselining • updated σy–σz • coordination with restoration operations	High
Campuses, industrial low-height zones	• Open geometry • low vegetation • supports ESG-sustainability MRV	• Reflective surfaces (warehouses, metal) • vehicle-induced turbulence	• Elevated mounting • Shielding • integration with activity data	High
Harbors	• Open dockside areas • can capture CO_2 from auxiliary engines	• High humidity, salt corrosion, moving obstacles	• Marine-grade housing • humidity control • careful path selection	Moderate

3.7 Cross-country transferability of the LIDAR–LoRa–CMM system

The cross-country transferability of the LIDAR–LoRa–CMM technology depends on the interaction of four parameters: (i) environmental geometry; (ii) atmospheric behavior and wind regimes; (iii) operational and management routines; and (iv) institutional and MRV readiness. Although originally developed and validated in Greece, the system shows high potential for replication across Mediterranean and non-Mediterranean European regions, provided that appropriate calibration and deployment adaptations are made.

- Greece provides the reference context for the system, as all calibration datasets, σ_y–σ_z dispersion parameters, background-correction routines and QC protocols were derived under Greek Mediterranean climatic conditions. The system performs optimally in open-air livestock, orchard and composting environments characteristic of Greece. Transferability to other Greek regions is immediate, requiring only routine baselining.
- Italy, Spain and Cyprus. Environmental and operational conditions in Italy, Spain and Cyprus closely mirror those of the Greek pilot sites. These countries share similar wind regimes, vegetation structures, farm geometries and manure-management practices, enabling near-direct transfer of installation geometry and calibration parameters. Institutional readiness is also high, due to advanced CAP eco-scheme implementation, strong advisory systems and active participation in MRV modernization initiatives.
- Other Mediterranean countries (Portugal, Malta, Southern France) share the same key environmental determinants: open agricultural geometries, low vegetation density, moderate wind speeds and warm-season microbial activity. Transferability is therefore very high.
- Non-Mediterranean EU countries (Central & Northern Europe). Transferability is feasible but requires more significant adaptation due to:
  - higher humidity, fog and persistent cloudiness reducing optical Signal-to-Noise-Ratio (SNR)
  - enclosed livestock housing, which does not support Gaussian plume propagation
  - shorter outdoor measurement windows during winter
  - stricter MRV certification requirements from national environmental agencies.

  In these countries, deployment must target open yards, manure-handling zones, outdoor composting platforms, restored land parcels or municipal green infrastructure. Regional σ_y–σ_z recalibration is essential, especially under humid or low-wind conditions.

Therefore, transferability is highest in Mediterranean regions (Greece, Cyprus, Italy, Spain, Malta, Portugal, southern France), moderate in temperate Central Europe, and conditional in humid Northern Europe where enclosure, fog and ventilation systems limit optical-path stability.

4. Transferability across sectors: SOC methodology

The Soil Organic Carbon (SOC) stock-change methodology developed under LIFE ClimaMED represents a scientifically coherent, low-TRL but strategically significant framework aimed at estimating SOC dynamics in Mediterranean agricultural systems using a hybrid measurement–model approach. Although the methodology remains at TRL 3–4 and requires further empirical calibration, its modularity, data-light requirements and technological simplicity make it a promising candidate for transfer to a wide range of productive sectors across Europe.

Unlike the LIDAR–LoRa–CMM system, which relies on advanced optical instrumentation and specific geometric conditions, the SOC methodology leverages in-field gas sensors, multispectral proxies, microclimatic variables, and management metadata to infer annual SOC changes. This gives it a fundamentally different transferability profile: the methodology is not constrained by canopy height or beam obstruction but instead by soil characteristics, vegetation structure, microclimatic stability and the availability of management and spectral data.

The following sections assess the suitability of the SOC methodology for four major sectoral groups, integrating scientific insights from all relevant ClimaMED deliverables (Protocols, Models, Replicability Plan) and providing a detailed narrative analysis of methodological opportunities, limitations, conditions and risks for transfer.

4.1 Agroforestry systems

Agroforestry systems, including olive groves, pistachio orchards, vineyards, orchard–pasture mosaics and tree–crop alley systems, represent one of the most favorable environments for transferring the SOC methodology. This conclusion is grounded in the fact that three of the five ClimaMED pilot sites (olive, pistachio, vineyard) were themselves perennial tree crop systems with structural and management characteristics typical of Mediterranean agroforestry.

Agroforestry systems exhibit well-defined microclimates, relatively stable vegetation structures and predictable management cycles that align well with the inputs required by the SOC model. The presence of perennial biomass, combined with annual understorey or inter-row vegetation, produces a layered pattern of Gross primary Production (GPP), respiration and carbon allocation that can be effectively captured through the NDVI-driven GPP module and the daily CO_2 flux measurements coming from the in-field sensors.

