LIFE FROSTDEFEND

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LIFE FROSTDEFEND Adaptation Plan

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LIFE FROSTDEFEND
Adaptation Plan

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Executive Summary

The LIFE-FROSTDEFEND Adaptation Plan has been developed within the framework of the LIFE-FROSTDEFEND project to strengthen the resilience of agricultural production systems against frost-related climate risks in vulnerable agricultural regions of Greece and France. The Adaptation Plan provides a structured and operational framework for reducing frost-related crop losses through the integration of early-warning systems, decision-support tools, stakeholder engagement and sustainable adaptation practices. The document is fully aligned with the objectives of the European Union Strategy on Adaptation to Climate Change, the Common Agricultural Policy (CAP) 2023–2027, the Greek National Climate Change Adaptation Strategy and the French National Climate Change Adaptation Plan (PNACC-3).

The project focuses primarily on frost-sensitive perennial crops, particularly citrus cultivations (i.e. lemons), which are highly vulnerable to low-temperature events occurring during flowering and fruit-setting stages. The main pilot area of the project is located in Achaia (Aigio) within the Region of Western Greece, while replication activities are implemented in Argolida (Argos), Laconia (Sparti) and Clermont-Ferrand (Puy-de-Dôme) in France. These areas were selected due to their agricultural importance, climatic characteristics, historical exposure to frost events and vulnerability to increasing climatic variability.

The Adaptation Plan is based on a comprehensive assessment of climate trends, frost-risk conditions, agricultural vulnerability and adaptive capacity. The analysis demonstrates that despite the long-term increase in average temperatures associated with climate change, frost risk remains significant due to increased climatic variability, altered seasonal dynamics and earlier crop phenology. Warmer winter conditions may accelerate flowering and vegetative development, thereby increasing crop exposure to late frost events. The assessment further highlights the importance of local topographical conditions, such as cold-air accumulation and thermal inversions, in increasing frost exposure in lowland and valley agricultural areas.

The vulnerability assessment identifies lemon cultivation as one of the most vulnerable crops due to the combined effects of:

- high exposure to frost events,
- elevated physiological sensitivity,
- significant economic dependence on citrus production,
- moderate adaptive capacity,
- increasing climatic uncertainty.

The monitoring framework of the plan additionally incorporates seasonal evaluation of operational practices and environmental performance indicators, including the

recording of spraying frequency, spraying dates, spraying compounds and intervention locations. These operational data support the estimation of CO_2 emissions and the assessment of emission reductions compared with conventional frost-protection approaches, such as the continuous use of heaters and wind machines. They also contribute to the long-term optimization of adaptation measures and the enhancement of operational preparedness.

Citrus cultivation and other perennial crops, including apricots, grapes, and pears, are also considered vulnerable, depending on local climatic and topographical conditions. The assessment additionally recognizes the socioeconomic importance of citrus production for local economies, agricultural cooperatives and rural employment, emphasizing that repeated frost-related damages may threaten long-term agricultural sustainability and farm income stability.

A central component of the project is the LIFE-FROSTDEFEND Early-Warning Tool, which combines meteorological forecasting, frost-risk monitoring and operational decision-support functions. The tool is designed to support farmers and agricultural stakeholders in anticipating frost events, optimizing the timing of protection measures and improving operational preparedness. The system incorporates real-time monitoring and data collection functions, including:

- frost-risk forecasting,
- intervention recording,
- farmer feedback,
- environmental performance assessment.

The collected data are used to improve adaptation planning, optimize frost protection practices and support continuous improvement of the adaptation framework. To this end, the Adaptation Plan proposes a comprehensive set of adaptation measures and countermeasures addressing both immediate operational needs and long-term agricultural resilience.

These include:

- Implementation of early-warning and preparedness systems;
- Optimization of the timing of frost-protection measures;
- Promotion of environmentally sustainable and cost-effective agronomic and ecosystem-based practices;
- Development of emergency frost response procedures;
- Stakeholder training and awareness activities.

The proposed measures aim to reduce unnecessary interventions, improve resource efficiency, reduce greenhouse gas emissions and strengthen adaptive capacity at farm and regional levels.

The stakeholder engagement strategy additionally aims to promote behavioral and attitude changes among farmers and agricultural stakeholders regarding climate adaptation, sustainable frost management and environmentally responsible agricultural practices. Through awareness-raising activities, training actions and participatory implementation processes, LIFE FROSTDEFEND supports the transition from reactive emergency responses towards preventive, data-driven and ecosystem-based adaptation approaches. Training activities, dissemination actions, workshops and consultation processes support knowledge transfer, behavioral change and increased awareness regarding climate adaptation and frost-risk management. The active involvement of end-users contributes to the operational relevance, acceptance and long-term sustainability of the proposed adaptation framework.

The LIFE-FROSTDEFEND Adaptation Plan also incorporates a structured monitoring and evaluation framework based on the continuous collection and analysis of climatic, agricultural, and operational data. Seasonal reviews and systematic monitoring procedures support the ongoing assessment and improvement of adaptation measures, helping to ensure their long-term effectiveness under changing climatic conditions. The monitoring strategy is aligned with climate-resilience reporting principles and adaptive management approaches promoted at both European and national levels. It enables measures to be regularly reviewed and adjusted in response to new data, emerging risks, implementation experience, and evolving local needs.

Special emphasis is additionally placed on the repeatability and scalability of the LIFE FROSTDEFEND framework across other frost-prone agricultural regions of the Mediterranean and wider European area. Transferability and replication represent major strategic objectives of LIFE-FROSTDEFEND. The methodology and operational framework developed within the project are designed to be scalable and applicable to additional frost-prone agricultural regions and crop systems beyond the pilot areas. The project therefore contributes not only to local agricultural resilience but also to broader European climate adaptation objectives by providing a practical, operational and transferable model for frost-risk management under changing climatic conditions.

Overall, the LIFE-FROSTDEFEND Adaptation Plan demonstrates that integrated frost-risk management based on early-warning systems, stakeholder participation and sustainable agricultural practices can significantly strengthen the resilience of vulnerable agricultural systems against climate-related frost risks.

1. Introduction

1.1 Project Description

The LIFE-FROSTDEFEND project aims to enhance the resilience of agricultural production systems to frost events, which are becoming increasingly frequent and unpredictable due to climate change. The project focuses on the development and implementation of an integrated frost-risk management approach that combines the monitoring of critical atmospheric and meteorological parameters, an early-warning system for frost damage, climate adaptation planning, and environmentally friendly frost-protection practices. The LIFE FROSTDEFEND project aims to develop and demonstrate the benefits of an innovative tool that monitors conditions in orchards and predicts the risk of frost. In this way, it seeks to reduce the damage caused by frost.

The project started in September 2021 and has a duration of four years. Its total budget amounts to €1.94 million, with funding as follows:

- €1.03 million from the European Union.
- €0.91 million from the project partners.

Through the implementation of pilot and replication activities in Greece and France, the project seeks to support farmers, agricultural cooperatives, public authorities, and other stakeholders in reducing the environmental, economic, and social impacts associated with frost-related crop damage. The whole idea is based on the recognition that climate variability and extreme weather events significantly affect agricultural productivity and threaten the sustainability of sensitive crop cultivation, particularly in Mediterranean regions. Frost incidents occurring during critical stages of the fruit life cycle can lead to severe production losses, reduced crop quality, and long-term economic impacts on rural communities. The LIFE-FROSTDEFEND project addresses these challenges by deploying a decision-support and early-warning tool designed to improve preparedness and facilitate more targeted and efficient frost-protection interventions.

The project additionally recognizes that frost occurrence and freezing injury cannot always be explained solely by minimum air temperature. Frost-related crop damage results from the interaction between climatic variability, crop phenology, local atmospheric conditions and biological ice nucleation processes occurring on plant surfaces. LIFE-FROSTDEFEND therefore adopts an integrated and multidisciplinary approach combining meteorological monitoring, environmental observations, phenological analysis and biological frost-risk assessment in order to improve preparedness and operational decision-making under changing climatic conditions.

The main objectives of LIFE-FROSTDEFEND are to:

- Improve the capacity of farmers and relevant stakeholders to anticipate, prepare for, and respond effectively to frost events;
- Reduce frost-related crop losses through timely, targeted, and cost-effective interventions;
- Promote environmentally sustainable frost-protection measures that generate lower greenhouse gas emissions and reduce air pollutant emissions;
- Enhance scientific knowledge of the relationships among atmospheric pollutants, ice-nucleation-active (INA) epiphytic bacteria, and frost formation;
- Improve understanding of crop frost hardiness and plant phenological development;
- Support climate adaptation planning and strengthen agricultural resilience at regional and local levels; and
- Facilitate the transfer, replication, and wider application of the proposed adaptation measures and tools in other frost-prone agricultural regions.

Project outcomes include among others the establishment of an operational frost early-warning and decision-support system, improved monitoring and assessment of frost risks, increased adoption of sustainable frost protection practices by farmers, and the development of an adaptation plan that aligns with national and European climate adaptation priorities. The project is also expected to contribute to the reduction of economic losses in agriculture, improved environmental performance of frost protection practices, and increased awareness among stakeholders regarding climate change adaptation in the agricultural sector. To this end, the project brought together research institutions, academic organizations, and technical partners from Greece and France with complementary expertise in climate science, agriculture, environmental monitoring, and adaptation planning.

More specifically, NCSR “Demokritos” (NCSR-D) contributes scientific and technical expertise in the real-time monitoring of atmospheric and meteorological parameters, the investigation of atmospheric drivers of frost formation, the evaluation of the environmental performance of the FROSTDEFEND tool, and stakeholder engagement activities. The Agricultural University of Athens (AUA) supports the design and implementation of agricultural monitoring activities in the pilot and replication plots, conducts research on the microbiology of airborne and epiphytic bacteria, facilitates stakeholder engagement, and contributes to the assessment of crop vulnerability and adaptation measures. INRAE provides expertise in plant phenology and vulnerability assessment and is responsible for the implementation of the project's activities in France. Additional project partners support technical implementation, field monitoring, dissemination, and stakeholder communication activities. ACUA supports the implementation of agricultural practices, sample collection in the pilot and replication

plots, and stakeholder engagement. MSENSIS has contributed to the development of the FROSTDEFEND web-based platform and mobile application.

Through their complementary roles and expertise, the participating organizations, the participating organizations act as intermediaries between the project and competent authorities, agricultural cooperatives, and farmers in both countries, facilitating knowledge transfer, stakeholder engagement, and the uptake and replication of project results.

1.2 Scope and Geographical Coverage

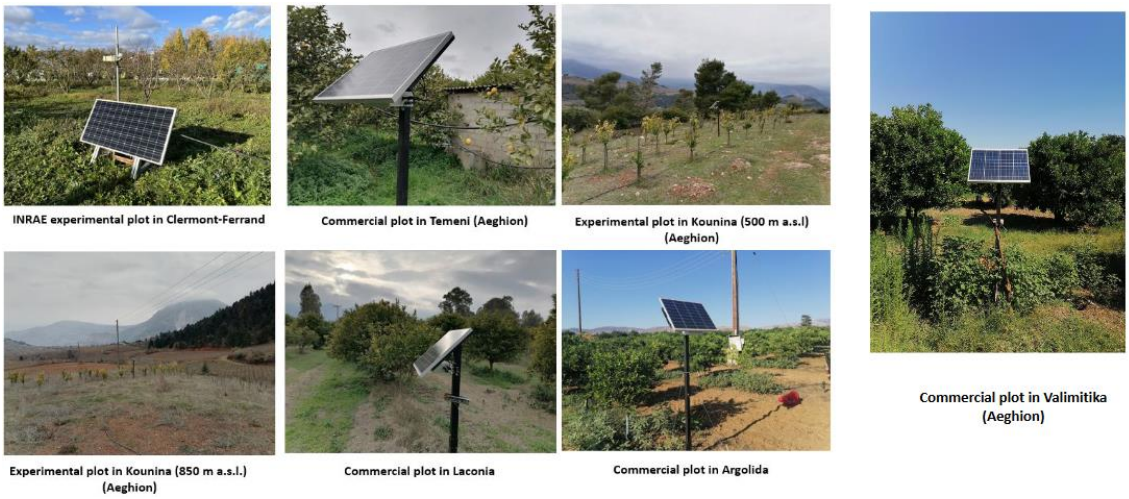
The LIFE-FROSTDEFEND adaptation plan focuses on agricultural regions in Greece and France that are vulnerable to frost events and where frost-sensitive crops constitute an important component of local agricultural production and economic activity. The geographical scope of the project includes both pilot and replication areas selected based on their climatic conditions, agricultural characteristics, historical frost impacts, and relevance for the implementation and transferability of the proposed adaptation measures. The main pilot area of the project is located in the Regional Unit of Achaia (NUTS3), within the Region of Western Greece (NUTS2), with field implementation activities centred in the area of Aigio (Figure 1).



Figure 1. LIFE FROSTDEFEND pilot area

The region is characterized by extensive citrus cultivation, with lemon production representing one of its most important agricultural activities. Due to their high sensitivity to low temperatures, citrus crops are particularly vulnerable to frost damage, which can result in substantial yield losses and reduced fruit quality. The Aigio pilot plots were selected as the main demonstration area for the development and application of the FROSTDEFEND tool, owing to the strategic importance of citrus production to the local economy and the active involvement of local stakeholders. The pilot area therefore serves as the principal site for field measurements and for the implementation, testing, and validation of the FROSTDEFEND tool under real farming conditions. In addition to the pilot area, the project includes replication activities in other regions of

Greece and France to assess the applicability and transferability of the proposed operational framework under different climatic and agricultural conditions (Picture 1).



Picture 1. LIFE FROSTDEFEND pilot and replication activities

In Greece, replication areas include Argolida (NUTS3) in the Region of Peloponnese (NUTS2), with implementation activities in the area of Argos, and Laconia (NUTS3), also in the Peloponnese Region, with activities centered in Sparti. Both regions are important agricultural zones with significant citrus and fruit tree cultivation and have experienced increasing frost-related risks associated with climate variability.

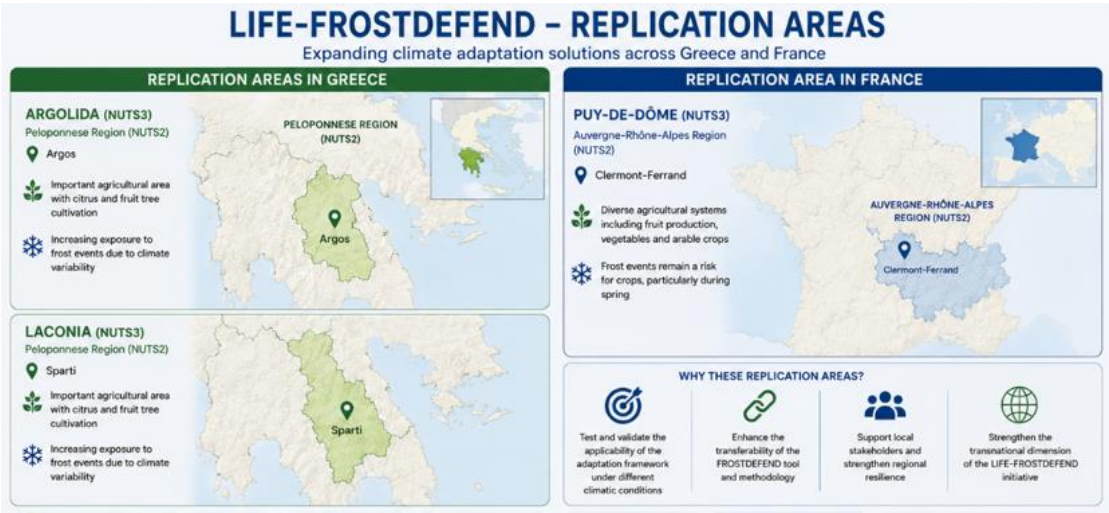


Figure 2. LIFE FROSTDEFEND replication areas

In France, the replication area is located in the Puy-de-Dôme Department (NUTS 3), within the Auvergne-Rhône-Alpes Region (NUTS 2). Implementation activities are conducted at the INRAE experimental site in Clermont-Ferrand. Although the area lies at the climatic margin of citrus cultivation, it offers valuable conditions for calibrating,

fine-tuning, and evaluating the FROSTDEFEND tool under environmental conditions that differ from those of the project's core citrus-growing regions. The site also provides an ideal testbed for assessing frost hardiness and vulnerability in other temperate fruit crops (i.e. apples, grapes, sweet cherries, pears, peaches, and plums). Its inclusion strengthens the transnational dimension of the LIFE-FROSTDEFEND project by supporting the assessment of the tool's applicability, adaptability, and transferability across diverse climatic and agricultural contexts (Figure 2).

Overall, the climatic characteristics of the selected regions reflect increasing variability in seasonal temperatures and a growing occurrence of extreme weather conditions associated with climate change. Although Mediterranean regions are generally characterized by mild winters, recent years have shown an increased frequency of unexpected cold spells and late frost events affecting agricultural production. The selected pilot and replication areas therefore provide a representative framework for assessing frost vulnerability, testing adaptation measures, and developing transferable climate resilience strategies for the agricultural sector.

1.3 Objectives of the Adaptation Plan

The LIFE-FROSTDEFEND Adaptation Plan (Figure 3) provides a structured framework of guidelines, measures, and strategic actions designed to reduce the impacts of frost events on agricultural production and strengthen the climate resilience of frost-sensitive cropping systems. The plan supports the implementation of climate adaptation policies in Greece and France, while promoting sustainable, practical, and cost-effective approaches to frost-risk management at both local and regional levels.

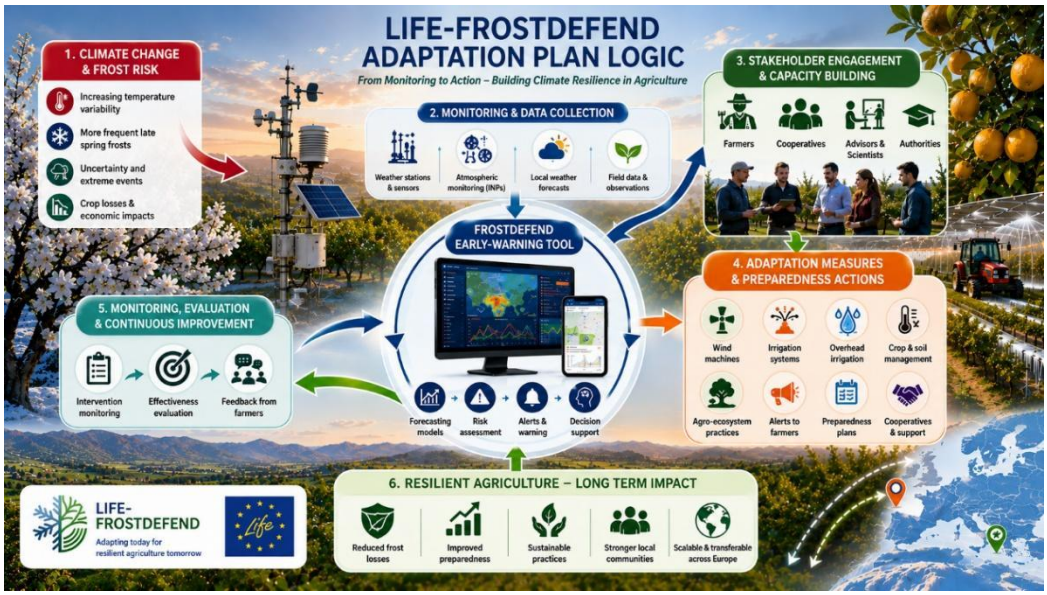


Figure 3. Conceptual framework of the LIFE-FROSTDEFEND Adaptation Plan

The LIFE-FROSTDEFEND Adaptation Plan aims to reduce frost-related crop losses by strengthening preparedness, monitoring, early warning, and response capacity. Frost events can cause substantial economic damage, particularly in citrus-producing areas where flowering and fruit-setting stages are highly sensitive to low temperatures. The plan therefore supports timely interventions, improved risk awareness, and more informed decision-making among farmers and agricultural stakeholders.

A central component of the plan is the FROSTDEFEND early-warning and decision-support tool, which provides timely information on frost risk and assists users in selecting appropriate protection measures based on weather forecasts, local environmental conditions, crop sensitivity, and phenological stage. Monitoring modules and farmer-feedback mechanisms support the continuous refinement of the tool and improve the reliability of adaptation planning.

The plan also promotes cost-effective and environmentally sustainable frost-protection practices. Conventional measures, such as heaters and wind machines, may involve high operating costs, substantial energy consumption, and increased greenhouse gas emissions. LIFE-FROSTDEFEND therefore supports more targeted interventions that optimize the timing and selection of protection measures, reduce unnecessary applications, and limit environmental impacts. These may include the appropriate use of copper-based products to reduce populations of ice-nucleation-active bacteria and their ice-nucleation activity. The project also improves understanding of the roles of atmospheric pollutants, ice-nucleating particles, and epiphytic bacteria in frost formation.

In the longer term, the adaptation framework seeks to strengthen the economic viability and climate resilience of frost-sensitive perennial cropping systems, including the potential re-establishment of lemon orchards abandoned following repeated frost damage. It also supports the wider replication of project outcomes by identifying measures that can be transferred to other frost-prone regions and crop types. This includes the dissemination of best practices, support for agricultural advisory and insurance services, and the integration of frost-risk management into broader climate adaptation planning.

Overall, the LIFE-FROSTDEFEND Adaptation Plan provides an integrated framework for reducing frost damage, improving resource efficiency, and strengthening the long-term resilience of vulnerable agricultural systems.

2. Policy and Strategic Framework

2.1 EU and National Adaptation Policies

Climate change adaptation is a central priority of the European and national policies, particularly for sectors such as agriculture that are directly exposed to climatic

variability and extreme weather events. Frost events, including late spring frosts, represent a significant climate-related risk for fruit production, as they can cause severe damage during sensitive phenological stages such as flowering, fruit setting and early fruit development. The LIFE-FROSTDEFEND Adaptation Plan is therefore positioned within the wider European and national policy framework for climate resilience, risk prevention, sustainable agriculture and informed decision-making.

At the EU level, the main policy reference is the new EU Strategy on Adaptation to Climate Change, adopted by the European Commission in 2021. The Strategy sets the objective of making adaptation "smarter, faster and more systemic", while strengthening international action for climate resilience. It emphasizes improved climate-risk knowledge, better use of data and digital tools, integration of adaptation across policy sectors, and the need to reduce climate-related economic losses. These priorities are directly relevant to LIFE-FROSTDEFEND, which combines monitoring, early warning, decision support and practical adaptation measures for frost-sensitive crops (European Commission, 2021). The project also supports the objectives of the European Climate Law, which establishes the EU's legally binding objective of climate neutrality and recognizes adaptation as a necessary pillar of climate action. The Climate Law highlights that adaptation progress across Europe remains uneven among sectors and regions and emphasizes the need for improved resilience and preparedness (European Commission, 2021a). LIFE-FROSTDEFEND contributes to addressing this gap by translating adaptation policy into practical agricultural tools and region-specific adaptation measures. The Common Agricultural Policy (CAP) 2023–2027 is also highly relevant, as CAP Strategic Plans aim to support a smart, resilient and diversified agricultural sector while strengthening climate action, environmental protection and sustainable rural development (European Commission, 2023). The LIFE-FROSTDEFEND approach is fully aligned with these priorities since it promotes climate-smart agriculture, sustainable frost protection practices, farmer advisory support and improved adaptive capacity through technological innovation.

In Greece, the principal policy framework is the National Adaptation Strategy (NAS), which establishes the national framework for adaptation planning and implementation. The strategy recognizes agriculture as one of the most climate-sensitive sectors due to its dependence on weather conditions, water availability and exposure to extreme climatic events among others. The Greek adaptation framework emphasizes the need for preventive planning, scientific monitoring, stakeholder participation and improved management of climate-related risks (MEEN, 2016). The LIFE-FROSTDEFEND Adaptation Plan is also aligned with the Regional Adaptation Action Plans (RAAPs) implemented across the 13 Greek regions, including Western Greece and the Region of the Peloponnese. These regional plans identify climate-related vulnerabilities and adaptation priorities for agriculture and promote measures that enhance local resilience and preparedness against climate hazards, including frost events.

In France, climate adaptation policy is primarily implemented through the third National Climate Change Adaptation Plan (PNACC-3). The French adaptation framework aims to strengthen the resilience of territories, economic sectors and infrastructure to climate change impacts while improving the integration of adaptation into local and sectoral planning (French Ministry for Ecological Transition, 2025). Agriculture is identified as a strategic sector requiring improved climate preparedness, risk reduction measures and sustainable management practices.

Within this broader policy context, LIFE-FROSTDEFEND contributes directly to agricultural climate resilience by addressing frost risks through an integrated adaptation approach. The project supports the transition from reactive and energy-intensive frost protection practices towards preventive, data-driven and environmentally sustainable solutions. Through the use of monitoring systems, early-warning tools, stakeholder engagement and continuous evaluation mechanisms, the project contributes to the implementation of European and national climate adaptation objectives.

2.2 Relation to Climate Mitigation Policies

Although the LIFE-FROSTDEFEND Adaptation Plan primarily focuses on climate adaptation and frost-risk resilience, the proposed framework also contributes significantly to the broader climate mitigation objectives at European and national levels. The project promotes environmentally sustainable agricultural practices, improved energy efficiency and reduction of greenhouse gas emissions associated with conventional frost protection methods. Through the optimization of frost protection interventions and the promotion of data-driven operational practices, LIFE-FROSTDEFEND supports the transition towards lower-emission and climate-smart agricultural systems.

At European level, the European Green Deal constitutes the central policy framework guiding the transition towards a climate-neutral and resource-efficient economy. The European Green Deal aims to achieve climate neutrality by 2050 while promoting sustainable agriculture, biodiversity protection, circular economy principles and reduced greenhouse gas emissions across all economic sectors (European Commission, 2019). Agriculture is recognized as a key sector both affected by climate change and contributing to climate mitigation efforts. LIFE-FROSTDEFEND contributes to these objectives by promoting more efficient frost protection practices capable of reducing unnecessary fuel consumption, energy use and associated emissions. The project is also aligned with the objectives of the “Farm to Fork Strategy”, which forms part of the European Green Deal and promotes the transition towards fair, healthy and environmentally friendly food systems (European Commission, 2020). The Strategy emphasizes sustainable agricultural production, reduced environmental impacts, efficient resource management and increased resilience of agricultural systems under climate change conditions. LIFE-FROSTDEFEND supports these priorities through the

development of operational tools that encourage targeted interventions, optimized use of agricultural inputs and reduction of environmentally intensive protection practices.

The Greek National Energy and Climate Plan (NECP) also promotes sustainable development, emission reductions and strengthening of climate resilience across economic sectors, including agriculture (MEEN, 2019). The LIFE-FROSTDEFEND framework supports these objectives by promoting:

- efficient resource management;
- reduced operational energy demand;
- sustainable agricultural adaptation practices;
- improved climate-risk preparedness.

In France, mitigation policy is implemented through the National Low-Carbon Strategy (SNBC), which constitutes the country's roadmap for reducing greenhouse gas emissions and achieving carbon neutrality by 2050 (French Ministry for Ecological Transition, 2020). The SNBC identifies agriculture as an important sector for both mitigation and climate resilience, emphasizing sustainable agricultural practices, reduced energy use and improved environmental performance. LIFE-FROSTDEFEND contributes to these priorities through the optimization of frost protection practices and promotion of lower-emission operational approaches.

Overall, LIFE-FROSTDEFEND contributes to climate change mitigation by optimizing frost-protection interventions and reducing unnecessary applications and operational activities. The project promotes lower-emission agricultural management practices by minimizing avoidable fuel consumption, reducing excessive spraying, and supporting the more efficient use of energy, water, and labour resources.

Specifically, the project contributes indirectly to climate mitigation through:

• reducing unnecessary fuel consumption associated with conventional frost-protection methods, such as heaters and wind machines;

• optimizing the timing and frequency of frost-protection interventions;

• improving the operational efficiency of agricultural management practices;

• promoting low-emission and environmentally sustainable adaptation measures; and

• strengthening climate-smart agricultural management and decision-making.

In addition, the environmental performance of frost-protection strategies may be assessed by estimating the CO_2 emissions associated with different intervention methods, such as wind machines, spraying systems, and heaters. Operational data,

including the type, timing, duration, and frequency of interventions, can support offline comparisons between optimized and conventional practices, providing an indication of potential emission reductions and informing the selection of more sustainable frost-management measures.

Lastly, LIFE-FROSTDEFEND demonstrates the strong interconnection between climate adaptation and mitigation policies within the agricultural sector. The project supports a transition towards more resilient, efficient and environmentally sustainable agricultural systems capable of addressing both current and future climate-related challenges while contributing to broader European and national climate objectives.

2.3 Relevance to Existing Plans and Policies

The LIFE-FROSTDEFEND Adaptation Plan has been designed to complement and support existing adaptation frameworks and sectoral policies at European, national and regional levels. Its primary added value lies in translating strategic adaptation priorities into practical tools, operational measures and farm-level guidance specifically targeting frost-related risks in agriculture. This plan is fully consistent with the structure and objectives of existing climate adaptation plans, particularly regarding vulnerability assessment, risk analysis, stakeholder participation, monitoring procedures and periodic review mechanisms. These components are considered essential elements of adaptation planning within EU and national policy frameworks

In Greece, the adaptation plan supports the implementation priorities of the Regional Adaptation Plans of Western Greece and the Peloponnese by focusing on one of the most climate-sensitive sectors in these regions, namely agriculture. The selected pilot and replication areas are characterized by significant citrus and fruit-tree cultivation, which are highly vulnerable to frost incidents. By providing operational guidance and improved preparedness tools, LIFE-FROSTDEFEND strengthens the regional capacity to address climate-related agricultural risks.

Similarly, in France, the replication activities in Puy-de-Dôme support the territorial and sectoral objectives of the French adaptation framework by testing adaptation measures under different climatic and agricultural conditions. This contributes to the broader national objective of strengthening the resilience of agricultural production systems to climate variability and extreme weather events. The adaptation plan also creates important synergies with agricultural risk management and insurance mechanisms. Climate-related losses in agriculture are increasingly affecting farm income stability and agricultural sustainability across Europe. European policy discussions emphasize the importance of strengthening risk-management instruments, insurance schemes and preventive adaptation actions in order to reduce vulnerability and improve resilience (EU CAP Network, 2024).

In Greece, the Hellenic Agricultural Insurance Organization (ELGA) plays a key role in compensating farmers for climate-related damages, including frost-related crop losses. The LIFE-FROSTDEFEND project may support such mechanisms by improving the availability and quality of frost-risk information, intervention records and crop-loss data. The systematic monitoring of frost incidents, protection measures and farmer feedback can contribute to improved risk assessment procedures, advisory support and evidence-based policy development. In addition, the project contributes to environmental and climate policy objectives through the promotion of more targeted and efficient frost protection practices. Conventional protection methods such as heaters and wind machines are often associated with high energy consumption, operational costs and greenhouse gas emissions. The FROSTDEFEND tool aims to optimize intervention timing and improve decision-making, thereby reducing unnecessary applications and promoting lower-emission adaptation practices.

3. Methodological Approach

3.1 Data Collection and Analysis

The methodological framework of the LIFE-FROSTDEFEND Adaptation Plan has been developed in accordance with the overall logic, operational objectives and scientific approach of the LIFE-FROSTDEFEND project, integrating climate science, agricultural vulnerability assessment, operational monitoring and stakeholder participation into a unified adaptation-planning framework. The methodology follows the principles of evidence-based climate adaptation and combines climatic, environmental, agricultural and socioeconomic information in order to support operational frost-risk management and long-term resilience of frost-sensitive agricultural systems. The approach is fully aligned with the objectives of the LIFE Programme regarding demonstration, operational applicability, transferability and policy integration.

The methodological approach combines quantitative and qualitative assessment methods and incorporates:

- climate and frost-risk analysis,
- agricultural vulnerability assessment,
- operational monitoring and forecasting,
- stakeholder engagement and participatory consultation,
- evaluation of adaptation practices,
- integration of scientific and field-level observations.

Particular emphasis is placed on the interaction between climatic variability, frost occurrence, crop phenology and agricultural vulnerability within the pilot and replication areas of Greece and France.

Climate and Frost-Event Data

A core component of the methodological framework concerns the collection, analysis and interpretation of climatic and frost-related data associated with frost occurrence, seasonal variability and agricultural exposure. The analysis incorporates both historical climatic information and real-time operational monitoring data in order to evaluate frost-risk conditions and support the development of localized adaptation measures.

The assessment includes:

- historical meteorological observations,
- minimum and maximum temperature records,
- occurrence of severe frost events,
- late spring frost episodes,
- local topographical and geomorphological characteristics influencing frost formation.

The methodological approach further considers the increasing climatic variability associated with climate change, including shifts in seasonal temperature patterns and earlier flowering periods that may increase crop exposure to late frost events.

Meteorological and environmental information is obtained through:

- local monitoring stations;
- regional and national meteorological services;
- Copernicus Climate Change Service/ECMWF (ERA5-Land datasets);
- project monitoring infrastructure;
- field observations and operational records.

The LIFE-FROSTDEFEND framework also incorporates atmospheric and environmental monitoring associated with the role of atmospheric pollutants and ice nucleation active (INA) bacteria in frost formation processes. This component represents one of the innovative scientific dimensions of the project because it links atmospheric environmental conditions with agricultural frost-risk assessment and operational preparedness.

A major scientific innovation of LIFE-FROSTDEFEND concerns the integration of meteorological, phenological and biological parameters into frost-risk assessment and operational forecasting procedures. Particular emphasis is placed on the role of epiphytic ice-nucleation-active (INA) bacteria colonizing leaves, flowers and young plant tissues. Scientific evidence indicates that such microorganisms may catalyze heterogeneous ice nucleation at relatively mild sub-zero temperatures, thereby

increasing frost susceptibility before crops reach their physiological freezing thresholds.

The collected climatic information supports:

- frost-risk characterization,
- identification of vulnerable agricultural zones,
- calibration of operational forecasting thresholds,
- evaluation of adaptation effectiveness,
- development of localized preparedness measures.

Agricultural and Crop-Related Data

The methodological framework additionally incorporates extensive agricultural and crop-related data collection focusing on frost-sensitive cultivation systems within the pilot and replication regions.

The analysis focuses primarily on:

- lemon cultivation,
- orange cultivation,
- additional citrus species,
- apricots,
- pears,
- grapes and other perennial cultivations exposed to frost-related risks.

Agricultural information includes:

- crop distribution and cultivation characteristics,
- phenological stages,
- historical crop-damage records,
- crop-specific frost sensitivity thresholds,
- frost protection practices,
- operational management procedures,
- characteristics of agricultural holdings and production systems.

Particular emphasis is placed on the assessment of crop phenology because frost sensitivity varies significantly according to the developmental stage of the crop. Earlier flowering induced by warmer winter conditions may substantially increase vulnerability to late frost events despite long-term increases in average temperature. This phenomenon has been identified as one of the major emerging climate risks for perennial Mediterranean crops and constitutes a key parameter within the LIFE-FROSTDEFEND assessment framework.

The methodology also incorporates operational observations associated with frost protection practices currently applied by farmers, including:

- activation timing of frost protection measures,
- spraying practices,
- use of heaters and wind machines,
- operational costs and limitations,
- environmental implications of interventions,
- effectiveness of adaptation measures under different frost conditions.

Field observations and seasonal monitoring activities support the evaluation of adaptation effectiveness and contribute to the refinement of operational recommendations and preparedness protocols.

Literature Review and Stakeholder Consultation

The methodological framework is additionally supported by an extensive review of scientific literature, European and national policy documents, adaptation strategies and technical reports related to climate change adaptation, frost-risk management and agricultural resilience.

The literature review focused on:

- climate change impacts on Mediterranean agriculture,
- frost-risk assessment methodologies,
- crop vulnerability and phenological shifts,
- operational forecasting systems,
- agricultural adaptation practices,
- ecosystem-based adaptation,
- climate resilience and climate-smart agriculture.

The review incorporated:

- IPCC assessment reports,
- EU adaptation policy documents,
- Regional Climate Change Adaptation Plans (PeSPKA),
- National Adaptation Strategies,
- scientific publications and technical guidelines,
- LIFE Programme documentation and project deliverables.

The methodological approach also incorporates participatory consultation procedures involving farmers, cooperatives, scientific institutions, advisory services and competent authorities. Stakeholder participation supports the integration of local knowledge and

operational experience into the adaptation-planning process and improves the practical applicability of the proposed framework.

3.2 Stakeholder Engagement

Stakeholder engagement constitutes a central methodological pillar of the LIFE-FROSTDEFEND Adaptation Plan and is integrated throughout all implementation phases of the project. The project recognizes that effective climate adaptation in agriculture cannot rely exclusively on technological tools and scientific monitoring but also requires active participation, cooperation and long-term engagement among all actors involved in agricultural production, advisory support, climate adaptation and environmental governance.

The stakeholder engagement framework follows a participatory and multi-level approach aiming to:

- strengthen communication and cooperation among stakeholders,
- improve awareness regarding frost-related climate risks,
- support operational preparedness and behavioral change,
- facilitate dissemination of best practices,
- strengthen local ownership of adaptation measures,
- improve long-term sustainability and transferability of project results.

Surveys and Questionnaires

Structured surveys and questionnaires were developed and implemented in order to collect information regarding:

- historical frost damages,
- existing frost protection practices,
- operational preparedness,
- farmer perceptions regarding climate risks,
- adaptation needs and constraints,
- effectiveness and costs of current protection methods,
- willingness to adopt innovative operational tools.

The surveys targeted farmers, cooperatives, agricultural advisors and local stakeholders within the pilot and replication areas and provided important information regarding the practical realities of frost-risk management at farm level. The collected information contributes to the refinement of operational recommendations and supports the development of adaptation measures better aligned with local agricultural conditions and stakeholder needs.

Farmer and Cooperative Consultations

Direct consultation with farmers, agronomists-farm advisors and agricultural cooperatives represents one of the most important components of the stakeholder engagement process. Workshops, technical meetings, field visits and participatory consultation activities were organized within the pilot and replication regions in order to facilitate knowledge exchange and improve operational understanding of frost-risk conditions. During these events, a network of farmers and farm advisors willing to participate in the LIFE FROSTDEFEND activities and adopt the proposed frost-risk management practices was established.

Farmers and cooperatives contribute through:

- provision of field observations and operational experience,
- participation in pilot implementation activities,
- evaluation of adaptation practices,
- feedback regarding forecasting performance and warning systems,
- identification of local climatic particularities and operational challenges.

Agricultural cooperatives and farm advisors additionally act as key intermediaries supporting communication between scientific partners and producers while facilitating dissemination of operational guidance and adaptation recommendations.

The participatory nature of the LIFE-FROSTDEFEND framework allows continuous refinement of adaptation measures according to:

- local experience,
- operational feasibility,
- climatic conditions,
- stakeholder priorities and expectations.

Consultation with Competent Authorities

The Adaptation Plan is intended to support implementation of national and regional climate adaptation strategies and may contribute to future integration of operational frost-risk management methodologies into agricultural planning, advisory mechanisms and agricultural insurance systems in Greece and France. The methodological framework additionally incorporates consultation with competent authorities and institutional stakeholders responsible for climate adaptation, agriculture, environmental management and agricultural risk assessment.

Relevant authorities and institutions include:

- Ministry of Environment and Energy of Greece,
- Ministry of Rural Development and Food,
- local and regional authorities,
- agricultural advisory bodies,
- Hellenic Agricultural Insurance Organization (ELGA),
- French agricultural and climate authorities.

Consultation with competent authorities supports:

- alignment of the adaptation framework with existing policy priorities,
- integration of project outputs into adaptation and resilience planning,
- strengthening of policy uptake and institutional cooperation,
- improvement of long-term transferability and operational continuity.

Overall, the methodological approach of LIFE-FROSTDEFEND combines scientific assessment, operational monitoring and participatory stakeholder engagement into an integrated adaptation framework capable of supporting evidence-based frost-risk management and long-term climate resilience of vulnerable agricultural systems in Greece and France.

4. Baseline Assessment

4.1 Climate and Frost Trends

The Mediterranean basin is considered one of the global climate change hotspots, with increasing exposure to temperature variability, extreme weather events and hydrological stress. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Southern Europe and the Mediterranean region are expected to experience significant climatic changes, including increasing mean temperatures, prolonged heatwaves, changing precipitation patterns and higher climatic instability (IPCC, 2022). Although average temperatures are projected to rise, recent scientific evidence indicates that frost events will continue to represent a major threat for agriculture, particularly due to changes in crop phenology and the occurrence of atypical cold spells during sensitive developmental stages.