Moreover, agroforestry systems are characterized by distinct seasonal management pulses (tillage, fertilization, irrigation, pruning waste decomposition) that generate measurable changes in surface GHG fluxes. These pulses were successfully captured in the ClimaMED pilots, enabling the SOC model to infer relationships between flux behavior and annual SOC changes. Because perennial systems store carbon both above- and below-ground, the

inclusion of NDVI as a proxy for canopy vigor provides an important integrative element that can improve SOC-change predictions over annual cropping systems.
The methodology supports the quantification of annual SOC change at parcel scale, providing a harmonized and data-light approach suitable for MRV frameworks such as CAP eco-schemes and the Carbon Removal Certification Framework (CRCF). It offers evidence-based estimates that integrate both biological activity (via GPP/RE signals) and management effects (via the tillage decay function and metadata). The model can capture inter-annual SOC trends in response to improved management practices such as cover cropping, reduced tillage, manure incorporation, mulching or deficit irrigation.

Despite these advantages, several limitations must be acknowledged. First, SOC processes in perennial systems can be highly heterogeneous due to root architecture, shade distribution and variable microclimates, which may introduce spatial noise into surface CO_2 flux measurements at sensor height. Second, in systems with very dense canopies or high biomass shading, NDVI may saturate, reducing its sensitivity in detecting productivity variations relevant to SOC dynamics. Finally, the empirical equations derived from the pilot sites of LUFE ClimaMED must undergo broader multi-site calibration before being considered fully representative.

Overall, transferability to agroforestry is high, particularly in Mediterranean orchard-type systems with medium-height trees and open inter-row areas. The methodology requires minimal structural adaptation and is conceptually aligned with carbon-farming schemes targeting perennial cropping.

4.2 Protected Agriculture

Protected agriculture (greenhouses, polytunnels and partially enclosed horticultural structures) presents a more complex environment for the SOC methodology. Unlike the LIDAR system, which faces major operational restrictions inside covered environments, the SOC methodology is not constrained by physical obstacles, as sensors operate independently of canopy height or enclosure structures.

The SOC methodology captures surface CO_2/CH_4 fluxes at 50 cm above ground, a height compatible with substrate-based horticultural production and greenhouse soils. Protected agriculture systems are characterized by intense management cycles, multiple cropping periods per year and frequent soil or substrate disturbances, all of which produce strong CO_2/CH_4 flux signals.

Moreover, microclimatic conditions inside greenhouses (higher temperatures, elevated humidity, controlled irrigation) can amplify soil respiration responses, making GHG flux-based inference of SOC dynamics more sensitive and easier to detect than in open-field systems. Because greenhouses typically involve strictly controlled management routines (irrigation scheduling, fertigation, substrate renewal), the availability and precision of management metadata can substantially improve SOC estimation accuracy.

Protected environments, however, introduce challenges. High humidity and condensation can affect sensor stability and require more frequent recalibration. Substrate-based systems using inert media (e.g., perlite, rockwool) cannot be evaluated with this methodology, as SOC dynamics are fundamentally absent. Rapid residue mineralization and multiple crop cycles per year can complicate the interpretation of short-term CO_2/CH_4 spikes. Moreover, NDVI acquisition may be limited by roof materials or spectral distortions caused by greenhouse plastic films.

Overall, transferability is moderate to high, depending on whether production is soil-based and whether microclimatic variables can be reliably logged. The methodology performs well in soil-based greenhouses and poorly in substrate-only systems.

4.3 Waste valorization and land-management sectors

This category includes organic-waste treatment sites, compost application fields, brownfield restoration areas, degraded soils, abandoned quarries and landfills under partial rehabilitation. These environments exhibit highly variable SOC dynamics driven by organic-matter inputs, surface disturbance, topsoil reconstruction and vegetative succession.
The SOC methodology is particularly relevant in such contexts because CO_2/CH_4 fluxes at the soil surface are directly linked to biological respiration and decomposition processes associated with soil restoration or degradation. When organic amendments are applied (compost, biosolids, shredded biomass) distinct CO_2/CH_4 pulses emerge that can be captured by the sensors. Over months or years, NDVI trends can document vegetation establishment, which is an essential driver of SOC accumulation.

Furthermore, these sectors typically lack cost-effective, rapid and repeatable SOC monitoring tools. The ClimaMED SOC approach provides a low-cost, scalable alternative that can support EU restoration frameworks (e.g., Soil Monitoring Law, LULUCF reporting, CRCF schemes), where evidence of carbon recovery or loss is needed.

Patchy vegetation cover and irregular micro-topography can complicate flux interpretation. In landfills or waste-managed soils, non-biogenic CO_2/CH_4 emissions (e.g., from chemical oxidation) may interfere with biological respiration signals. Areas with persistent anaerobic pockets may exhibit CH_4 emissions that are difficult to incorporate into SOC-change models without supplementary measurements.