The Greek National Adaptation Strategy identifies agriculture as one of the sectors with the highest vulnerability to climate change because of its direct dependence on meteorological conditions, water availability and temperature stability (MEEN, 2016). The Strategy highlights that increasing climate variability may intensify risks associated with extreme weather events, including frost, drought and heat stress. The Regional Climate Change Adaptation Plan (PEPCCA) of Western Greece, identifies the agricultural sector as a critical component of the regional economy and one of the most climate-sensitive sectors in the Region. According to the Plan, Western Greece is

expected to experience increasing average temperatures, reduction in annual precipitation and changes in seasonal climatic conditions, with direct implications for agricultural productivity (Region of Western Greece, 2021). The Plan further notes that although the overall number of frost days may decrease in the long term, the occurrence of late frost events following unusually warm winter periods may increase crop vulnerability, especially for perennial cultivations.

The pilot area of Achaia, particularly the wider area of Aigio, presents climatic conditions characterized by mild and relatively humid winters, warm summers and strong agricultural dependence on citrus cultivation. The area is exposed to radiative frost conditions during periods of atmospheric stability and low wind intensity, particularly in inland and low-altitude agricultural zones where cold-air accumulation may occur. The Regional Adaptation Plan highlights that citrus cultivation in Achaia is particularly vulnerable to abrupt temperature fluctuations and frost events occurring during flowering and fruit-setting periods. The PEPCCA also identifies increasing climate uncertainty as a major challenge for agricultural planning and emphasizes the need for operational adaptation measures, improved monitoring systems and climate-risk early-warning mechanisms. The LIFE FROSTDEFEND project directly contributes to these regional priorities through the development of a frost-risk monitoring and decision-support system specifically adapted to local agricultural conditions.

In the Region of Peloponnese, the PEPCCA identifies agriculture as one of the sectors with very high climate sensitivity due to the economic importance of citrus crops, olive cultivation and horticultural production (Region of Peloponnese, 2022). The Plan emphasizes that climate change is expected to alter the frequency and intensity of extreme weather events, including frost episodes affecting lowland and semi-mountainous agricultural areas. The replication area of Argolida, particularly the Argos plain, is characterized by intensive citrus cultivation and irrigated agricultural systems. The Regional Adaptation Plan notes that local climatic conditions, including thermal inversions and cold-air accumulation phenomena, may increase frost exposure in specific cultivation zones. Orange and lemon orchards are considered highly sensitive due to their dependence on stable winter and spring temperatures. Similarly, the area of Laconia, with implementation activities around Sparti, experiences significant local climatic variability associated with topographical influences and cold-air movement from surrounding mountainous areas. The Eurotas valley and adjacent agricultural zones may experience radiative frost episodes under conditions of atmospheric stability. The Regional Adaptation Plan of Peloponnese specifically highlights the vulnerability of perennial crops in lowland areas exposed to abrupt temperature drops and changing climatic conditions.

The French replication area in Puy-de-Dôme, within the Auvergne-Rhône-Alpes Region, is characterized by continental climatic influences and significant temperature

variability between winter and spring periods. Agricultural systems in the region, including fruit cultivation and vineyards, are periodically exposed to damaging spring frost events. French climate adaptation policies identify agriculture as a sector requiring enhanced resilience due to increasing climatic instability and extreme weather risks (French Ministry for Ecological Transition, 2025).

Climate projections for Southern Europe suggest that average temperatures will continue to rise during the coming decades; however, climate variability and changes in seasonal dynamics may increase frost-related risks for sensitive crops. Earlier flowering caused by warmer winter temperatures may expose crops to frost damage even under conditions of decreasing annual frost frequency (EEA, 2024). Consequently, future frost risk is increasingly linked to phenological sensitivity, timing of frost occurrence and the adaptive capacity of agricultural systems.

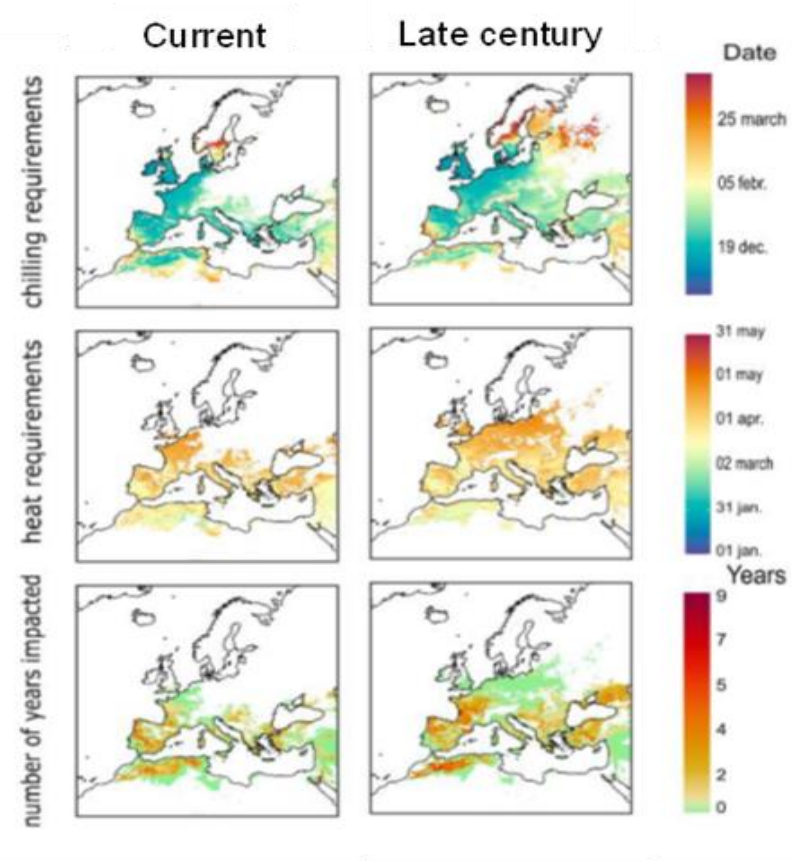


Figure 4. Spatial distribution of projected phenological and frost-related risks for fruit crops across Europe under current and late-century climatic conditions. The upper panels show the estimated date on which chilling requirements are fulfilled, the middle panels indicate the date of heat-requirement fulfilment, and the lower panels show the projected number of years affected by adverse phenological or frost conditions. Late-century projections suggest delayed chilling fulfilment in southern Europe, earlier heat accumulation in several regions, and a geographical redistribution of frost and phenological risks across European fruit-growing areas (Jorant et al., publication in preparation).

Figure 4 illustrates projected changes in the fulfilment of chilling and heat requirements, together with the frequency of years affected by frost or phenological constraints, under current and late-century climatic conditions. Under the current climate, chilling requirements are generally fulfilled during winter across most European fruit-growing regions. By the end of the century, warmer winters are expected to delay chilling fulfilment, particularly in southern and Mediterranean Europe, increasing the risk of insufficient chilling, delayed or irregular endodormancy release, and associated phenological disorders.

At the same time, warmer conditions may advance the fulfilment of heat requirements and expand the potential climatic suitability for fruit production towards parts of northern and eastern Europe. However, earlier phenological development may also increase crop exposure to late-spring frost, especially in parts of western and central Europe. The projected number of affected years therefore indicates a redistribution, rather than a uniform reduction, of climate-related risks. While frost constraints may decline in some areas, risks associated with insufficient winter chilling or post-budbreak frost may persist or emerge elsewhere.

These projections highlight the need for crop- and location-specific adaptation measures that account for both frost exposure and changing chilling and heat accumulation patterns when assessing future fruit-production suitability and planning frost-risk management strategies (Jorant et al., in preparation).

4.2 Agricultural Profile of the Target Areas

The pilot and replication areas included in the LIFE FROSTDEFEND project are characterized by strong agricultural specialization, high dependence on perennial cultivations and significant exposure to climate-related risks affecting agricultural productivity and rural economies. Agriculture constitutes one of the most important productive sectors in all participating regions, contributing substantially to local employment, agri-food production, exports and socioeconomic cohesion. The selected implementation areas were specifically chosen due to their agricultural importance, the presence of frost-sensitive crops and their increasing exposure to climatic variability and frost-related hazards under changing climate conditions.

Within the Region of Western Greece, and particularly in the Regional Unit of Achaia, agriculture represents a major pillar of regional economic activity. According to the Regional Climate Change Adaptation Plan (PeSPKA) of Western Greece, the agricultural sector contributes significantly to regional gross value added, rural employment and export-oriented agri-food activities, while simultaneously presenting elevated vulnerability to climate-related pressures including droughts, heatwaves, temperature variability and frost events. Citrus cultivation, olive groves, vineyards and horticultural crops dominate agricultural production systems throughout the Region, with citrus cultivation holding particular strategic importance for local agricultural income and export activity.

The pilot area of Aigio in Achaia is historically associated with intensive lemon cultivation and citrus production. The area benefits from favorable Mediterranean climatic conditions, fertile soils, adequate solar radiation and suitable geomorphological characteristics that support high agricultural productivity. Lemon orchards constitute one of the dominant agricultural activities of the area and are closely connected with local producer organizations, agricultural cooperatives, packing and processing facilities and export-oriented commercial activities. The agricultural economy of the wider Aigialeia region therefore depends significantly on the stability and productivity of citrus cultivation systems. Despite these favorable agroclimatic conditions, citrus production in Achaia remains highly vulnerable to climatic instability and frost-related risks. The Regional Adaptation Plan identifies perennial cultivations, particularly citrus species, among the crops presenting elevated climate sensitivity due to their dependence on stable winter and spring temperatures and their vulnerability during flowering and fruit-setting periods. Even relatively short-duration frost events may result in substantial reductions in productivity, deterioration of fruit quality and long-term damage to tree vitality. This vulnerability is intensified by the increasing climatic variability observed across Mediterranean regions, where warmer winter conditions may accelerate crop phenology and expose flowering crops to late frost events.

The agricultural structure of Achaia is additionally characterized by fragmented farm holdings, mixed cultivation systems and heterogeneous levels of technological modernization and adaptive capacity. Many farms remain small or medium-sized family agricultural holdings with varying access to operational forecasting tools, climate information systems and frost-protection infrastructure. These structural characteristics increase the importance of localized advisory support, climate services and operational early-warning systems capable of supporting informed farmer decision-making under uncertain climatic conditions. The LIFE-FROSTDEFEND framework therefore addresses not only physical climate vulnerability but also operational and institutional adaptation needs at local level.

The replication area of Argolida, within the Region of Peloponnese, constitutes one of the most productive and economically important citrus cultivation zones in Greece. The Argos plain supports extensive orange and lemon orchards largely based on irrigated agriculture and export-oriented production systems. According to the Regional Climate Change Adaptation Plan of Peloponnese, citrus production in Argolida faces increasing climate-related pressures associated with:

- water scarcity,
- changing precipitation patterns,
- increasing climatic variability,
- temperature fluctuations,
- frost-related hazards affecting perennial crops.

The concentration of citrus production in lowland agricultural areas significantly increases exposure to radiative frost phenomena and cold-air accumulation under specific meteorological conditions. Local topographical characteristics, restricted air circulation and thermal inversions may create localized frost-prone zones capable of causing severe crop damage despite generally mild regional climatic conditions. The Regional Adaptation Plan therefore highlights the need for improved preparedness, operational monitoring systems and targeted adaptation measures for vulnerable agricultural systems. Laconia, with implementation activities focused around the wider Sparti and Eurotas valley area, also supports highly important agricultural production systems including citrus fruits, olive groves, horticultural crops and irrigated perennial cultivations. Agricultural activity in the region is strongly influenced by local topography, geomorphological conditions and climatic variability associated with surrounding mountainous zones. The Eurotas basin constitutes a major agricultural zone where low-altitude cultivation areas may experience cold-air accumulation and radiative frost formation during winter and early spring periods.

The Regional Climate Change Adaptation Plan of Peloponnese identifies the agricultural systems of Laconia as particularly sensitive to climate-related hazards due to:

- dependence on temperature-sensitive crops,
- exposure to abrupt temperature declines,
- increasing occurrence of climatic extremes,
- sensitivity of irrigated production systems,
- long-term pressures associated with climate variability.

Citrus cultivation in Laconia may therefore experience significant frost-related impacts during periods of atmospheric stability and low wind intensity, particularly during critical phenological stages. The increasing variability of winter and spring temperatures further intensifies uncertainty regarding agricultural planning and crop management.

The French replication area in Puy-de-Dôme, located within the Auvergne-Rhône-Alpes Region, presents a substantially different agroclimatic context compared to the Mediterranean pilot regions of Greece. Agricultural systems in the region include vineyards, fruit-tree cultivations, mixed farming systems and agricultural landscapes periodically exposed to spring frost episodes and continental climatic influences. The inclusion of the French replication area significantly strengthens the transnational and transferability dimension of LIFE-FROSTDEFEND because it enables evaluation of adaptation methodologies under different climatic regimes, crop systems and operational conditions.

The region experiences strong seasonal temperature variability and recurrent spring frost episodes capable of affecting vineyards and fruit cultivations during flowering and vegetative development periods. The French implementation activities therefore contribute to assessing the adaptability and operational applicability of the LIFE-FROSTDEFEND framework beyond Mediterranean climatic conditions and strengthen the European demonstration value of the project.

The mapping and characterization of frost-sensitive crops are central components of the LIFE-FROSTDEFEND adaptation methodology. The project focuses primarily on citrus and temperate fruit crops that are frequently exposed to frost-related risks. These crops are mainly cultivated in lowland and coastal agricultural areas, where generally mild winter conditions favor perennial Mediterranean agriculture, but occasional frost events can cause severe economic and environmental impacts.

Crop vulnerability is strongly influenced by:

- altitude,
- slope orientation,
- proximity to the sea,
- local air circulation patterns,
- topographical depressions,
- thermal inversion conditions,
- phenological timing.

Agricultural areas characterized by restricted air movement and cold-air accumulation present particularly high susceptibility to radiative frost formation and therefore require enhanced monitoring and preparedness measures.

The agricultural characteristics (Figure 5) of the participating regions clearly demonstrate the necessity for integrated frost-risk management approaches combining:

- localized climate monitoring,
- operational forecasting systems,
- early-warning mechanisms,
- sustainable frost-protection practices,
- stakeholder engagement,
- continuous monitoring and adaptation planning.

Within this context, LIFE-FROSTDEFEND contributes to strengthening agricultural resilience and climate preparedness by providing a scientifically robust and operationally applicable framework capable of supporting vulnerable agricultural systems under increasing climatic uncertainty and evolving frost-risk conditions.

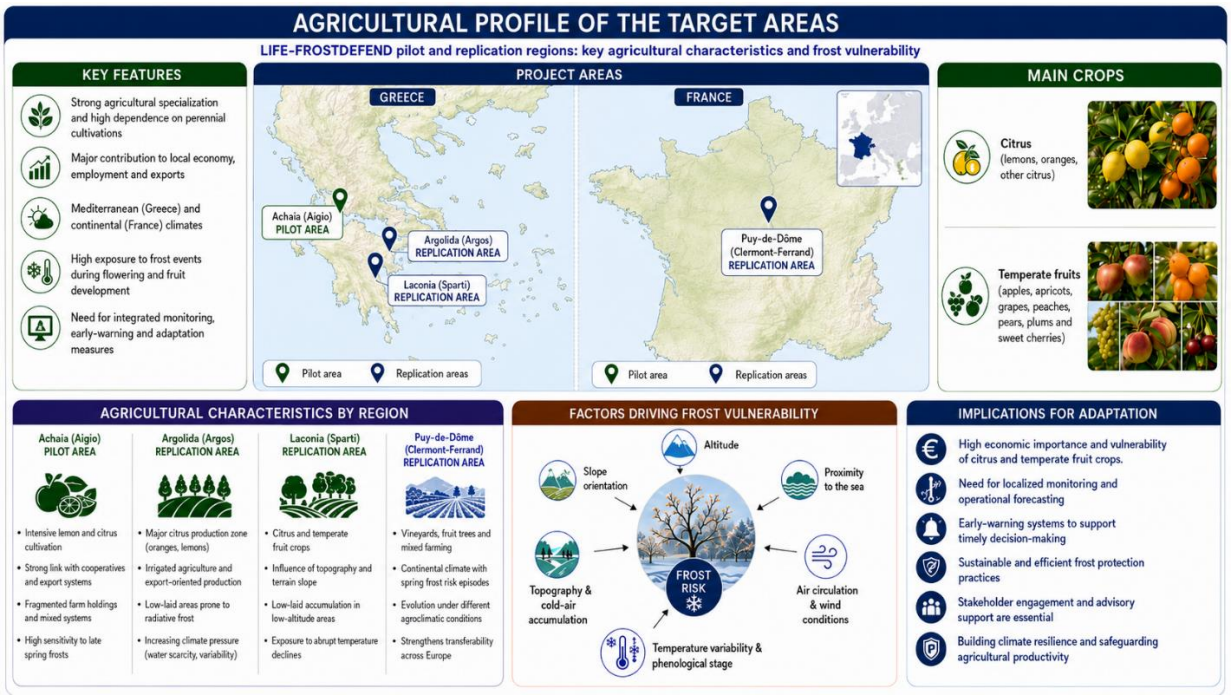


Figure 5. Agricultural profiles of the target areas

5. Vulnerability and Risk Assessment

The vulnerability assessment developed within the framework of the LIFE FROSTDEFEND Adaptation Plan follows the conceptual framework proposed by the Intergovernmental Panel on Climate Change (IPCC AR6), according to which vulnerability is determined by the combined interaction of exposure, sensitivity and adaptive capacity (IPCC, 2022). The methodological structure is additionally aligned with:

- the European Commission Guidelines on Climate Resilience and Climate Proofing of Infrastructure (European Commission, 2021),
- the methodologies applied within the Greek Climate Resilience Documentation Reports ("Εκθέσεις Τεκμηρίωσης Κλιματικής Ανθεκτικότητας Έργων"),
- the methodological guidance of the Adaptation Hub of Greece (Climate-ADAPT Greece / AdaptiveGreece),
- the Regional Climate Change Adaptation Plans (PeSPKA) of Western Greece and Peloponnese.

The assessment framework adopts a sector-specific and spatially differentiated approach appropriate for agricultural systems exposed to frost-related climatic risks. Particular emphasis is placed on perennial Mediterranean cultivations characterized by high sensitivity to abrupt temperature variability and late frost events.

The vulnerability assessment focuses on the pilot and replication regions of the LIFE-FROSTDEFEND project:

- Achaia (Aigio) – Region of Western Greece,
- Argolida (Argos) – Region of Peloponnese,
- Laconia (Sparti) – Region of Peloponnese,
- Puy-de-Dôme (Clermont-Ferrand) – Auvergne-Rhône-Alpes Region, France.

The assessment primarily concerns citrus cultivation systems, particularly lemon orchards, which present very high sensitivity to frost conditions during flowering and fruit-setting stages. Additional frost-sensitive perennial cultivations including oranges, apricots, pears and vineyards are also assessed in order to support the transferability and replication dimensions of the project (FAO, 2023).

For the purposes of the Adaptation Plan, vulnerability is assessed qualitatively as a function of exposure, sensitivity, and adaptive capacity, as follows:

$$Vulnerability = f(Exposure, Sensitivity, Adaptive\ Capacity)$$

where:

- Exposure reflects the magnitude, frequency and spatial occurrence of frost hazards;
- Sensitivity reflects the degree to which crops and agricultural systems are affected by frost conditions;
- Adaptive Capacity reflects the ability of farmers, institutions and agricultural systems to anticipate, respond and adapt to frost-related risks.

Methodological Framework of the Vulnerability Assessment

The assessment methodology combines:

- climatic and meteorological analysis,
- agricultural vulnerability assessment,
- spatial and topographical evaluation,
- operational and socioeconomic analysis,
- stakeholder consultation and field observations.