Concluding, transferability is high in restoration and waste-valorization sectors, provided that the surface serves as an active biological system undergoing carbon transformation.

4.4 Urban soils, green infrastructure, nature-based solutions and mine/quarry restoration sites

Urban and peri-urban soils, restored mine lands, riverbank rewilding, parklands and nature-based solutions (NBS) areas represent emerging priorities in EU climate and soil policies. These systems typically combine engineered substrates, managed vegetation and restoration interventions, making them highly relevant for empirical SOC monitoring.
Urban soils and NBS areas often undergo rapid changes in vegetation cover and soil structure due to planting, mulching, irrigation or soil replacement. These interventions generate marked variations in soil respiration that are detectable by surface CO_2/CH_4 sensors. NDVI and other spectral proxies also respond strongly to vegetation establishment and decline, offering robust indicators for SOC modelling.

In mine and quarry restoration, where soils are reconstructed from overburden or mineral spoil, SOC accumulation begins from near-zero baselines. This makes the methodology particularly valuable for quantifying early-stage carbon gains and validating restoration success, especially under CRCF or regional rewilding initiatives.

Urban environments may introduce interference from anthropogenic CO_2 sources (traffic, heating systems), requiring careful site selection. Heterogeneous substrates, frequent soil disturbance and engineered materials may create atypical decomposition patterns that diverge from agricultural soils. Similarly, in mine-restoration areas, extreme heterogeneity in substrate texture and mineralogy may reduce the predictive accuracy of model coefficients calibrated in typical agricultural soils.

Overall, transferability is high, with the caveat that urban GHG background variability and engineered substrates require adapted calibration routines.
Table 2 provides a consolidated assessment of the transferability of the SOC stock-change methodology across the four productive sectors examined in this deliverable. It synthesizes the key advantages, limitations, methodological constraints and the overall suitability of each sector for the application of the SOC estimation framework developed under LIFE ClimaMED.

4.5 Cross-country transferability of the SOC methodology

The cross-country transferability of the SOC stock-change methodology developed under LIFE ClimaMED is determined primarily by

1. the availability and quality of input data (CO_2/CH_4 surface fluxes, management metadata, multispectral indices, meteorological variables),
2. the representativeness of vegetation and soil structures relative to those used for calibration,
3. the institutional readiness of Member States to integrate model-based SOC estimates into their monitoring and MRV frameworks.

Table 2. Consolidated Evaluation Table – Transferability of the SOC Methodology

Sector	Advantages	Limitations	Key Constraints	Overall Suitability
Agroforestry systems	• Strong alignment with perennial crop dynamics • measurable flux pulses • reliable NDVI response • rich management metadata.	• Spatial heterogeneity in root zones and shading • NDVI saturation in dense canopies.	• Requires multi-site calibration • inter-row variability affects flux interpretation.	High
Protected agriculture	• Stable microclimate enhances flux sensitivity • predictable management cycles • soil-based systems detectable.	• Condensation affects sensors • substrate-only systems incompatible • spectral distortion under greenhouse films.	• Needs reliable environmental logging • limited applicability in inert-media systems.	Moderate–High (soil-based)
Waste valorization and land management sectors	• Strong CO_2/CH_4 signals from restoration - amendment processes • suitable for monitoring SOC recovery trajectories.	• Possible interference from non-biogenic CO_2.	• Requires careful siting • high substrate heterogeneity.	High
Urban soils, NBS, mines/quarries	• Responsive vegetation and soil processes • valuable for early-stage SOC accumulation • strong spectral signals.	• Urban anthropogenic CO_2 noise • engineered soils behave atypically.	Calibration must reflect artificial substrates and background CO_2 variability.	High

Unlike the LIDAR system, whose transferability depends strongly on geometry and atmospheric behavior, the SOC methodology exhibits broader geographical applicability but requires careful calibration when exported beyond Mediterranean soil–climate domains (Friedlingstein, et al., 2022).

- Greece serves as the reference environment for the SOC methodology, since all empirical equations, NDVI–GPP relationships, tillage decay functions and flux-based indicators were developed and validated using Greek Mediterranean pilot sites. The dry-warm seasonal patterns, mixed perennial cropping, and moderate soil organic matter levels of Greek agroecosystems provide a well-defined context where soil respiration dynamics, vegetation signals and management pulses align closely with the model structure. Transfer within Greece is therefore straightforward and requires only routine baselining and site-specific contextualization of management data (Ray et al., 2011; Pérez-Priego, et al., 2018).
- Cyprus, Italy and Spain present environmental and agronomic conditions highly similar to those of the ClimaMED pilots. Their Mediterranean climate, characterized by warm, dry summers and mild winters, supports comparable patterns of biological activity, irrigation cycles and soil respiration. Orchard systems, vineyards, annual crops, mixed

agroforestry mosaics and greenhouse complexes in Cyprus, Italy and Spain exhibit vegetation dynamics that can be reliably represented by NDVI-driven GPP proxies (Chiesi, et al., 2019). Their soil types (Cambisols, Luvisols, Calcisols) and SOC baselines fall within the same functional range as those used for model calibration (Jones et al., 2014; Panagos, et al., 2018).

Consequently, the SOC methodology can be transferred to these countries with minimal structural adaptation, requiring mainly: verification of local NDVI–GPP relationships; calibration of flux-response coefficients under national management regimes; and harmonization of metadata collection to account for tillage, irrigation, and organic-amendment practices.

Institutional readiness is also high. All three countries are actively engaged in CAP eco-schemes, carbon-farming discussions and the implementation of the CRCF, making them strong candidates for near-term scaling.

- Mediterranean regions outside the ClimaMED consortium share key environmental determinants (open canopies, seasonal drought, high solar radiation, rapid respiration responses to rainfall, and mixed perennial systems) that are well aligned with the SOC methodology (López-Bermúdez, et al., 2015). Transferability is therefore very high, provided that new calibration datasets are collected to capture local soil textures, irrigation strategies and vegetation phenologies. In coastal areas of Portugal and Malta, higher salinity and limestone-rich soils may require local adjustment of decomposition coefficients and SOC-stability parameters. Southern France and the Adriatic regions present vegetation and soil structures well within the model's applicability domain and require primarily harmonization of management metadata.
- Non-Mediterranean EU countries (Central, Eastern and Northern Europe). Transferability to temperate and boreal regions is feasible but requires substantial recalibration. The SOC methodology relies on Mediterranean-type relationships between NDVI, GPP, soil respiration and management-induced pulses. In Northern and Central Europe, cooler temperatures, lower evaporative demand, reduced radiation, and longer periods of soil moisture saturation generate different respiration patterns and SOC turnover dynamics (Smith, et al., 2020; Zimmermann, et al., 2007). Grasslands, maize–silage rotations, managed pasture systems, and peat-influenced soils present decomposition pathways that diverge strongly from those in dry Mediterranean climates.

  To extend applicability into these regions, the model must undergo a structured programme of recalibration, including (Luo, et al., 2018):
  - local fitting of NDVI–GPP curves under temperate and boreal vegetation,
  - region-specific decomposition coefficients for high-moisture soils,
  - revised tillage decay functions under cooler climates,
  - multi-season flux monitoring to capture early-spring and late-autumn respiration events,
  - and validation against long-term SOC datasets or eddy-covariance observations.

  Institutionally, several Northern EU countries (e.g., Denmark, Germany, Netherlands, Austria) maintain advanced soil laboratories and high-resolution soil inventories, facilitating calibration but requiring stricter verification procedures before the methodology can be integrated into official MRV schemes (Arrouays, et al., 2020; van Wesemael, et al., 2019).

Overall, the SOC methodology demonstrates very high transferability across Mediterranean countries, where environmental, agronomic and vegetation conditions closely correspond to those of the ClimaMED pilot sites (Luo, et al., 2018). Transferability remains moderate to high in non-Mediterranean EU regions, contingent on extensive recalibration and multi-season validation to align model behavior with local carbon-cycle dynamics. With these adaptations, the SOC methodology can form the basis for harmonized, measurement-informed SOC monitoring and CRCF-compatible carbon-farming applications across Europe.

Part B – Roadmap for EU wide transferability

5. Roadmap for transferability

5.1 Purpose, scope and logic of the Roadmap

Part B provides an operational, forward-looking Roadmap for the transferability and upscaling of the two LIFE ClimaMED innovations, i.e. the LIDAR–LoRa–CMM system for parcel-level GHG monitoring and the SOC stock-change methodology for annual soil-carbon estimation. While Part A examined sectoral suitability, technical conditions and cross-country feasibility, Part B translates these analytical results into a structured implementation pathway that can be adopted by regional authorities, Member States, Paying Agencies, advisory services and carbon-farming actors.
The Roadmap outlines the sequence of actions, enabling conditions, resource needs and institutional coordination mechanisms required to move from proof-of-concept and pilot validation toward broader regional and EU-level deployment. This approach is consistent with the LIFE programme's expectations for post-project transferability and complements the EU's emerging frameworks for land-based GHG monitoring, including the Soil Monitoring Law, the CAP 2023–2027 eco-schemes, and the Carbon Removal Certification Framework (CRCF) (European Commission, 2024).