The assessment process follows the stages presented below (Table 1):

Table 1. Assessment process

Assessment Stage	Main Parameters
Hazard Characterization	Frost frequency, minimum temperatures, severe frost events
Exposure Analysis	Spatial occurrence of frost-prone areas
Sensitivity Assessment	Crop vulnerability, phenological stages, physiological thresholds
Adaptive Capacity Assessment	Forecasting systems, preparedness, financial and institutional capacity
Vulnerability Evaluation	Combined analysis of exposure, sensitivity and adaptive capacity
Adaptation Prioritization	Identification of adaptation needs and operational measures

5.1.1 Exposure

According to the IPCC framework, exposure refers to the presence of people, livelihoods, agricultural systems and assets in places that could be adversely affected by climate hazards (IPCC, 2022). Within LIFE-FROSTDEFEND, exposure relates to the frequency, severity, timing and spatial occurrence of frost events affecting agricultural production systems.

The exposure assessment incorporates:

- historical frost-event records,
- minimum air temperature observations,
- severe frost occurrence,
- late spring frost events,
- topographical and geomorphological conditions,
- atmospheric stability and cold-air accumulation patterns.

Special attention is given to radiative frost conditions and temperature inversions occurring in lowland agricultural depressions and valley systems where cold air accumulates under stable atmospheric conditions (Vitasse et al., 2018).

The exposure indicators (Table 2) used within the assessment are presented below. It should be stressed that the exposure assessment additionally considers atmospheric and biological processes capable of influencing freezing occurrence and frost severity. Environmental conditions such as relative humidity, atmospheric stability and particulate matter concentrations may influence the abundance and activity of biological ice nucleators within the phyllosphere. Consequently, LIFE-FROSTDEFEND applies an integrated exposure assessment framework combining meteorological, environmental and biological frost-risk drivers.

Table 2. Frost Exposure Indicators

Indicator	Description	Vulnerability Relevance
Frost Days	Days with Tmin ≤ 0°C	Indicates frost frequency
Severe Frost Events	Tmin ≤ -2°C	Associated with crop damage
Late Frost Occurrence	Frost events during March–April	High impact on flowering
Absolute Minimum Temperature	Lowest recorded Tmin	Indicates severity
Duration of Frost	Hours below threshold	Influences damage intensity
Topographical Susceptibility	Valleys, depressions, lowlands	Increases cold-air accumulation

The pilot area of Achaia presents generally mild Mediterranean climatic conditions; however, localized radiative frost events occur periodically during late winter and early spring, particularly under conditions of atmospheric stability and weak wind circulation. The Regional Climate Change Adaptation Plan of Western Greece identifies citrus cultivation as highly exposed to abrupt temperature fluctuations and frost-related hazards (Region of Western Greece, 2021).

Similarly, the Argos plain in Argolida and parts of the Eurotas valley in Laconia present elevated exposure due to:

- low elevation,
- restricted air circulation,
- cold-air drainage from surrounding mountainous areas,
- frequent temperature inversions.

The French replication area of Puy-de-Dôme presents higher climatic variability and recurrent spring frost episodes associated with continental climatic influences and strong seasonal temperature fluctuations (Météo-France, 2023).

Based on the assessment results, frost exposure is classified as:

- High in principal citrus-producing zones,
- Medium–High in valley and lowland perennial cultivation systems,
- Moderate in areas with improved air circulation and reduced topographical susceptibility.

5.1.2 Sensitivity

Sensitivity refers to the degree to which crops and agricultural systems are adversely affected by frost-related climatic conditions (IPCC, 2022). Within LIFE-

FROSTDEFEND, sensitivity assessment focuses primarily on physiological crop susceptibility during critical phenological stages.

The assessment considers:

- critical temperature thresholds (Table 3),
- duration of low-temperature exposure,
- phenological timing,

Lemon cultivation is characterized by particularly high frost sensitivity (Table 4) due to:

- low tolerance to sub-zero temperatures,
- vulnerability during flowering and fruit-setting,
- susceptibility of young tissues and shoots,
- reduced recovery capacity after severe frost episodes.

Table 3. Indicative Critical Temperature Thresholds

Temperature	Indicative Impacts
-2°C to -3°C	Flower and young fruit damage
-4°C to -5°C	Significant crop losses
Below -6°C	Severe woody tissue damage

Table 4. Sensitivity Classification of Main Crops

Crop	Sensitivity Level	Main Vulnerability Factors
Lemons	High	Extremely frost-sensitive
Oranges	Medium–High	Sensitive during flowering
Apricots	High	Early flowering
Pears	Medium	Moderate tolerance
Vineyards	Medium	Vulnerable to spring frost

The assessment confirms that the highest impacts occur when frost episodes coincide with flowering and fruit-setting periods. Climatic warming may paradoxically increase sensitivity because warmer winters induce earlier flowering and vegetative development, increasing exposure to late frost episodes (Vitasse et al., 2018).

The Regional Climate Change Adaptation Plans of Western Greece and Peloponnese identify citrus cultivations among the most climate-sensitive agricultural systems due to their dependence on stable thermal conditions and vulnerability to extreme weather events (Region of Western Greece, 2021; Region of Peloponnese, 2022).

5.1.3 Adaptive Capacity

Adaptive capacity (Table 5) refers to the ability of agricultural systems, institutions and stakeholders to anticipate, prepare for and respond effectively to frost-related risks (IPCC, 2022).

The adaptive capacity assessment considers:

- availability of early-warning systems,
- access to localized climate information,
- operational preparedness,
- use of frost-protection infrastructure,
- farmer knowledge and technical expertise,
- institutional support mechanisms,
- insurance and compensation systems,
- financial capacity for implementation of adaptation measures.

Table 5. Adaptive Capacity Indicators

Indicator	Description
Forecasting Capacity	Availability of frost-warning information
Technical Preparedness	Existing protection infrastructure
Institutional Support	Advisory and cooperative support
Financial Capacity	Ability to implement measures
Knowledge and Training	Farmer awareness and expertise
Monitoring Systems	Access to operational climate data

Adaptive capacity varies significantly among regions and farm types. Although many farmers possess practical experience regarding frost protection, several limitations remain associated with:

- fragmented agricultural holdings,
- high operational costs,
- unequal access to technological tools,
- limited localized forecasting information,
- limited institutional coordination.

The Greek National Climate Change Adaptation Strategy identifies the strengthening of climate information systems, preparedness mechanisms and adaptation capacity within the agricultural sector as major adaptation priorities (MEEN, 2016).

LIFE-FROSTDEFEND contributes directly to improving adaptive capacity through:

- operational frost forecasting,
- localized early-warning services,

- real-time climate-risk information,
- farmer training and awareness raising,
- optimization of intervention timing,
- reduction of unnecessary operational measures,
- support for advisory and insurance services.

The project therefore strengthens both:

- technical adaptive capacity (forecasting, monitoring, preparedness),
- and institutional adaptive capacity (cooperation, advisory support, stakeholder engagement).

5.1.4 Overall Vulnerability Assessment

The vulnerability assessment covers four LIFE FROSTDEFEND project areas with distinct frost-risk profiles: the Aigio pilot area in Achaia, Greece, assessed for citrus cultivation, with emphasis on lemon production, across a lowland site and two higher-elevation plots; the Argolida replication area; the Laconia replication area; and Puy-de-Dôme, France, assessed for temperate fruit crops and vineyards.

The assessment follows an exposure, sensitivity, and adaptive capacity framework. Exposure refers to the occurrence, intensity, duration, and seasonal timing of frost conditions. Sensitivity refers to the degree to which crops are affected by frost during specific phenological stages. Adaptive capacity refers to the ability of farmers, institutions, and agricultural systems to anticipate, prepare for, respond to, and reduce frost-related impacts.

The frost indicators used in this section are wet-bulb temperature (Twet) for the Greek citrus-growing areas and minimum air temperature (Tmin) for Clermont-Ferrand. The assessment for Clermont-Ferrand also uses a simulated crop-specific critical temperature curve for grapevines. Wet-bulb temperature is used as an operational frost-risk indicator because it integrates air temperature and atmospheric humidity and is relevant to plant exposure and frost-protection decisions. In the interval-based figures, the temperature classes are mutually exclusive: each hour in the Greek figures and each day in the Clermont-Ferrand frost-day figure is counted only once in the applicable class.

Interpretation of temperature intervals and vulnerability classes

The same numerical temperature intervals are used across the assessment, although the temperature variable differs: Twet is used for the Greek citrus areas and Tmin for Clermont-Ferrand. The -6°C threshold defines the severe/critical exposure class used in the project. For the Greek citrus areas, Twet below -6°C is treated as the project-critical class associated with complete citrus damage in the project threshold definition; however, this assessment does not infer actual plot-level damage from temperature alone. For Puy-de-Dôme, Tmin below -6°C is used as the severe frost class for comparative exposure assessment; actual damage to grapevines and other temperate fruit crops remains dependent on crop species, cultivar, phenological stage, and exposure duration. The interval from -6°C to -2°C is interpreted as potentially damaging, but not as a high-risk category by itself. Risk increases with prolonged exposure, overlap with sensitive phenological stages, and occurrence in the -10°C to -6°C or below -10°C classes.

Temperature interval	Interpretation for vulnerability assessment
-2°C <= Twet/Tmin < 0°C	Light frost interval. Represents freezing conditions but does not, by itself, imply severe crop damage.
-6°C <= Twet/Tmin < -2°C	Potentially damaging frost interval. Effects depend on duration, crop stage, cultivar, plant tissue, local topography, and protection measures. This interval is not classified as high risk by itself.
-10°C <= Twet/Tmin < -6°C	Severe/critical frost interval. For Greek citrus, this is the project-critical exposure class associated with complete damage in the project threshold definition; actual plot-level damage is not inferred from temperature alone. For Puy-de-Dôme, the interval is used as the severe frost class for comparative exposure assessment, while crop damage remains dependent on crop species, phenological stage, and exposure duration.
Twet/Tmin < -10°C	Extreme frost interval with high potential for severe damage; actual effects depend on exposure duration, crop type, cultivar, and phenological stage.

Overall vulnerability is not assigned from temperature intervals alone. It is derived from the combined interpretation of frost exposure, crop sensitivity, adaptive capacity, and, when available, documented historical damage, including ELGA compensation records. Compensation payments are used as evidence of realized regional economic losses, not as a direct measure of frost intensity or plot-level exposure. This approach avoids assigning high vulnerability solely because crop sensitivity is high when exposure is comparatively lower or limited mainly to isolated events.

Class	Operational interpretation for exposure and overall vulnerability
Low	Limited frost occurrence and limited relevance to the assessed crop system.
Medium	Recurrent frost occurrence, but with comparatively limited duration or overlap with sensitive stages; historical impacts are limited or not consistently evident.
Medium-High	A clear frost signal and high crop sensitivity, but with less persistent or severe exposure and/or less documented damage than high-vulnerability cases.
High	Recurrent and agriculturally relevant frost exposure combined with high crop sensitivity and/or documented damaging events.
Very high	Very frequent or prolonged exposure, including repeated spring frost or recurrent severe/extreme intervals. In this assessment, the class is applied to relative exposure where the historical signal is clearly strongest, not to overall vulnerability.

Achaia - Aigio citrus cultivation

This subsection assesses citrus cultivation across three Aigio plots: the lowland citrus-producing area and two higher-elevation plots at approximately 550 and 850 m a.s.l. All three

are treated as citrus cultivation systems; their vulnerability is differentiated primarily by frost exposure.

Aigio in Achaia is an important citrus-producing area, particularly for lemon cultivation. Citrus crops are sensitive to freezing temperatures, especially when exposure persists and fruits or sensitive tissues are present. Available LIFE FROSTDEFEND project material reports a complete loss of lemon production in the wider Aigio area during the severe frost event of 2004. ELGA records also show frost-related compensation payments for citrus in Achaia in multiple years. These sources confirm significant historical impacts at the regional level, but the compensation data do not distinguish among the three Aigio plots. Plot-level exposure is therefore assessed from Figures 6-11, while the regional damage evidence is used as corroborating information. Historical meteorological data for the Greek regions were obtained from Open-Meteo.

Lowland Aigio citrus area

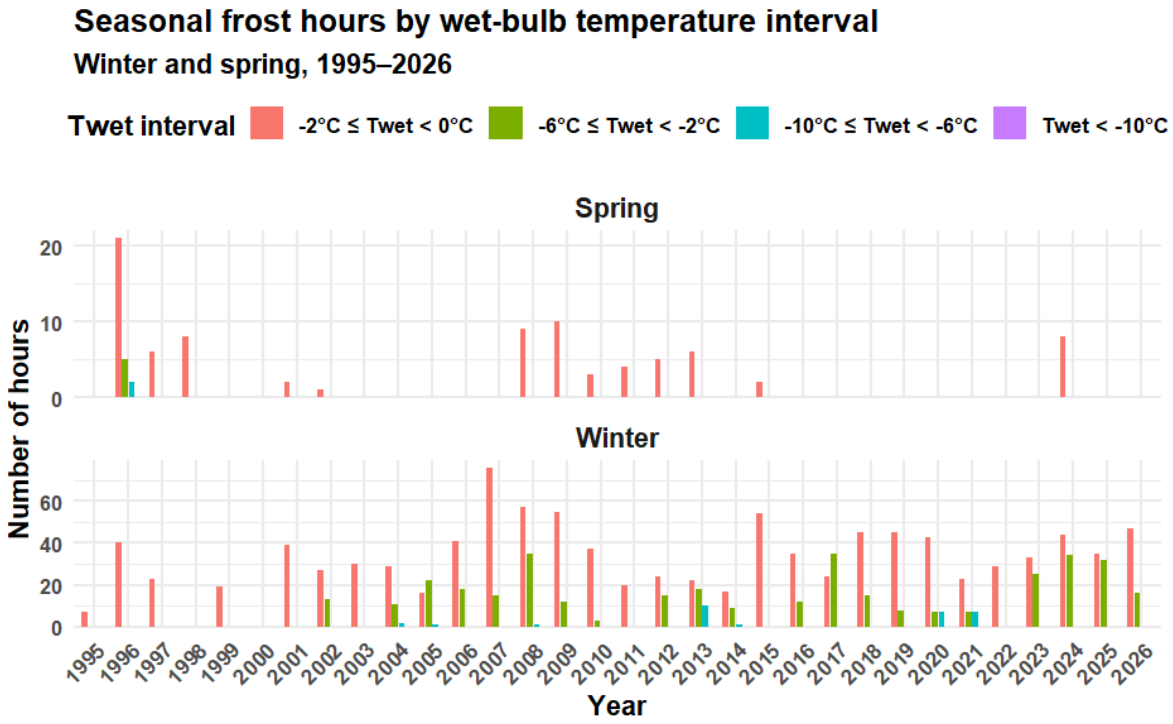


Figure 6. Seasonal frost hours by wet-bulb temperature (Twet) interval in the lowland Aigio citrus area (1995-2026).

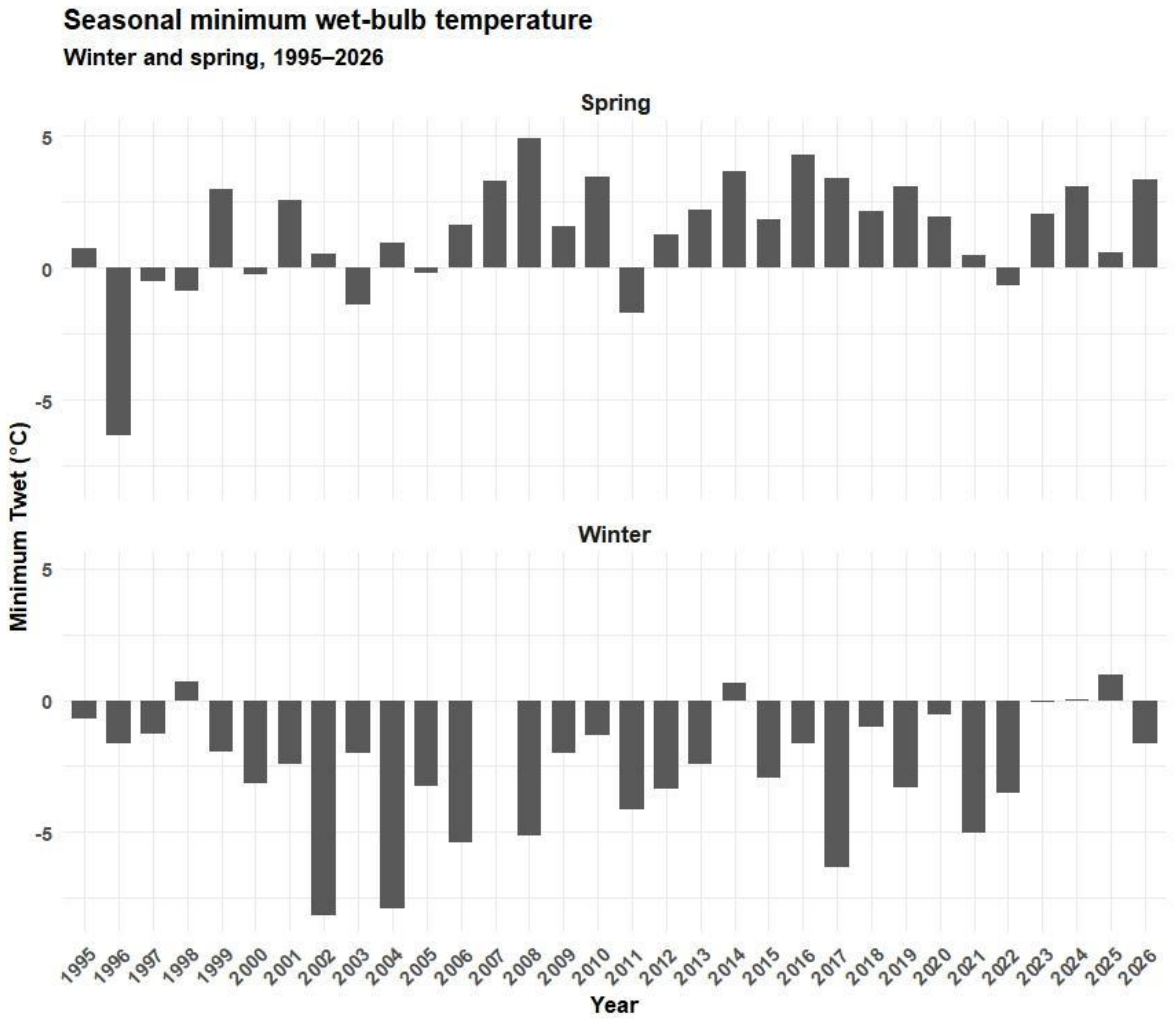


Figure 7. Seasonal minimum wet-bulb temperature in the lowland Aigio citrus area (1995-2026).

Figures 6 and 7 show recurrent frost conditions in the lowland Aigio citrus area during 1995-2026, with the main frost signal occurring in winter. The -2°C <= Twet < 0°C interval dominates, while the -6°C <= Twet < -2°C interval occurs in several years and hours below -6°C are isolated. Spring frost hours are fewer and less persistent than at the higher-elevation plots, although they remain relevant when they coincide with sensitive citrus stages.

Exposure in the lowland Aigio citrus area is classified as medium. The historical Twet plots show recurrent winter frost but lower frost duration and less spring exposure than the plots at approximately 550 and 850 m a.s.l. Overall vulnerability is also classified as medium. Documented losses in the wider Aigio area confirm that exceptional regional events can be severe, but they do not establish plot-specific damage in the lowland area.

Component	Assessment	Justification
Exposure	Medium	Historical Twet analysis shows recurrent winter frost, but frost duration and spring occurrence are lower than at the 550 m and 850 m citrus plots. Exposure below -6°C is isolated.

Sensitivity	High	Lemon and other citrus crops are sensitive to freezing temperatures, particularly when fruits or sensitive tissues are present and exposure is prolonged.
Adaptive capacity	Medium	The available material does not provide plot-specific data on protection measures, infrastructure, or operational readiness. A medium regional-level class is therefore used and should not be interpreted as a plot-specific measurement.
Overall vulnerability	Medium	High crop sensitivity is moderated by comparatively lower frost exposure in the lowland plot. Regional historical losses confirm that exceptional events can be severe but do not establish plot-specific damage.

Aigio citrus replicate plot at approximately 550 m a.s.l.

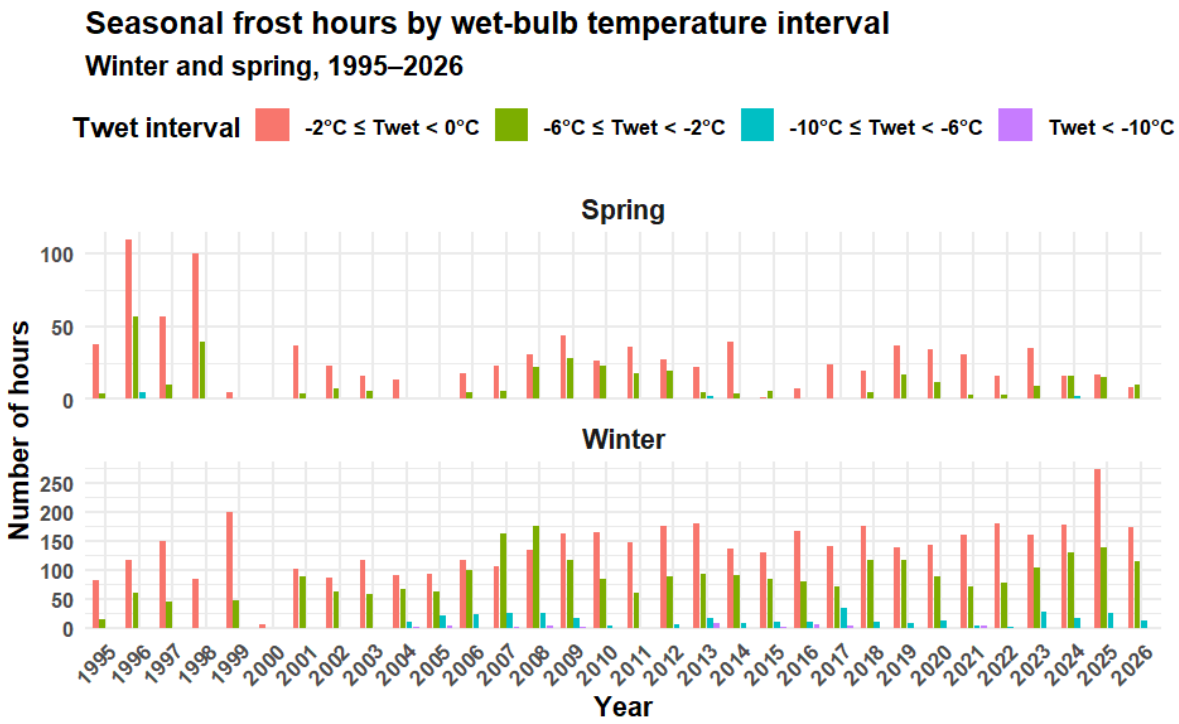


Figure 8. Seasonal frost hours by wet-bulb temperature (Twet) interval in Aigio at approximately 550 m a.s.l. (1995-2026).

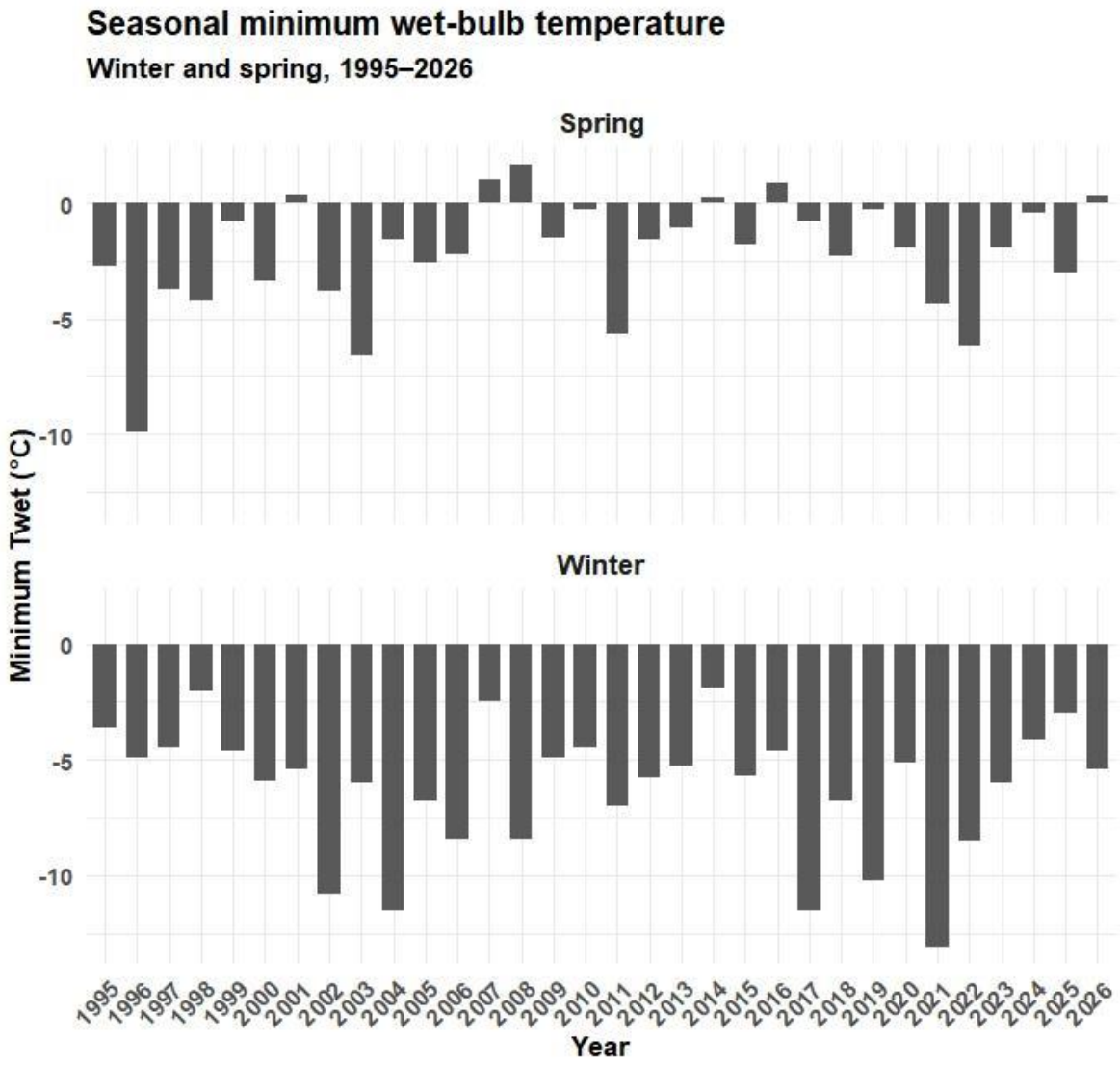


Figure 9. Seasonal minimum wet-bulb temperature in Aigio at approximately 550 m a.s.l. (1995-2026).

Figures 8 and 9 show a stronger frost-exposure signal at the citrus plot located at approximately 550 m a.s.l. than in the lowland Aigio citrus area. Winter frost hours are more frequent and prolonged, and spring frost is more evident. Exposure in the -2°C <= Twet < 0°C and -6°C <= Twet < -2°C intervals is recurrent; the -10°C <= Twet < -6°C class also occurs in multiple winter seasons and in a smaller number of spring seasons, while Twet below -10°C appears in isolated years.

Exposure at the 550 m citrus plot is classified as high. This classification is based on the longer frost duration, lower seasonal minimum Twet values than in the lowland plot, and recurrent occurrence of the severe interval below -6°C. Sensitivity remains high because the plot is assessed as citrus cultivation. Adaptive capacity is classified as medium at the regional level because the available material does not provide plot-specific evidence on protection infrastructure, management practices, or operational readiness that would justify a different classification.

Component	Assessment	Justification

Exposure	High	The plot shows recurrent winter and spring frost. The -2°C <= Twet < 0°C and -6°C <= Twet < -2°C intervals are frequent, the -10°C <= Twet < -6°C interval occurs in multiple seasons, and Twet below -10°C occurs in isolated years. Exposure is stronger than in the lowland plot.
Sensitivity	High	The plot is assessed as citrus cultivation; citrus crops are sensitive to freezing conditions, particularly during prolonged exposure and sensitive crop stages.
Adaptive capacity	Medium	The available material does not provide plot-specific evidence on protection, preparedness, or infrastructure. The regional medium classification is therefore retained.
Overall vulnerability	High	Higher frost exposure than in the lowland citrus area, combined with high citrus sensitivity, supports a high vulnerability classification.

Aigio citrus replicate plot at approximately 850 m a.s.l.

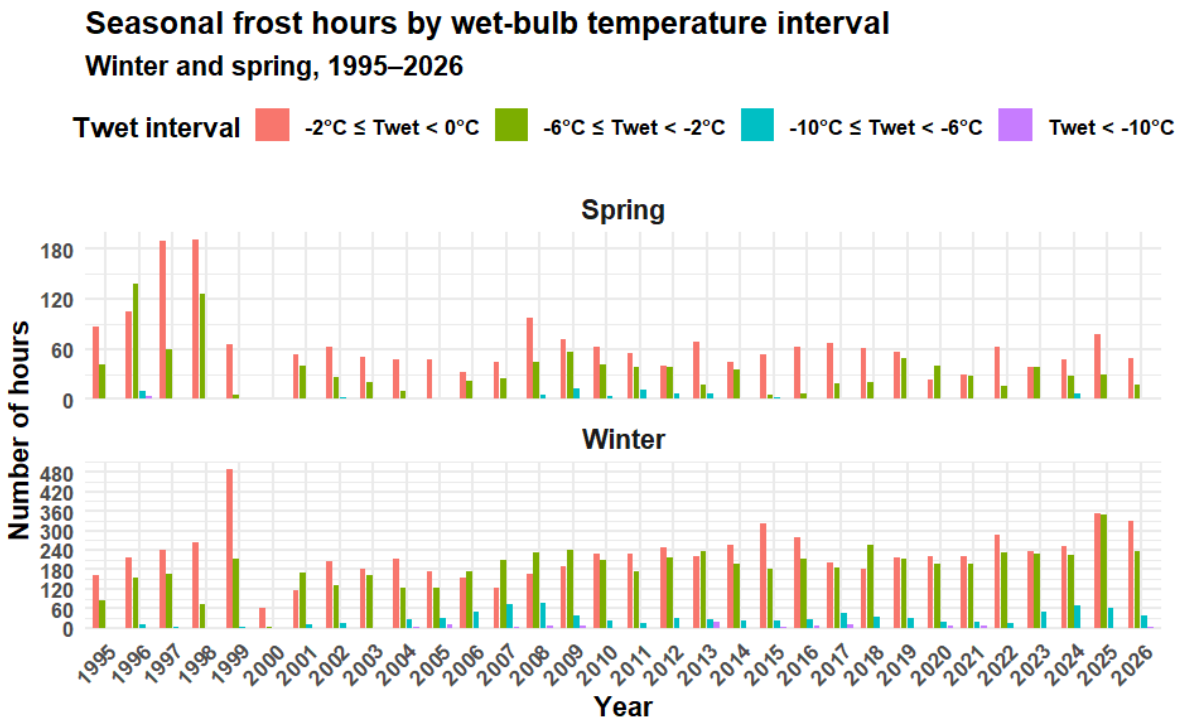


Figure 10. Seasonal frost hours by wet-bulb temperature (Twet) interval in Aigio at approximately 850 m a.s.l. (1995-2026).

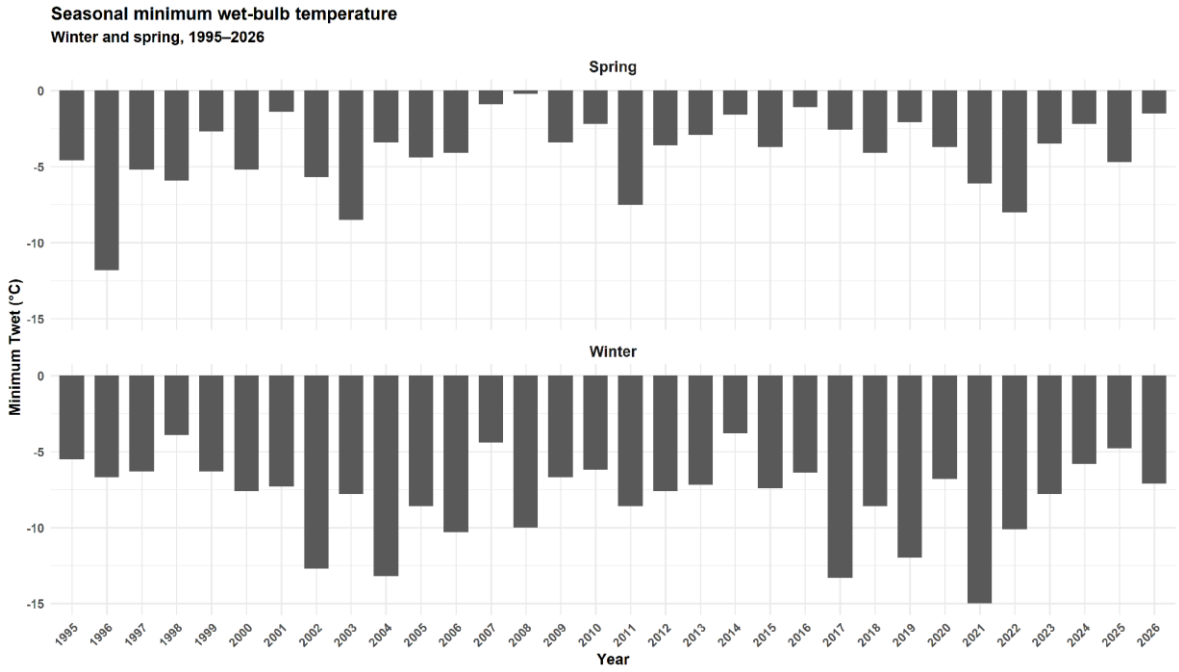


Figure 11. Seasonal minimum wet-bulb temperature in Aigio at approximately 850 m a.s.l. (1995-2026).

Figures 10 and 11 show the strongest frost-exposure signal among the Aigio citrus plots. The 850 m plot records frequent and prolonged winter frost, recurrent spring frost, and substantial exposure in the -2°C <= Twet < 0°C and -6°C <= Twet < -2°C intervals. The -10°C <= Twet < -6°C class occurs repeatedly, while Twet below -10°C occurs in isolated years. Spring frost is also more frequent and persistent than in the lowland plot.

Exposure at the 850 m citrus plot is classified as very high relative to the other Aigio plots. Sensitivity is high because the plot is assessed as citrus cultivation. Adaptive capacity is classified as medium at the regional level because no plot-specific evidence supports a differentiated assessment. Overall vulnerability is classified as high. The very high class is applied to exposure only; the overall class is not raised above high because the assessment is qualitative and no plot-specific damage records or protection-capacity data are available for this plot.

Component	Assessment	Justification
Exposure	Very high	This plot has the strongest exposure signal among the Aigio citrus plots, with frequent and prolonged winter frost, recurrent spring frost, repeated exposure in the -10°C <= Twet < -6°C interval, and isolated occurrence below -10°C.
Sensitivity	High	The plot is assessed as citrus cultivation; citrus crops are sensitive to freezing temperatures and prolonged frost exposure.
Adaptive capacity	Medium	The available material does not provide plot-specific evidence on protection measures or operational preparedness. The regional medium classification is therefore retained.

Overall vulnerability	High	Very high exposure and high citrus sensitivity support high vulnerability. The very high class is not assigned to overall vulnerability because the assessment is qualitative and plot-specific damage and protection-capacity data are unavailable.

Integrated interpretation for the Aigio citrus pilot area

The three Aigio plots show a clear exposure gradient. The lowland citrus area has recurrent but comparatively lower exposure and medium overall vulnerability. The 550 m plot has longer frost duration and more frequent spring frost, supporting high overall vulnerability. The 850 m plot has the strongest exposure signal, with very high exposure and high overall vulnerability. Citrus sensitivity is high and adaptive capacity is classified as medium at the regional level for all three plots; differences in overall vulnerability are therefore driven mainly by the exposure shown in the figures. Regional damage and compensation evidence does not distinguish among the plots.

Aigio plot	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability
Lowland citrus area	Medium	High	Medium	Medium
Citrus plot at approximately 550 m a.s.l.	High	High	Medium	High
Citrus plot at approximately 850 m a.s.l.	Very high	High	Medium	High

Argolida - citrus cultivation

Argolida is an important citrus-producing area, and frost is a recurrent climatic hazard for citrus orchards. The seasonal frost-hour analysis for Argos in 1995-2026 shows substantial interannual variability in the occurrence and duration of freezing conditions. Most frost hours occur in winter and are concentrated in the -2°C <= Twet < 0°C interval. Several years also include hours in the -6°C <= Twet < -2°C interval, with isolated winter exposure below -6°C. These conditions may be damaging when they persist and when fruits or sensitive tissues are present.

Spring frost hours are generally fewer than winter frost hours, but they remain relevant when they coincide with flowering, fruit set, or early fruit development. The spring signal is intermittent. Figure 12 does not show 2022 as an exceptional spring-frost year; the documented 2022 damage event discussed below occurred in January and is therefore a winter event.

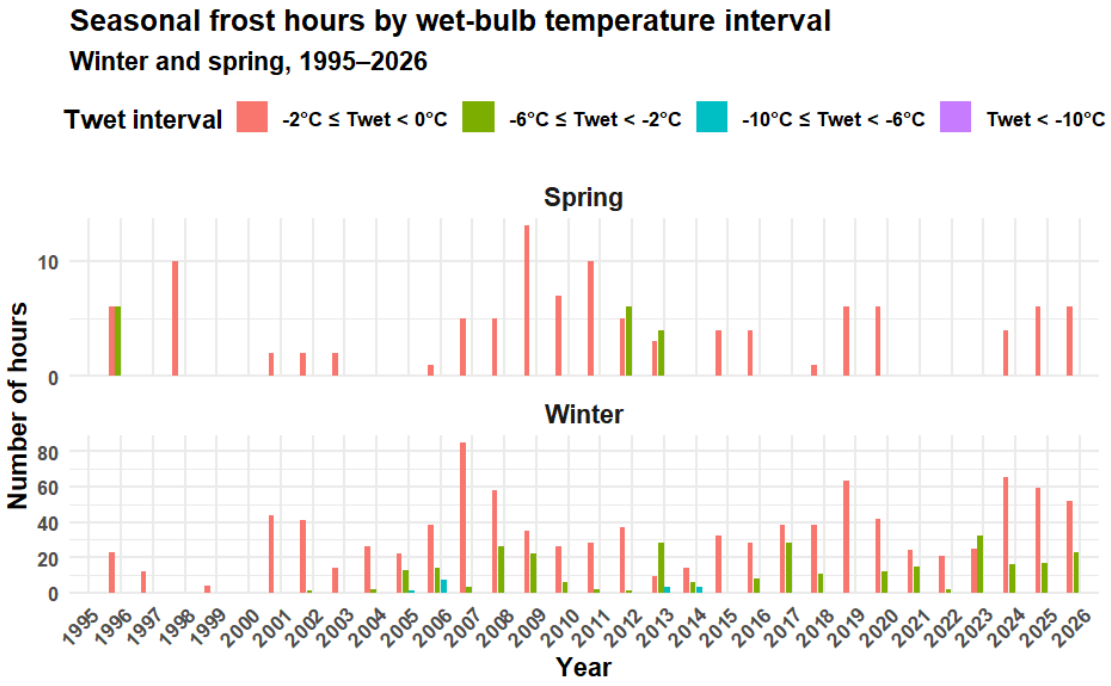


Figure 12. Seasonal frost hours by wet-bulb temperature (Twet) interval in Argos (1995-2026).