From a methodological standpoint, this Roadmap adopts an integration logic aligned with recent advances in measurement-based agricultural MRV (Paustian et al., 2016; Smith et al., 2020) and soil-carbon estimation frameworks (Arrouays et al., 2020; Luo et al., 2018). For LIDAR, the focus is on the conditions required for robust optical performance, stability of dispersion modelling, and integration with regional MRV systems. For SOC, the focus shifts toward data availability, climatic compatibility, vegetation representativeness and calibration needs across Mediterranean and non-Mediterranean regions.

Overall, Part B functions as a practical blueprint, articulating how technological, institutional and operational factors converge to support the scaling of ClimaMED results across European productive sectors and governance contexts

5.2 Vision for cross-sector transferability (2030-2035 horizon)

The vision is progressive, evidence-based scaling, beginning with Mediterranean agricultural systems and expanding—through sector-specific adaptations—to a broader range of productive environments across Europe.

- Short-term vision to 2030: Consolidation and multi-sector operational readiness
  By 2030, the ClimaMED technologies could achieve full operational readiness across Mediterranean agricultural and land-based productive sectors whose environmental geometry, management regimes and microclimatic dynamics closely resemble the Greek pilot sites. This includes livestock yards, agroforestry systems (olive, pistachio, vineyard), composting and waste-valorization facilities, and semi-open land-management environments. In these sectors, the LIDAR–LoRa–CMM system can be deployed with minimal structural adaptation, while the SOC stock-change methodology can reliably estimate annual SOC variations once local calibration datasets are collected. The short-term horizon thus focuses on sector replication within Mediterranean countries, extending pilots to real operational settings and ensuring the availability of metadata, NDVI time series and local flux-response coefficients.
- Medium-term vision to 2035: Expansion to more complex productive sectors
  Between 2030 and 2035, transferability could expand to more structurally complex or environmentally challenging sectors. These include soil-based protected agriculture, urban soils, nature-based solutions (NBS) areas, reconstructed mine/quarry substrates, industrial low-height zones and harbour environments. In these contexts, transferability depends on the development of sector-specific deployment protocols (e.g. dust-resistant housings, humidity protection, bespoke σ_y–σ_z coefficients, substrate-specific SOC decomposition parameters) and multi-season calibration. By 2035, these sectors could reach full operational integration, provided that adaptation, calibration and validation actions are completed according to the timelines identified in the Replicability Plan.
- Long-term vision: Stable cross-sector integration and sustained replication
  Beyond 2035, the objective is to ensure stable cross-sector deployment of both technologies through harmonised protocols, streamlined calibration packages and integration into regional MRV workflows and decision-support systems. The long-term trajectory foresees an ecosystem in which agricultural, restoration, waste-management and peri-urban productive sectors can consistently utilise LIDAR-based GHG data and SOC-modelling outputs to monitor emissions, track carbon gains and support climate-aligned management decisions.

5.3 Step-by-step transfer pathway for the LIDAR–LoRa–CMM system

The transferability of the LIDAR–LoRa–CMM system to new productive sectors and European regions follows a phased pathway that reflects both the technological maturity of the instrument (TRL 7–8) and the practical constraints observed during the ClimaMED demonstration.

Transfer begins with a comprehensive pre-deployment assessment, in which the receiving sector or region evaluates its readiness to host LIDAR-based measurements. This includes characterising wind regimes, atmospheric stability, humidity patterns and potential sources of optical interference. As shown in the ClimaMED pilot and in analogous open-path DIAL deployments (Wang et al., 2022), the reliability of differential absorption retrievals depends strongly on signal-to-noise ratio, which can be reduced by particulate loads, high humidity, fog or rapid temperature gradients. At this stage, operators must map potential optical paths, identify beam obstructions, assess installation height options, and determine whether protective housings or corrosion-resistant components are required, particularly in coastal, industrial or waste-management environments where humidity or dust are recurrent.

Following this assessment, the technology enters the adaptation and calibration phase, which is essential when transferring to a new productive sector. Although the LIDAR core retrieval algorithms remain constant, the dispersion modelling components (σy, σz coefficients, stability-class assignments and plume-geometry assumptions) must be recalibrated to the microclimatic and structural conditions of the target environment. The σy–σz values derived from agricultural sites cannot be assumed valid for composting platforms with large thermal gradients, semi-open landfills with heterogeneous emission fields, or agroforestry systems with partial canopy obstruction (Baldocchi, 2014; Manolis et al., 2019). Calibration requires a minimum deployment of several months under different stability regimes to validate flux behaviour. Sector-specific QC filters must also be tailored to distinguish true emission pulses (e.g., manure turning, compost aeration, irrigation rewetting, landfill cap degassing) from artefacts caused by machinery, sudden dust plumes or shifting reflective surfaces.

Once calibration is established, the system proceeds to the pilot operational phase, during which measurements are carried out over extended periods (3–12 months depending on sector) to confirm robustness across full seasonal cycles. This phase reflects the core insight from the Replicability Plan: agricultural and open-waste-management sectors can reach operational performance by approximately 2030, whereas more complex settings (harbours, industrial zones, engineered soils) require extended testing and are aligned with a 2035 horizon. The pilot phase validates the stability of plume modelling, the resilience of telemetry under fluctuating weather conditions, and the integration of LIDAR outputs into local MRV systems or digital platforms (CMM included). It also serves to refine background-correction parameters, particularly in regions with variable anthropogenic CO_2 signatures or high advection.

The next phase involves integration into sectoral workflows and MRV systems, which is critical for long-term adoption. Here the focus shifts from purely technical performance to institutional and operational embedding. Regional authorities, cooperatives, waste-management operators or harbour administrations must establish protocols for data retrieval, interpretation and use in decision-making or compliance reporting. Experience from the ClimaMED pilots indicates that the LIDAR–LoRa–CMM ecosystem becomes significantly more effective when paired with structured metadata (management logs, timing of manure handling or compost turning, irrigation events) and when integrated into advisory systems that support mitigation planning.

Finally, the scaling phase involves replication across multiple sites within the same sector (and across countries) with similar environmental conditions. Scaling depends on the existence of trained personnel, maintenance capacity, compatible telemetry infrastructure and institutional incentives (e.g., CAP eco-scheme requirements, CRCF-compliant carbon-farming schemes). Risks in this stage include under-maintenance of the optical components, failure to update σy–σz coefficients when environmental conditions change, and inconsistent metadata reporting. With appropriate mitigation, i.e., periodic recalibration, updated baseline datasets, protective housings and harmonised metadata standards, the LIDAR system can achieve stable multi-sector deployment by 2030 in Mediterranean contexts and by 2035 in more complex industrial and coastal environments.

Table 3 consolidates the full transferability pathway for the LIDAR–LoRa–CMM system across Mediterranean, Central and Northern European productive sectors. It summarizes the phased implementation steps, responsible actors, indicative resource requirements and key risk-mitigation measures needed to enable effective scaling of the technology from 2025 to 2035. The table integrates the timeline, institutional responsibilities and budgetary considerations into a unified operational framework, offering a clear, evidence-based overview of how the LIDAR system can transition from pilot-level deployment to full multi-sector integration across Europe.

5.4 Step-by-step transfer pathway for SOC methodology

The transfer pathway for the SOC stock-change methodology reflects its lower technological readiness level (TRL 3–4) and its dual nature as both a scientific framework and a potential operational tool for future carbon-farming and soil-health monitoring schemes. Unlike the LIDAR–LoRa–CMM system, which is already near-operational and legally anchored in Greece, the SOC methodology still requires several iterative cycles of empirical validation, model refinement and institutional testing before it can be integrated into formal MRV architectures. The pathway therefore follows a research–development–deployment logic, starting with Mediterranean agroforestry systems and progressively extending to additional sectors and climatic regions, while maintaining strong links with long-term soil monitoring and CRCF-aligned certification frameworks.

The first phase focuses on consolidation and extended piloting in Mediterranean agroforestry and soil-based protected agriculture, building directly on the Greek pilot fields that underpinned the original model equations. In this phase, the priority is to expand the empirical base from a handful of sites to a statistically meaningful network of fields representing the main Mediterranean perennial systems (olive, pistachio, vineyard, mixed orchards) and soil-based greenhouses. This requires installing additional CO_2/CH_4 surface-flux sensors at 50 cm height, harmonizing measurement protocols, and collecting multi-year datasets that combine flux time series, NDVI and other multispectral indices, meteorological variables, and detailed management metadata (tillage, irrigation, fertilization, residue management). The aim is to refine and re-parameterize the NDVI–GPP relationships, tillage decay functions and flux-response coefficients for each major crop–soil–climate combination, using repeated soil analyses as a reference for annual SOC-change estimates (Rey et al., 2011; Pérez-Priego et al., 2018; Chiesi et al., 2019). During this phase, the methodology remains pre-operational: outputs are used primarily for scientific evaluation, sensitivity analysis and uncertainty quantification, rather than for formal reporting or payment decisions.

The second phase aims at multi-site calibration and sectoral expansion within Mediterranean countries, in line with the high cross-country transferability identified for Cyprus, Italy, Spain and other Mediterranean regions. Here, the methodology will be tested across the four sectoral groups described in Part A (agroforestry systems, soil-based protected agriculture, waste-valorization and land-management sites, and urban soils/NBS areas) with coordinated experimental designs. In each participating country, a small number of representative sites per sector should be instrumented with identical sensor packages, spectral data sources and management templates, to allow joint calibration of key model components:

- NDVI–GPP curves under different vegetation types
- decomposition coefficients for amended vs. non-amended soils
- sector-specific flux signatures in restoration and waste-valorization projects
- background-correction procedures in urban and peri-urban environments

This phase also includes the development of standard operating procedures (SOPs) for sensor deployment, data quality control and metadata collection, along with the first testing of the methodology as a "supporting line of evidence" in CAP eco-schemes, CRCF pilot actions or national soil-health initiatives. The main risk in this phase is over-interpreting early calibration results; mitigation requires conservative use of the model (e.g. for trend detection and comparative assessments) and systematic cross-checking against repeated SOC laboratory measurements and, where available, eddy-covariance observations (Smith et al., 2020; van Wesemael et al., 2019).