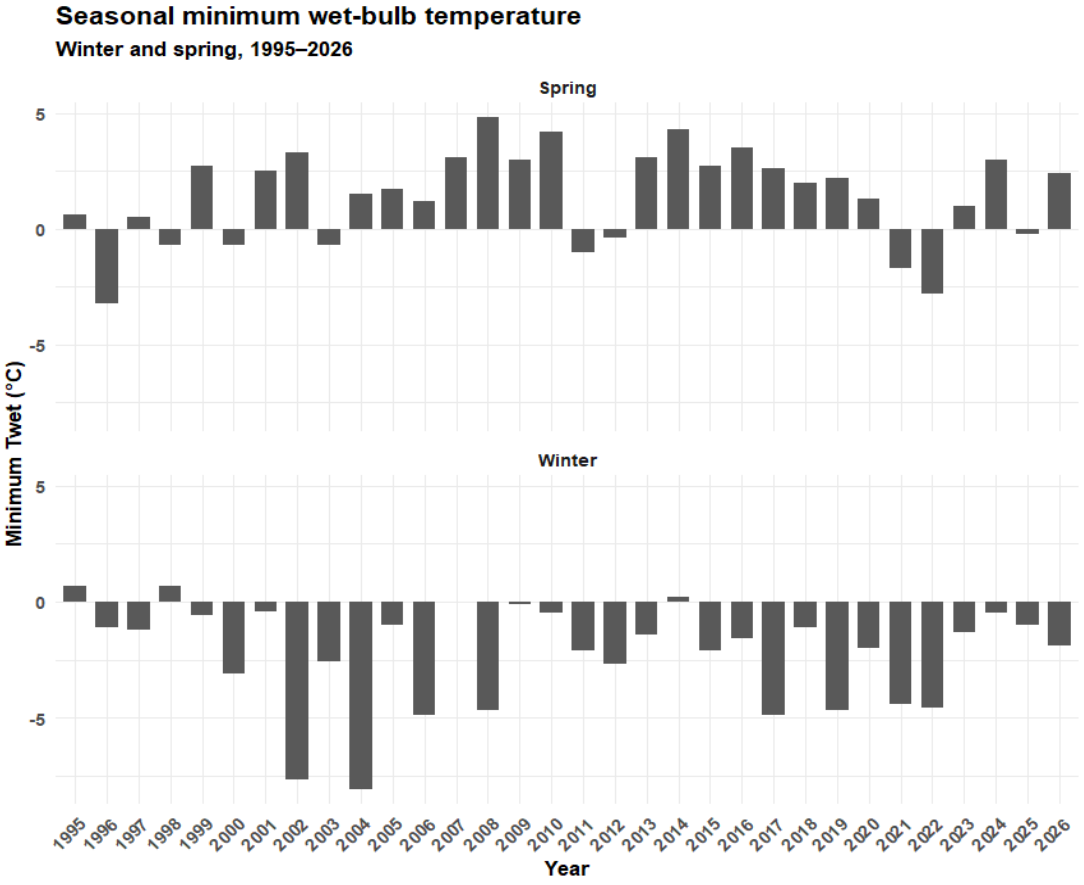


Figure 13. Seasonal minimum wet-bulb temperature in Argos (1995-2026).

Figures 12 and 13 show that winter frost in Argos is more frequent and generally more intense than spring frost. The plots indicate a clear frost signal, but not the strongest exposure among the project areas; exposure is therefore classified as medium-high rather than high. Documented evidence from the Region of Peloponnese indicates that the January 2022 frost event caused serious damage to citrus crops in Argolida, affecting approximately 130,000 tonnes of standing production and making much of it non-marketable because of internal fruit freezing. This regional damage evidence supports a high overall vulnerability classification, but it does not change the exposure class or provide plot-level exposure information.

Adaptive capacity in Argolida is assessed as medium. Available project information indicates practical experience with frost events and the use of frost-protection practices in parts of the citrus sector. Active protection remains constrained by cost, dependence on infrastructure and energy, uneven access to localized early-warning information, and the difficulty of protecting large areas during severe or prolonged events. This is a regional qualitative assessment rather than a plot-specific measurement.

Component	Assessment	Justification
Exposure	Medium-High	The seasonal frost-hour analysis shows recurrent winter frost and intermittent spring frost. The -2°C <= Twet < 0°C interval dominates, with events in the -6°C <= Twet < -2°C interval and isolated winter exposure below -6°C. Frost duration is lower than at the higher-elevation Aigio plots.
Sensitivity	High	Citrus crops are sensitive to freezing temperatures, particularly when exposure is prolonged and fruits or sensitive tissues are present.
Adaptive capacity	Medium	Available project information indicates practical experience and some protection practices, but limitations remain related to cost, infrastructure, energy, localized warnings, and operational reliability. The assessment is regional rather than plot-specific.
Overall vulnerability	High	Medium-high exposure and high crop sensitivity, together with documented major regional damage during the January 2022 event and medium adaptive capacity, support a high vulnerability classification.

Laconia - Sparta citrus cultivation and frost-sensitive perennial crops

Sparta and the wider Eurotas valley support citrus cultivation and other frost-sensitive perennial crops. The available frost-hour and seasonal minimum Twet figures show recurrent winter frost and intermittent spring frost. In low-lying inland areas, cold-air accumulation can increase exposure during radiative frost conditions.

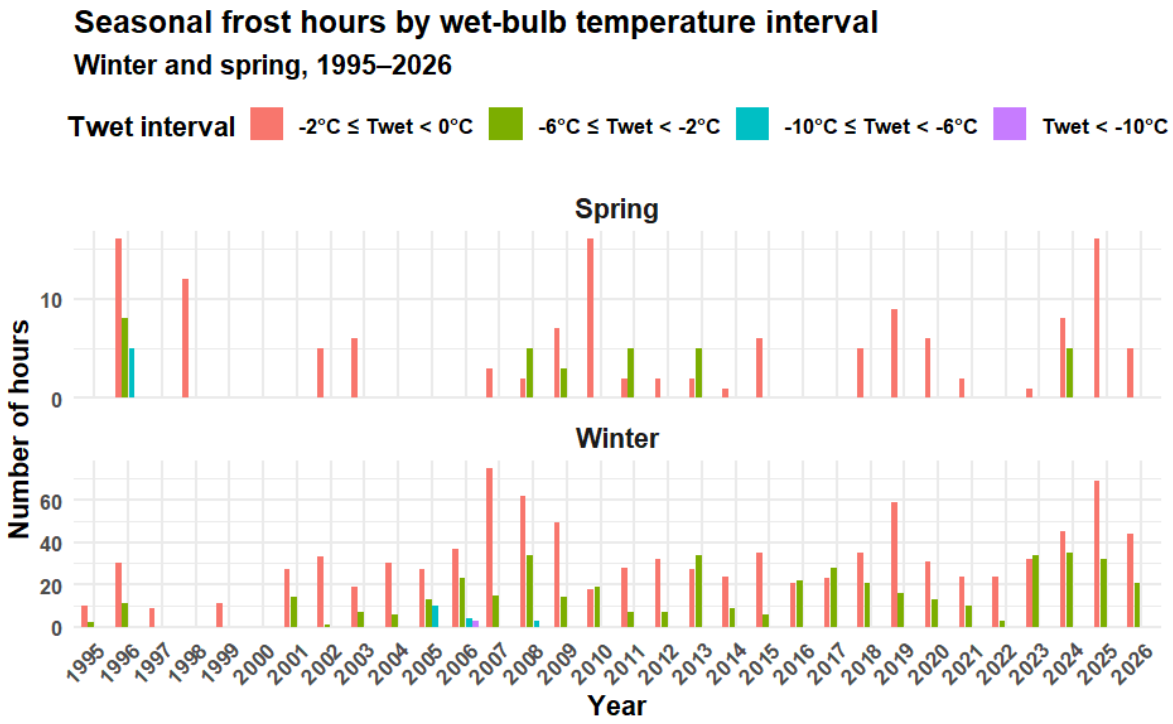


Figure 14. Seasonal frost hours by wet-bulb temperature (Twet) interval in Sparta (1995-2026).

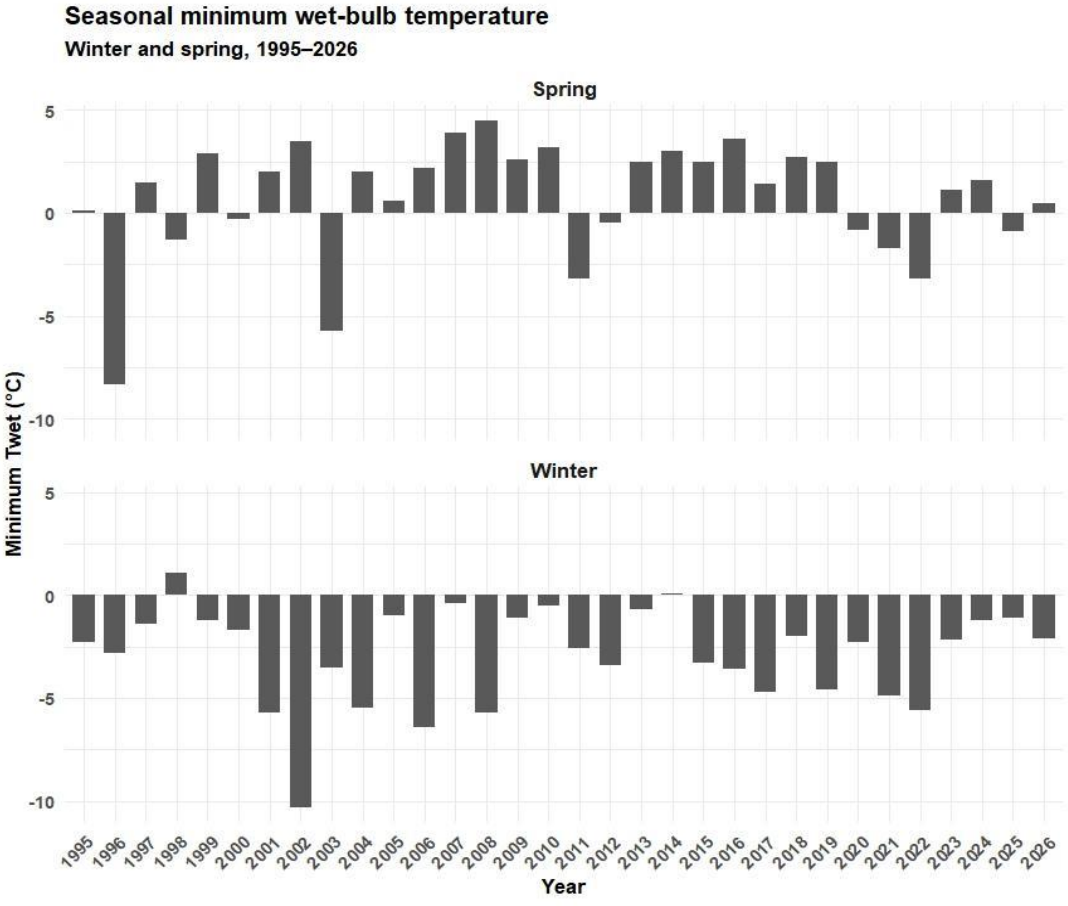


Figure 15. Seasonal minimum wet-bulb temperature in Sparta (1995-2026).

Figures 14 and 15 show that winter is the dominant frost season in Sparta. Most frost hours occur in the -2°C <= Twet < 0°C interval, with recurrent exposure in the -6°C <= Twet < -2°C interval and isolated events below -6°C. Spring frost is less frequent but remains relevant where it overlaps with sensitive phenological stages. The available material does not provide a documented Sparta-specific citrus-loss event comparable to the January 2022 event in Argolida. Exposure and overall vulnerability are classified as medium-high because the plotted exposure is agriculturally relevant but less persistent than at the higher-elevation Aigio plots, and the available evidence does not support a high overall class. Sensitivity is high. Adaptive capacity is assessed as medium at the regional level, using the same qualitative basis and data limitations applied to the Greek citrus areas.

Component	**Assessment**	**Justification**
Exposure	Medium-High	Historical indicators show recurrent winter frost, intermittent spring frost, and isolated exposure below -6°C. Frost duration is lower than at the higher-elevation Aigio plots.
Sensitivity	High	Citrus and other perennial crops are sensitive to freezing temperatures, particularly during prolonged exposure and sensitive phenological stages.
Adaptive capacity	Medium	The available material supports only a regional qualitative assessment. Practical experience and protection practices may be present, but economic, infrastructure, and operational constraints remain.
Overall vulnerability	Medium-High	Medium-high exposure, high crop sensitivity, and medium adaptive capacity support a medium-high classification. The available material does not provide additional plot-specific evidence supporting a high class.

Overall, the ELGA compensation series provides independent evidence that frost has caused recurrent regional economic losses in citrus production across Achaia, Argolida, and Laconia. Payments are recorded in multiple years in all three regions, with pronounced peaks that support the regional relevance of the vulnerability findings. The records corroborate the high overall vulnerability classification for Argolida, the medium-high classification for Laconia, and significant historical impacts in Achaia. Because the compensation data are regional, they do not distinguish among the three Aigio plots; their ranking remains based on the distinct exposure signals in Figures 6-11. Compensation amounts are used as evidence of realized economic impacts, not as a direct measure of frost intensity or plot-level exposure.

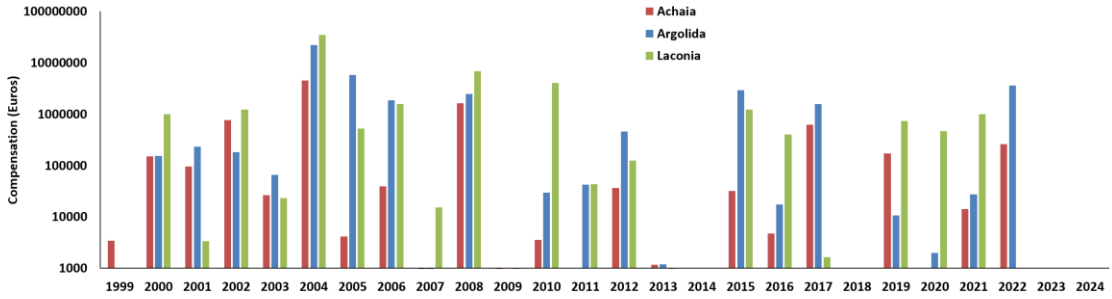


Figure 16. Annual ELGA compensation payments for frost-related damage to citrus in Achaia, Argolida, and Laconia.

Puy-de-Dôme - temperate fruit crops and vineyards

The Puy-de-Dôme replication area differs from the Greek citrus areas because the assessed crops are temperate perennial crops, including grapevines and other fruit crops. The Clermont-Ferrand historical analysis for 1995-2026 shows regular frost days in both winter and spring. Winter frost is generally more frequent and more intense, but the most agriculturally critical risk for temperate perennial crops and vineyards is late spring frost, when crop tolerance has declined. The spring frost-day analysis shows repeated occurrence in the -2°C <= Tmin < 0°C and -6°C <= Tmin < -2°C intervals. Colder spring days below -6°C occur in several years, and days below -10°C occur in a few years. These events may coincide with budburst, early shoot development, flowering, or early fruit development.

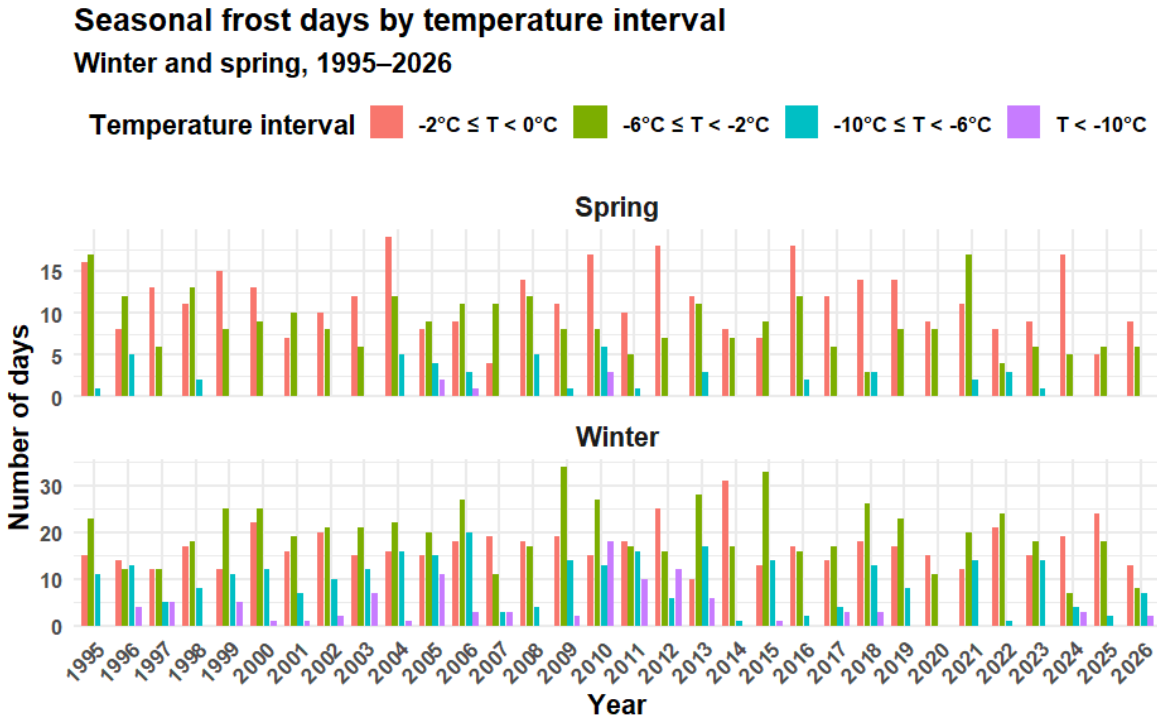


Figure 17. Seasonal frost days by minimum air-temperature interval in Clermont-Ferrand (1995-2026) (Données climatologiques de base).

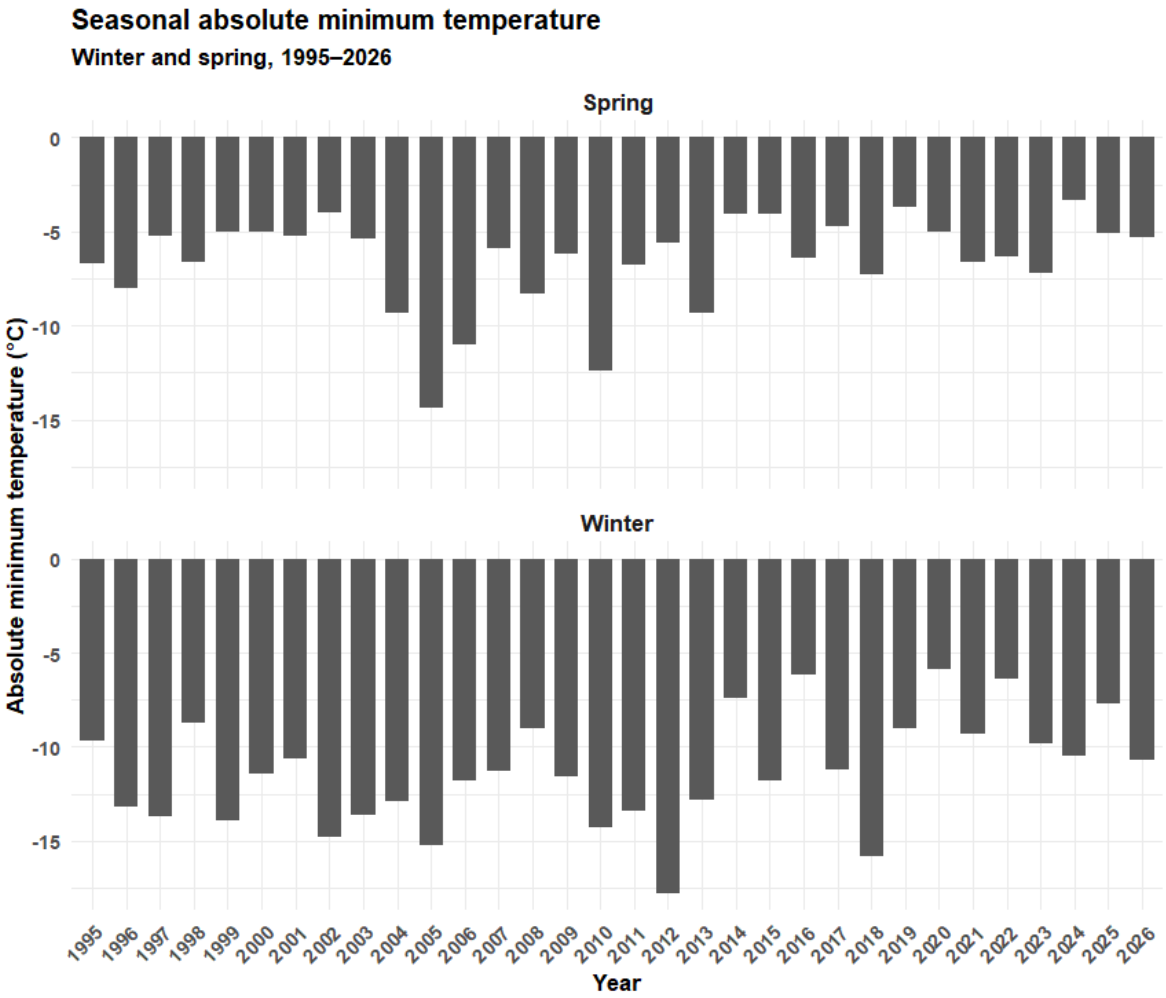


Figure 18. Seasonal absolute minimum air temperature in Clermont-Ferrand (1995-2026) (Données climatologiques de base)

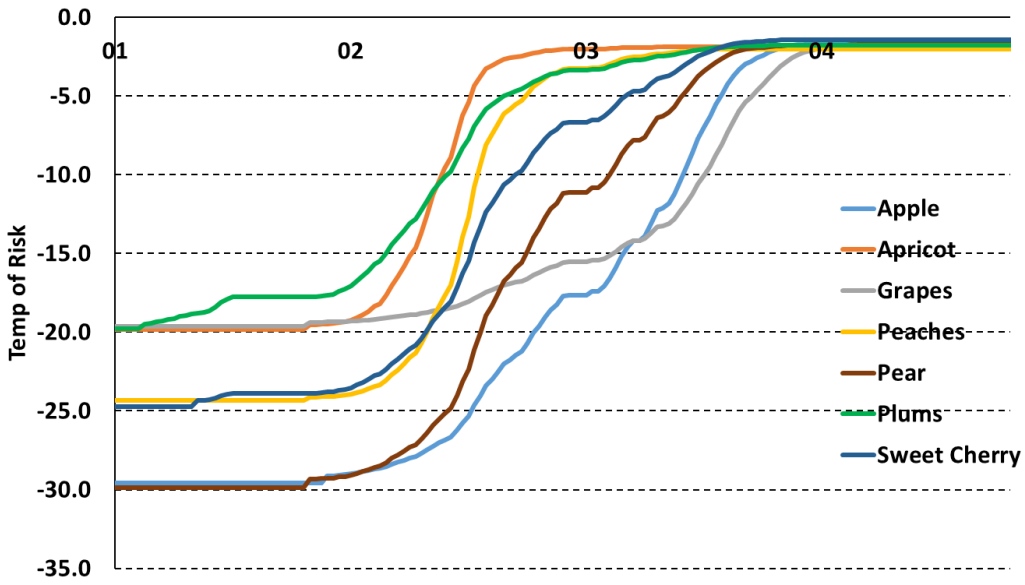


Figure 19. Simulated seasonal evolution of the critical frost-damage temperature (Tcritical; Temp of Risk) for selected temperate fruit crops (apple, apricot, grapevine, peach, pear, plum, and sweet cherry) during the 2024 growing season. The x-axis presents the months of the year, starting from 1 January.

The simulated crop-specific critical-temperature (Tcritical) curves support the sensitivity assessment for the selected temperate fruit crops represented in Figure 19: apple, apricot, grapevine, peach, pear, plum, and sweet cherry. The curves indicate marked differences among species during dormancy, with simulated critical temperatures of approximately -20°C to -30°C. From late winter into spring, the thresholds become rapidly less negative and converge to within a few degrees of 0°C as development advances. This common pattern indicates a substantial reduction in frost tolerance, although the timing differs among species. The curves are used here as qualitative sensitivity indicators for the 2024 simulation and should not be interpreted as universal field damage thresholds; actual injury depends on species, cultivar, phenological stage, acclimation, exposure duration, tissue temperature, and local conditions.

When the historical frost climatology is considered together with the simulated Tcritical curves, a clear vulnerability pattern emerges. Severe winter frost generally occurs while these perennial crops are dormant and comparatively frost tolerant. Spring frost, by contrast, can overlap with the period in which frost tolerance declines rapidly, with species-specific timing. The principal vulnerability is therefore the coincidence of frost occurrence with advancing phenological development, rather than exceedance of a single fixed threshold for all crops. The severe spring frost event in France in April 2021 caused major damage to grapevines and fruit trees in regions where young leaves had unfolded after unusually warm March conditions (Vautard et al., 2023).

Adaptive capacity in Puy-de-Dôme is assessed as medium-high. Available project information indicates relatively strong meteorological, agricultural, technical, and advisory capacity, including monitoring infrastructure and frost-protection knowledge. However, implementation of active protection measures may be constrained by cost, feasibility, plot characteristics, water availability, environmental considerations, and operational limitations during severe events. The classification is regional and qualitative.

Component	Assessment	Justification
Exposure	High	Clermont-Ferrand records show recurrent spring frost days in the -2°C <= Tmin < 0°C and -6°C <= Tmin < -2°C intervals, with colder days below -6°C in several years and days below -10°C in a few years.
Sensitivity	High	Grapevines and other temperate fruit crops become highly sensitive during spring development. The simulated Tcritical curve shows a rapid rise in the critical damage temperature from March to late April, indicating decreasing frost tolerance.
Adaptive capacity	Medium-High	Available project information indicates relatively strong technical, institutional, monitoring, and advisory capacity, but implementation of protection measures may be limited by cost, feasibility, and operational constraints.
Overall vulnerability	High	Recurrent spring frost exposure combined with high crop sensitivity during budburst and early growth supports a high overall vulnerability classification.

Comparative assessment and final classification

The four project areas exhibit different frost-risk mechanisms. In Aigio, Argolida, and Sparta, vulnerability is primarily linked to citrus sensitivity and, where documented, losses from severe frost events. Within the Aigio pilot area, the lowland plot has medium overall vulnerability, while the 550 m and 850 m plots have high overall vulnerability; the 850 m plot has very high exposure but remains high overall. In Argolida, medium-high exposure combined with documented regional citrus damage in January 2022 supports high overall vulnerability. In Sparta, the available material supports medium-high exposure and medium-high overall vulnerability because the historical frost signal is relevant but less persistent than at the higher-elevation Aigio plots and no additional evidence supports a high class.

In Puy-de-Dôme, vulnerability is mainly linked to spring frost affecting temperate fruit crops and vineyards during sensitive phenological stages. The key risk is the overlap between frost occurrence and the rapid reduction in crop frost tolerance during spring development.

Despite these differences, the results support improved operational frost-risk management in all four areas. Relevant measures include localized monitoring, wet-bulb temperature and frost-duration indicators for the Greek citrus areas, minimum-temperature and frost-day monitoring for Clermont-Ferrand, crop-specific phenological information, and early-warning tools. These elements are directly relevant to the LIFE FROSTDEFEND approach, which aims to improve preparedness, optimize frost-protection interventions, and reduce agricultural losses under climatic variability.

Region / plot	Main crop system assessed	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability

Aigio lowland, Greece	Citrus cultivation, with emphasis on lemons	Medium	High	Medium	Medium
Aigio, approximately 550 m a.s.l., Greece	Citrus cultivation	High	High	Medium	High
Aigio, approximately 850 m a.s.l., Greece	Citrus cultivation	Very high	High	Medium	High
Argolida, Greece	Citrus cultivation	Medium-High	High	Medium	High
Sparta, Greece	Citrus cultivation and frost-sensitive perennial crops	Medium-High	High	Medium	Medium-High
Puy-de-Dôme, France	Temperate fruit crops and vineyards	High	High	Medium-High	High

Implementation relevance, monitoring indicators and limitations

For adaptation planning and project monitoring, the vulnerability assessment should be interpreted together with implementation indicators collected during LIFE FROSTDEFEND operation. The figures and matrices identify where vulnerability is expected to be higher, but final evaluation of project effectiveness should rely on measured or documented indicators during implementation.

Monitoring element	Indicator to be reported during implementation	Purpose
Operational coverage	Number of pilot plots, farms, crop types and hectares covered by the monitoring and warning system.	Documents the spatial and sectoral reach of the adaptation action.
Warning performance	Number of frost-risk warnings issued, lead time, observed frost occurrence, false alarms and missed events where verification data are available.	Demonstrates whether the tool provides operationally useful early warning.
Use of warnings	Number of producers or stakeholders receiving warnings, number of reported protection activations, and timing of interventions.	Links the warning system to practical adaptation decisions.
Damage and avoided-loss evidence	Observed damage after frost events, compensation records where available,	Supports evidence-based assessment of socioeconomic and agricultural impact.

	producer reports, and crop-specific loss data when verified.	
Capacity building	Training events, participants, advisory material, user feedback and integration with local services.	Documents improvement in adaptive capacity.

The assessment highlights the importance of socioeconomic vulnerability factors. Small and medium-sized farms can be particularly vulnerable due to limited financial resources, dependence on single-crop systems, reduced access to advanced technological infrastructure and high operational costs associated with active frost protection. The assessment further indicates that many existing frost-protection practices remain largely reactive rather than preventive, frequently relying on generalized weather forecasts or empirical experience rather than localized operational forecasting systems.

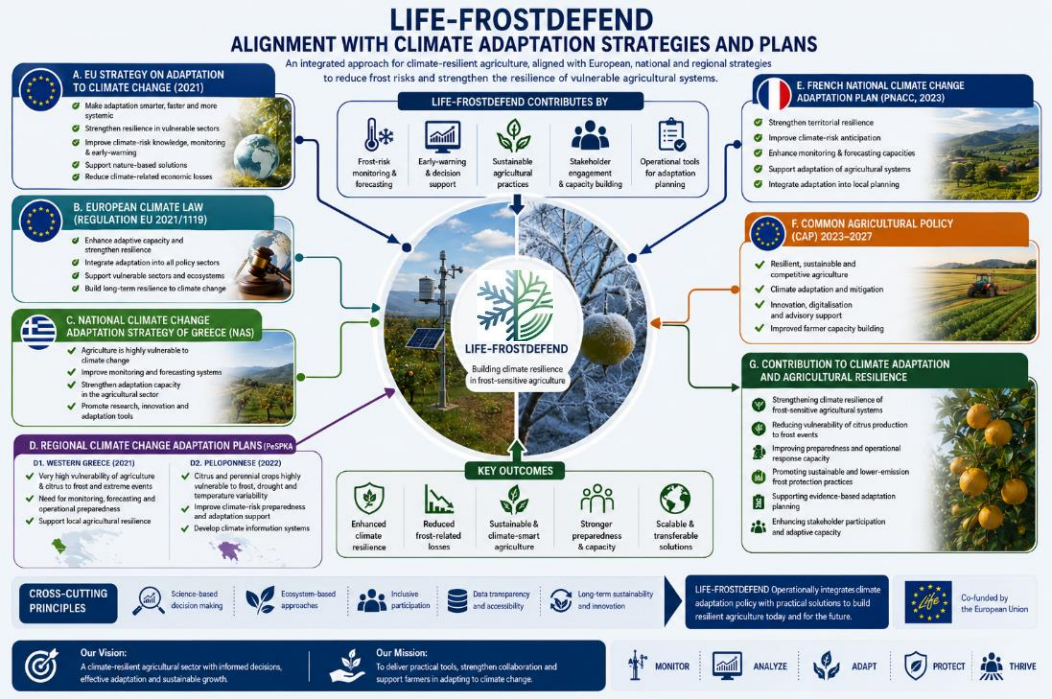


Figure 20. LIFE FROSTDEFEND vulnerability assessment visualization

The LIFE-FROSTDEFEND framework directly addresses these weaknesses through:

- localized frost monitoring,
- operational forecasting and early-warning,
- stakeholder engagement,
- evidence-based adaptation planning,
- optimization of intervention timing,
- continuous monitoring and evaluation.

Overall, the assessment (Figure 20) demonstrates the urgent need for integrated, operational and climate-resilient frost adaptation strategies capable of reducing both the physical and socioeconomic impacts of frost events on vulnerable agricultural systems under future climate conditions.

6. LIFE-FROSTDEFEND Early-Warning Tool

6.1 Tool Description and Functions

The LIFE FROSTDEFEND Early-Warning Tool constitutes one of the core outputs of the project and is designed to support farmers, agricultural cooperatives and relevant stakeholders in anticipating and managing frost-related risks more effectively. The tool combines meteorological monitoring, frost forecasting capabilities and operational decision-support functions in order to improve preparedness and reduce the impacts of frost incidents on agricultural production.

The system is developed as an integrated frost-risk management platform capable of collecting, processing, and analyzing environmental and agricultural information relevant to frost occurrence and crop vulnerability. It is designed to function as an operational early-warning mechanism, providing farmers with advance information on expected frost conditions before critical temperature thresholds are reached. By integrating meteorological forecasts, local climatic observations, and field-level information, the system delivers timely frost-risk alerts classified as Low, Medium, High, or Very High, together with operational guidance on potential frost events that may affect sensitive crops.

Alerts (48hr and 24hr in advance of an event) are designed to support proactive rather than reactive responses, allowing farmers sufficient time to organize and implement protection measures when necessary. The forecasting component focuses particularly on periods of elevated agricultural vulnerability, such as flowering and fruit-setting stages of citrus crops and other frost-sensitive cultivations.

The LIFE FROSTDEFEND tool also incorporates decision-support functions that assist growers in selecting appropriate frost protection interventions based on the severity of the expected event, local climatic conditions and crop sensitivity. The system aims to optimize the timing and selection of protection measures while reducing unnecessary or premature interventions that may increase operational costs and environmental burdens.

Unlike conventional frost-warning systems based exclusively on generalized temperature forecasts, the LIFE FROSTDEFEND tool incorporates meteorological observations, crop phenology, atmospheric environmental monitoring and indirect biological frost-risk indicators. Continuous monitoring of temperature, humidity,

particulate matter mass concentrations and atmospheric conditions supports identification of environmental situations potentially associated with increased biological ice nucleation activity and elevated frost susceptibility.

Decision-support functions may include guidance regarding:

- Timing of frost protection interventions;
- Selection of appropriate protection practices;
- Evaluation of forecast severity and duration;
- Identification of high-risk cultivation periods;
- Operational preparedness recommendations.

By integrating meteorological forecasting with practical agricultural guidance, the tool contributes to improved farm-level decision-making and strengthens the adaptive capacity of local agricultural systems.

The LIFE-FROSTDEFEND Early-Warning Tool further supports a more sustainable and environmentally efficient approach to frost protection by encouraging targeted interventions and reducing unnecessary use of energy-intensive protection practices. In this way, the tool contributes not only to climate adaptation but also to broader environmental and climate mitigation objectives.

6.2 Monitoring and Data Collection

An important component of the LIFE FROSTDEFEND tool is the establishment of a monitoring and data collection framework capable of supporting both operational frost management and long-term adaptation planning. The monitoring system is designed to collect technical, environmental and agricultural information associated with frost incidents, crop protection interventions and adaptation effectiveness. The tool incorporates a dedicated monitoring module through which information related to frost protection practices implemented by farmers can be systematically recorded and analyzed.

The monitoring infrastructure additionally incorporates IoT-based environmental sensor systems installed in pilot orchards and replication areas. These systems continuously collect localized environmental and climatic data supporting real-time operational monitoring of frost-risk conditions. Sensor calibration and validation procedures were implemented prior to deployment in order to improve data reliability and operational accuracy.

The collected information includes:

- Number of sprayings and interventions;

- Timing and date of interventions;
- Type of protection methods used;
- Geographic location of interventions;
- Meteorological conditions during frost events;
- Crop-specific observations and operational responses.

The recording of intervention timing and applied measures is particularly important for evaluating the effectiveness and efficiency of frost protection practices under different climatic conditions. Through systematic monitoring, the project aims to identify practices that provide effective crop protection while minimizing operational costs and environmental impacts.

In addition to technical intervention data, the monitoring framework incorporates farmer feedback on the effectiveness of the measures applied. Farmers participating in the project are encouraged to provide information on the protection actions undertaken and the estimated extent of frost damage.

The collection of farmer feedback represents an important participatory component of the adaptation framework, allowing the project to integrate practical experience and local knowledge into the evaluation process. The incorporation of end-user perspectives supports the continuous improvement of the tool and contributes to the development of realistic and operationally feasible adaptation recommendations.

The collected data can be analyzed on a seasonal basis in order to assess frost-risk patterns, intervention effectiveness and operational performance of different adaptation measures. Seasonal analysis allows the identification of trends related to frost occurrence, crop vulnerability and effectiveness of protection responses under varying climatic conditions. An additional objective of the monitoring framework is the estimation of potential reductions in greenhouse gas emissions associated with more targeted frost protection practices. Conventional frost protection methods, such as heaters and wind machines, may involve significant energy consumption and associated CO2 emissions. By improving forecasting accuracy and supporting more efficient intervention planning, the LIFE FROSTDEFEND tool aims to reduce unnecessary use of such practices and promote lower-emission adaptation approaches.

The monitoring system therefore contributes not only to agricultural adaptation but also to broader environmental sustainability objectives through improved resource efficiency and optimization of operational practices.

6.3 Integration of the tool into Adaptation Planning

The LIFE FROSTDEFEND Early-Warning Tool is designed not only as an operational support mechanism but also as a strategic component of the broader adaptation planning framework developed within the project (Figure 21).

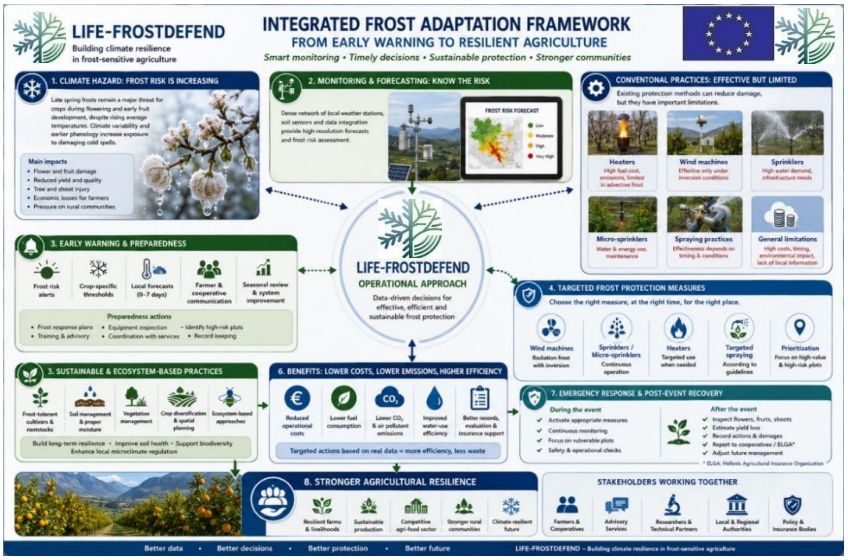


Figure 21. LIFE FROSTDEFEND adaptation framework

The information generated through monitoring, forecasting and farmer feedback is intended to support continuous improvement of adaptation practices and strengthen climate resilience planning at local and regional levels. The integration of collected data into adaptation planning enables the identification of recurring frost-risk patterns, vulnerable cultivation zones and crop-specific sensitivities. Through seasonal analysis and long-term evaluation of frost events and intervention responses, the project supports the development of evidence-based adaptation measures tailored to local agricultural conditions.

The monitoring outputs generated by the tool contribute to:

- Improvement of frost-risk assessment methodologies;
- Optimization of frost protection practices;
- Identification of high-risk agricultural areas;
- Evaluation of adaptation effectiveness;
- Support of agricultural advisory services;
- Improvement of preparedness and operational planning;
- Support of climate-risk communication and awareness raising.

The adaptation planning process further benefits from the incorporation of farmer observations and operational experiences. The participatory approach adopted within LIFE FROSTDEFEND allows adaptation measures to be continuously refined based on practical implementation results and stakeholder needs. This contributes to increased

acceptance and applicability of the proposed measures among end-users. The collected data may also support competent authorities, agricultural cooperatives and insurance organizations in improving climate-risk management approaches and understanding the economic implications of frost events. Enhanced availability of local frost-risk information may contribute to more informed decision-making regarding agricultural planning, advisory support and future adaptation policies.

The integration of monitoring and forecasting data into adaptation planning further supports the transferability and replication objectives of the project. The methodology developed within LIFE FROSTDEFEND may be adapted and applied in additional frost-prone agricultural regions beyond the pilot areas, supporting broader climate resilience objectives within the agricultural sector. Overall, the LIFE FROSTDEFEND Early-Warning Tool represents a key mechanism linking operational frost management with long-term climate adaptation planning. Through continuous monitoring, stakeholder participation and evidence-based analysis, the tool contributes to the development of more resilient, informed and sustainable agricultural systems capable of responding effectively to future climate-related challenges.