The third phase entails progressive integration into MRV workflows and cautious extension to non-Mediterranean EU regions, with a strong emphasis on recalibration and uncertainty management. In Central and Northern Europe, where cooler climates, higher soil moisture and different land-use systems (grasslands, maize–silage rotations, peat-influenced soils) generate distinct SOC turnover dynamics, the methodology cannot be transferred directly. Instead, it must undergo a structured recalibration programme, including long-term flux monitoring under temperate and boreal vegetation, region-specific decomposition parameters for high-moisture soils, revised tillage decay functions for cooler climates, and explicit treatment of snow-cover and freeze–thaw effects (Zimmermann et al., 2007; Luo et al., 2016). During this phase, the SOC methodology should be integrated with existing national soil-inventory and monitoring frameworks - rather than replacing them - by serving as a complementary, high-frequency layer that helps interpret observed SOC changes between sampling campaigns and supports the design and evaluation of mitigation practices.

Across all phases, successful transfer of the SOC methodology depends on a set of horizontal enablers. These include: stable access to relatively low-cost CO_2/CH_4 sensors and multispectral data; interoperable data systems capable of storing and processing high-frequency flux measurements; robust training for technicians and advisory services on sensor operation, data interpretation and uncertainty communication; and institutional willingness to recognize model-based SOC estimates as an auxiliary information source within MRV and certification systems, in line with evolving EU guidance on soil monitoring and carbon removals (Arrouays et al., 2020; Friedlingstein et al., 2022; European Commission, 2024).
If these conditions are met, the SOC methodology can evolve from a scientific prototype into a mature, measurement-informed SOC estimation framework, first for Mediterranean agroecosystems by around 2030 and subsequently, after extensive recalibration, for a broader set of European productive sectors in the 2030–2035 horizon.

Table 4 summarizes the phased transferability pathway of the SOC stock-change methodology across Mediterranean, Central and Northern European productive sectors. It integrates the methodological maturity, calibration needs, sectoral adaptation requirements, institutional roles and indicative resource needs. The table consolidates the timeline, responsible actors and costs into a single operational framework, reflecting the scientific development trajectory of the SOC methodology from TRL 3–4 towards wider applicability by 2035.

Table 3. Roadmap for Transferability of the LIDAR–LoRa–CMM System (2025–2035)

Phase	Period	Key activities	Responsible actors	Resources and indicative costs	Risks and mitigation
Phase 1: Mediterranean pilot expansion	2025–2028	• Deployment of additional units in orchards, vineyards, livestock yards and composting facilities • σy–σz calibration in IT–ES–CY–PT • Development of dust- and humidity-proof housings • Integration with LoRa networks and CMM platforms.	Research institutes, regional authorities, technology suppliers, farmers cooperatives	• €120,000–€180,000 per pilot • €4,000–€7,000 housings[3]	Risks: humidity, sea spray, dust loads. Mitigation: marine-grade housings, dust filters.
Phase 2: Regional scaling in Mediterranean countries	2028–2030	• Multi-site replication • Integration of LIDAR flux data into MRV systems and eco-scheme pilots • Training of regional technicians • Harmonization of metadata and QC procedures.	Ministries, paying agencies, cooperatives, MRV operators	• €40,000–€70,000 per additional site • €5,000–€7,000 per training programme	Risks: QC drift, winter data gaps. Mitigation: periodic recalibration, automated QC routines.
Phase 3: Cross-sector expansion and Central–Northern EU adaptation	2030–2035	• Deployment in harbors, industrial zones, landfills, restored lands • Development of region-specific σy–σz coefficients for Central/Northern EU • Advanced protective housings • Integration into national MRV and CRCF systems.	Environmental agencies, industrial/port authorities, waste-management operators, national MRV institutions	€300,000–€600,000 cluster-wide	Risks: fog, humidity, reflective surfaces. Mitigation: elevated mounting, optical shielding, corrosion-resistant housings.

[3] Protective housing refers to a weather-resistant enclosure specifically designed to shield the LIDAR device from humidity, dust, sea spray, temperature fluctuations and corrosive environmental conditions, ensuring stable optical performance and uninterrupted long-term operation.

Table 4. Roadmap for transferability of the SOC stock-change methodology (2025–2035)

Phase	Period	Key activities	Responsible actors	Resources and indicative costs	Risks and mitigation
Phase 1: Mediterranean consolidation and extended piloting	2025–2028	• Expansion of SOC pilots across Med agroforestry and soil-based protected agriculture • Installation of additional CO_2/CH_4 sensors • Multi-year flux datasets • Calibration of NDVI–GPP functions • Refinement of model coefficients	Research institutes, agricultural authorities, pilot farmers, universities	• €60,000–€120,000 per extended pilot network • €3,000–€6,000 per sensor set • €8,000–€10,000 for soil analyses	Risks: small dataset bias, sensor drift, metadata inconsistencies. Mitigation: repeated calibration, harmonized protocols.
Phase 2: Multi-site Mediterranean calibration and sectoral expansion	2028–2030	• Calibration across four sectors (agroforestry, protected agriculture, waste valorization, restoration/urban soils) • Development of SOPs for sensors and metadata • Spectral-data harmonization across countries • Testing as a supporting line of evidence in eco-schemes and soil-health programmes.	Ministries, paying agencies; farmers cooperatives, municipal restoration units, MRV operators	• €40,000–€90,000 per country calibration package • €10,000–€15,000 per spectral-data workflow setup	Risks: over-interpretation of early coefficients; urban CO_2 interference. Mitigation: cross-checks with SOC lab data.
Phase 3: Integration into MRV systems and temperate/boreal recalibration	2030–2035	• Recalibration for Central/Northern EU • Flux monitoring under temperate - boreal vegetation • New decomposition coefficients for high-moisture soils • Integration into national soil monitoring • Treatment of snow/freeze-thaw effects • Uncertainty analysis.	National soil institutes, MRV agencies, research consortia, regional authorities	• €150,000–€200,000 regional recalibration campaigns • €20,000–€30,000 per multi-season dataset	Risks: climatic mismatch, model uncertainty, heterogeneous substrates. Mitigation: region-specific coefficients, long-term monitoring.

6. Conclusions

The Transferability Plan and its implementation Roadmap demonstrate that the LIFE ClimaMED innovations can be credibly and systematically scaled across Mediterranean productive sectors and, with appropriate adaptation, to wider European contexts.

The LIDAR–LoRa–CMM system, having reached TRL 7–8 and having been legally adopted by Greece, shows the strongest near-term transferability potential, particularly in open-air livestock operations, orchard-based agroforestry systems, composting units and semi-open land-management environments. Across these sectors, environmental geometry, emission behavior and management routines align closely with the conditions under which the technology was developed and validated, enabling operational deployment by 2030 with limited structural adjustments.

More complex sectors, industrial low-height zones, harbor environments, engineered restoration substrates and urban/peri-urban systems, require additional calibration, protective housings, and sector-specific protocols. In these cases, transferability aligns with a 2030–2035 horizon, consistent with the Replicability Plan. Cross-country analysis confirms that Mediterranean regions (Greece, Cyprus, Italy, Spain, Portugal, Malta, southern France) are compatible with the LIDAR system's current calibration envelope, while Central and Northern Europe require new σy–σz coefficients, humidity-resilient configurations, and adapted operational guidelines.

The SOC stock-change methodology follows a different trajectory. Its lower TRL (3–4) and early-stage empirical base mean that scaling must proceed through multi-phase scientific consolidation, beginning with Mediterranean agroforestry systems and soil-based protected agriculture, followed by multi-site calibration in Mediterranean countries and finally structured recalibration for temperate and boreal regions.

By 2030, the methodology can reach operational maturity across Mediterranean sectors; by 2035, it can expand into Central and Northern Europe after extensive recalibration, multi-season flux monitoring and integration with national soil-inventory frameworks.

Across both technologies, successful transferability requires:

- robust calibration datasets, adapted to sector and region
- interoperable MRV architectures, enabling ingestion and processing of high-frequency GHG/SOC data
- institutional readiness, including alignment with CAP eco-schemes, CRCF pilots and national MRV systems
- capacity building for authorities, cooperatives and advisory bodies
- sustained maintenance and quality-control routines to ensure long-term empirical reliability.

The Roadmap presented in Part B provides a unified operational framework, detailing phased actions, responsible actors, resource needs, risks and mitigation measures, for progressing from pilot-level demonstrations to broad EU-wide deployment. It ensures that scaling is sequenced, evidence-based, risk-aware and policy-aligned, allowing the ClimaMED innovations to contribute meaningfully to the evolution of European land-sector MRV, agricultural decarbonization and soil-health governance over the 2025–2035 horizon.

With sustained investment, coordinated institutional uptake and continuous scientific refinement, the LIFE ClimaMED innovations can serve as cornerstone technologies for the emerging European measurement-based climate-agriculture architecture, supporting both national commitments and EU-level targets for climate neutrality and soil resilience.

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