7. Proposed Adaptation Measures and Countermeasures

7.1 Existing Frost Protection Practices: Current Methods and Limitations

Frost and late spring frost events constitute some of the most critical climate-related hazards affecting perennial and frost-sensitive agricultural systems. These events are particularly damaging when they occur during sensitive phenological stages such as budburst, flowering, fruit setting and early fruit development. Although average temperatures are increasing under climate change, recent scientific evidence indicates that climatic variability, unstable winter conditions and earlier phenological development may increase crop exposure to damaging late frost episodes (IPCC, 2022; Vitasse et al., 2018). Warmer winter and early spring conditions may accelerate flowering and vegetative growth, thereby increasing the likelihood that crops will be exposed to subsequent cold outbreaks during vulnerable developmental stages.

This phenomenon is especially relevant for Mediterranean agricultural systems and high-value perennial crops such as lemons, oranges, apricots, pears and vineyards, where even short-duration frost events may result in substantial reductions in yield quantity, fruit quality and long-term tree productivity. In several regions of Greece and Southern Europe, repeated frost events during recent years have generated considerable economic losses, increased operational uncertainty and heightened pressure on agricultural adaptation systems.

Existing frost protection practices are generally classified into passive and active protection measures. **Passive measures** aim to reduce the inherent vulnerability of

agricultural systems before frost events occur and typically include appropriate site selection, use of frost-tolerant cultivars and rootstocks, orchard design, pruning management, vegetation control, soil management and optimization of local microclimatic conditions. These measures generally provide long-term resilience benefits and lower operational costs; however, they may not always provide sufficient protection during severe frost episodes. **Active frost** protection measures are implemented immediately before or during frost events and include heaters, fuel-based systems, wind machines, sprinkler and micro-sprinkler irrigation systems, targeted spraying applications and other emergency response techniques. According to FAO technical guidance, active protection methods may provide effective crop protection under specific frost conditions, particularly radiation frost events; however, they are often energy-intensive, operationally demanding and highly dependent on accurate timing and local meteorological conditions (FAO, 2005).

Fuel-based heaters and orchard heating systems are among the oldest and most widely used active frost protection measures. These systems aim to increase air temperature around the crop canopy and reduce freezing conditions near sensitive plant tissues. Although heaters may provide satisfactory protection under mild radiation frost conditions, they are associated with substantial operational costs, high fuel consumption and increased greenhouse gas emissions. Their effectiveness is also significantly reduced during advective frost events, where strong cold-air advection and wind limit the capacity of localized heating systems to maintain protective temperatures (FAO, 2005).

Wind machines are widely used in orchards exposed to radiation frost and temperature inversion conditions. Their operation is based on vertical mixing between warmer air layers above the crop canopy and colder air near the surface. Under favorable inversion conditions, wind machines may substantially reduce frost damage. However, their effectiveness decreases considerably when inversion layers are weak or absent and during severe advective frost conditions characterized by strong winds and large-scale cold-air masses (FAO, 2005; Bourgeois et al., 2005). In addition, wind machines involve significant installation and maintenance costs and may generate noise-related impacts in rural areas.

Sprinkler and micro-sprinkler irrigation systems are considered among the most effective active frost protection techniques when properly designed and continuously operated during frost events. These systems protect plant tissues through the release of latent heat during the freezing process of water on plant surfaces. However, their effectiveness depends on uninterrupted water supply, adequate hydraulic infrastructure and precise operational management. In Mediterranean regions already affected by water scarcity and increasing drought conditions, the long-term sustainability of irrigation-based frost protection systems may be constrained by growing pressure on

water resources and increasing competition among agricultural, urban and environmental water uses (FAO, 2005a; FAO, 2005b).

In some agricultural systems, farmers also apply **spraying practices** and chemical formulations intended to reduce frost damage or improve plant resistance under cold conditions. However, the effectiveness of such practices remains highly variable and strongly dependent on timing, climatic conditions, crop type and proper application methods. In many cases, premature or unnecessary applications may increase production costs and environmental burdens without providing proportional protection benefits.

Within the framework of the LIFE FROSTDEFEND project, four copper-based spraying treatments were evaluated for their effectiveness in reducing bacterial ice-nucleation activity and limiting frost damage in citrus trees (Figure 22). All tested products reduced bacterial populations within a few days of application. For two of the four products, ice-nucleation activity on the leaves was reduced by 100% within 48 hours, and this effect persisted for more than 11 days after spraying. The results were encouraging. When the treatments were applied at least 48 hours before a frost event, frost symptoms were reduced by 35% compared with those observed in unsprayed trees. These findings indicate that timely application of copper-based treatments may help protect citrus crops against frost damage.

Overall, current frost-risk management practices remain predominantly reactive, fragmented and insufficiently integrated with operational climate services and evidence-based adaptation planning. Several important limitations continue to reduce the effectiveness, sustainability and economic feasibility of conventional frost protection approaches. These include high energy and operational costs, dependence on highly accurate timing, reduced effectiveness during severe or advective frost events, high water demand associated with irrigation-based systems, greenhouse gas emissions from fuel-based practices and limited availability of localized real-time frost-risk information. In addition, existing practices are often poorly integrated with agricultural advisory services, climate adaptation planning and agricultural insurance mechanisms.

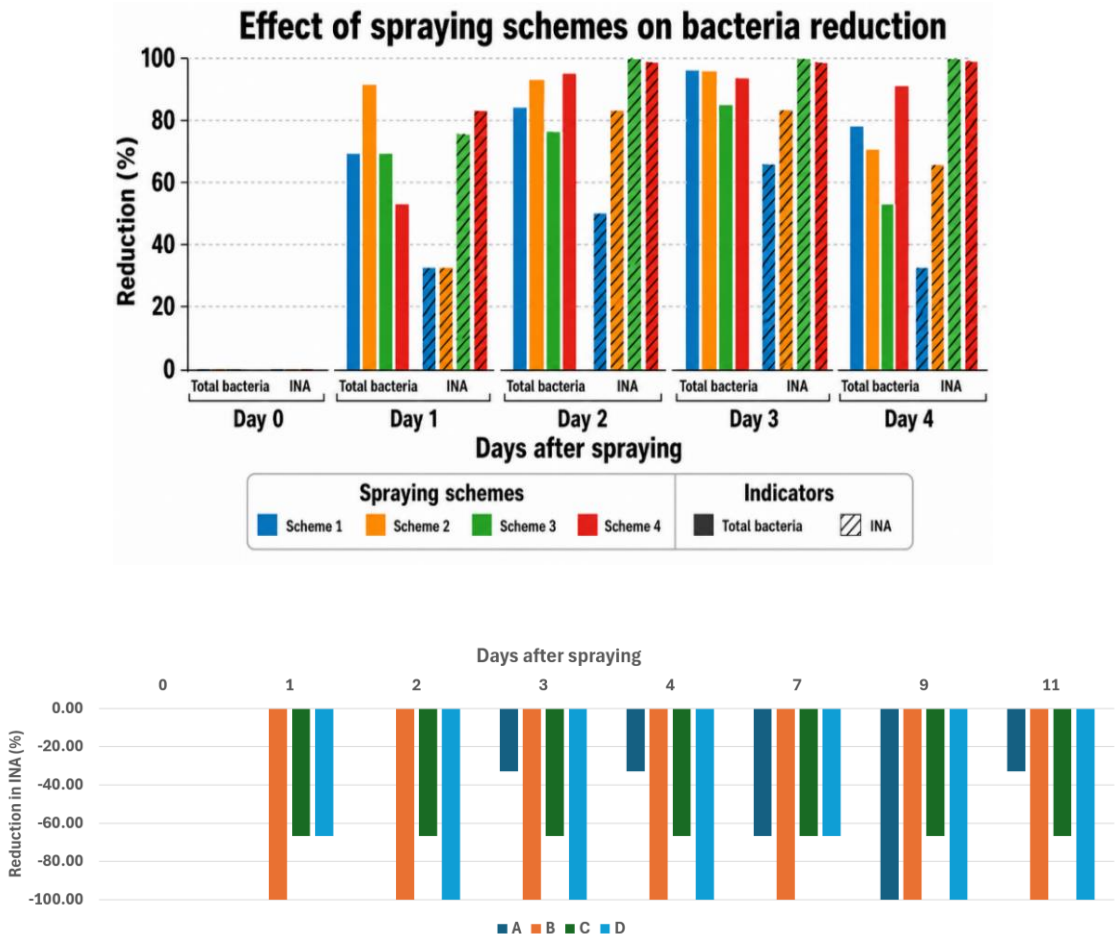


Figure 22: Effect of copper-based spraying treatments on bacterial ice-nucleation activity (A: Copper sulfate pentahydrate, B: Copper hydroxide, C: Copper sulfate, D: Copper oxychloride)

Consequently, there is an increasing need for integrated, data-driven and operationally efficient frost adaptation frameworks capable of combining localized monitoring, forecasting, preparedness and targeted intervention measures. Within this context, LIFE-FROSTDEFEND aims to support the transition from reactive and resource-intensive frost protection approaches towards preventive, climate-smart and operationally optimized adaptation systems.

7.2 Efficient Frost Protection Guidelines

The effectiveness of frost protection measures depends strongly on the accuracy and timing of operational decisions. Activation of protection systems after critical temperature thresholds have already been exceeded may result in irreversible crop damage, whereas premature activation under low-risk conditions may lead to unnecessary fuel consumption, excessive water use and increased labour costs.

According to FAO technical guidance, efficient frost protection requires accurate assessment of local meteorological conditions, temperature evolution, frost type and crop-specific vulnerability thresholds in order to determine the appropriate timing and duration of interventions (FAO, 2005).

Within the LIFE FROSTDEFEND framework, frost-protection practices are supported through the integration of real-time meteorological monitoring, localized minimum-temperature forecasting, crop-specific critical temperature thresholds, and phenological-stage assessment. The methodology also incorporates relevant environmental and biological observations associated with atmospheric conditions and potential ice-nucleation processes that may influence frost formation and crop susceptibility. By combining climatic, environmental, phenological, and operational information, the framework supports evidence-based frost-risk assessment, localized forecasting, and adaptation planning. Table 7 summarizes the main monitoring categories, parameters, and their operational roles within the framework.

The FROSTDEFEND operational tool translates these monitoring inputs into localized frost-risk information, forecasts, and practical decision-support guidance for farmers, cooperatives, and advisory services. This can help stakeholders improve preparedness and make more timely and informed decisions on the implementation of frost-protection measures when meteorological and crop conditions indicate an elevated risk. In this way, the tool can contribute to reducing unnecessary interventions and to more efficient allocation of financial, technical, and natural resources.

The LIFE FROSTDEFEND approach also supports more sustainable and cost-efficient frost management. Conventional measures, including heaters, wind machines, and irrigation-based protection systems, can be effective under specific conditions but may involve substantial energy use, greenhouse gas emissions, water consumption, and other resource requirements. Their application should therefore be targeted to periods of elevated frost risk and, where possible, informed by early-warning and decision-support tools. The frost-risk prediction tool developed within LIFE FROSTDEFEND can support more timely and informed decisions regarding the implementation of such protection measures.

In parallel, LIFE FROSTDEFEND has evaluated copper-based spraying schemes as a potential approach for reducing frost damage, with particular emphasis on the timing of application. Their use may be particularly relevant as an additional protection option during periods of elevated frost risk, subject to the crop, local conditions, and the demonstrated effectiveness of the treatment. The framework also considers the use of frost-tolerant cultivars and rootstocks where suitable options are available and their adoption is agronomically and economically feasible.

The integrated monitoring and decision-support approach (Table 6) adopted by LIFE-FROSTDEFEND is fully consistent with the objectives of the EU Strategy on Adaptation to Climate Change, which emphasizes smarter, data-driven and more systemic adaptation supported by climate services, early-warning systems and operational preparedness mechanisms (European Commission, 2021). Through the combination of scientific monitoring, operational forecasting and stakeholder-oriented adaptation support, the project contributes to strengthening agricultural resilience while reducing the environmental and socioeconomic costs associated with conventional frost protection practices.

Table 6. LIFE-FROSTDEFEND Integrated Monitoring Components

Monitoring Component	Variables	Operational Role
Meteorological Monitoring	Temperature, humidity	Frost forecasting
Atmospheric Monitoring	$PM_{2.5}$, CO_2	Environmental proxy assessment
Phenological Monitoring	Temperature, photoperiod, frost hardiness	Crop vulnerability assessment
Biological Indicators	INA bacterial activity (indirect estimation)	Biological frost-risk assessment
IoT Monitoring Systems	Real-time environmental measurements	Localized operational support
Decision-Support Functions	Alerts, intervention timing	Preparedness and adaptation

This approach is fully aligned with the EU Strategy on Adaptation to Climate Change, which emphasizes the need for smarter, faster and more systemic adaptation based on improved climate-risk knowledge, digital climate services and evidence-based local adaptation planning (European Commission, 2021).

7.3 Proposed Adaptation Measures

7.3.1 Early-Warning and Preparedness Measures

Early-warning systems. The development and use of early-warning systems constitute a priority adaptation measure for frost-sensitive agriculture. Early-warning systems can reduce climate-related losses by improving preparedness and enabling timely action before the occurrence of damaging events. In the context of LIFE FROSTDEFEND, the early-warning tool provides farmers with localized frost-risk information, helping them decide whether, when and how to activate protection measures.

The measure includes:

- installation and use of localized frost monitoring systems;

- collection of meteorological and field-level data;
- generation of frost-risk alerts;
- communication of warnings to farmers and cooperatives;
- integration of crop-specific thresholds;
- seasonal review of forecast performance.

This measure directly addresses the lack of localized operational information, which is one of the main limitations of conventional frost protection.

Preparedness protocols. In addition to early-warning alerts, farmers and cooperatives should develop preparedness protocols before the frost season. These protocols should define responsibilities, communication channels, available equipment, activation thresholds and emergency response procedures.

Preparedness measures include:

- preparation of frost response plans at farm or cooperative level;
- regular inspection of protection equipment;
- identification of high-risk plots;
- pre-season farmer training;
- coordination with advisory services;
- systematic recording of frost events and actions taken.

This measure is considered highly relevant because frost protection requires rapid and coordinated action during short time windows.

7.3.2 Agronomic and Ecosystem-Based Practices

Cultivar and rootstock selection. Selection of more frost-tolerant cultivars and rootstocks is an important long-term adaptation option, particularly in regions where frost events repeatedly damage sensitive crops. This measure is especially relevant for future re-cultivation decisions in areas where lemon orchards have been abandoned due to frost risk. Climate adaptation literature identifies cultivar selection and crop diversification as important agricultural adaptation options (EEA, 2020; Climate-ADAPT, 2024).

Soil and vegetation management. Soil moisture, vegetation cover and surface management influence local microclimatic conditions and frost formation. Well-managed soil can improve heat storage during the day and heat release during the night, while excessive vegetation cover may reduce heat absorption and increase frost risk under certain conditions. Appropriate management should therefore be adapted to the local frost mechanism and crop system (FAO, 2005a).

Recommended practices include:

- maintaining suitable soil moisture before frost events where feasible;
- avoiding excessive weed or grass cover in frost-prone orchards during critical periods;
- improving organic matter and soil structure;
- maintaining drainage and avoiding waterlogging;
- using vegetation strategically to support ecosystem functions without increasing frost exposure.

Crop diversification and spatial planning. In high-risk zones, diversification of crops or relocation of highly sensitive cultivations to less frost-prone areas may reduce vulnerability. This is particularly relevant for lowland areas where cold-air accumulation is frequent. Regional adaptation planning highlights the importance of adjusting agricultural practices to local climate risks and strengthening the resilience of vulnerable agricultural systems.

Ecosystem-based approaches. Ecosystem-based adaptation measures can support long-term resilience by improving soil health, biodiversity and landscape functionality. Although such measures may not replace active frost protection during severe events, they can contribute to improved adaptive capacity and sustainability of agricultural systems.

7.3.3 Emergency Frost Response Measures

Activation of protection systems during frost events. Emergency response measures are required when forecasted conditions indicate high frost risk for sensitive crops. The selection of the appropriate response depends on frost type, crop stage, available infrastructure and expected event duration.

Emergency measures may include:

- activation of wind machines during radiation frost and temperature inversion conditions;
- use of sprinkler or micro-sprinkler systems where water availability and infrastructure allow;
- targeted spraying according to agronomic recommendations;
- prioritization of high-value or highly vulnerable plots;
- continuous monitoring during the event;
- post-event assessment of crop damage.

The use of these emergency measures should be based on the FROSTDEFEND early-warning tool and local observations. This reduces the risk of unnecessary activation and supports more efficient use of energy, water and labour.

Post-event inspection and recovery. Following a frost event, farmers should assess crop damage and avoid premature pruning or removal of damaged tissues until the full extent of damage is clear. Technical guidance for citrus crops recommends delayed assessment after frost damage, since immediate pruning may increase stress or remove tissues that could recover (UC ANR, 2005).

Post-event measures include:

- inspection of flowers, young fruits and shoots;
- estimation of yield loss;
- recording of applied protection measures;
- reporting of damages to cooperatives or insurance bodies;
- adjustment of future management practices based on observed damage.

7.4 Cost-Benefit, Environmental and Social Considerations

Economic feasibility. The economic feasibility of frost adaptation measures depends on installation cost, operating cost, crop value, expected avoided losses and frequency of frost events. Active protection systems such as heaters, wind machines and sprinklers may reduce crop losses, but they require investment and operational expenditure. Their cost-effectiveness is therefore strongly linked to correct timing and frequency of use (FAO, 2005a; FAO, 2005b).

The FROSTDEFEND tool improves economic feasibility by supporting:

- more accurate activation of protection measures;
- reduced unnecessary operating hours;
- lower fuel and electricity consumption;
- better prioritization of high-risk areas;
- improved documentation of interventions and losses.

This is particularly important for small and medium-sized farms, where repeated frost protection costs can place significant pressure on farm income.

Environmental performance and sustainability. Frost protection methods can have environmental impacts, particularly when they rely on fossil fuels, high electricity consumption or excessive water use. Fuel-based heaters contribute to greenhouse gas emissions and local air pollutants, while irrigation-based methods may increase

pressure on water resources. In this context, the LIFE FROSTDEFEND approach promotes targeted, lower-emission and resource-efficient adaptation.

Expected environmental benefits include:

The integrated methodological framework of LIFE FROSTDEFEND may additionally improve the environmental efficiency of frost protection by reducing unnecessary interventions triggered solely by generalized temperature forecasts. Improved differentiation between low-risk and operationally significant frost conditions may contribute to lower fuel consumption, reduced water use and optimized application of frost-protection practices.

- reduction of unnecessary fuel use;
- lower CO_2 emissions compared with conventional continuous activation;
- reduced air pollutant emissions;
- improved water-use efficiency;
- better alignment with sustainable agriculture and climate adaptation objectives.

The monitoring module of the FROSTDEFEND tool can support the estimation of eCO_2 emissions by recording intervention timing, number of applications, type of measure used and location. These data can be compared with conventional frost protection scenarios, such as continuous use of heaters or wind machines, to estimate avoided emissions and operational savings.

Socioeconomic Considerations. Frost events can generate significant socioeconomic impacts on agricultural production systems, rural economies and local communities. In the participating regions of LIFE-FROSTDEFEND, agriculture represents an important economic activity closely linked to employment, exports, local processing industries and rural development. Consequently, repeated frost incidents may have direct and indirect impacts extending beyond individual farm losses. The most immediate impacts of frost events concern crop damage and production losses (Figure 16). Citrus crops, particularly lemons and oranges, are highly sensitive to low temperatures during flowering and fruit development stages. Frost incidents may result in reduced fruit set, damage to flowers and young fruits, deterioration of fruit quality and, in severe cases, destruction of productive trees. Such impacts directly affect agricultural income and farm viability.

In recent years, several frost events in Greece have caused significant damages to citrus-producing regions, leading to reduced yields and increased financial pressure on farmers. In some areas, repeated climate-related losses have discouraged the continuation of frost-sensitive cultivations, particularly lemon orchards that require stable production conditions and long-term investment. The gradual abandonment of certain cultivations may also affect local agricultural identity and reduce the economic

diversity of rural areas. Economic impacts are further intensified by the operational costs associated with frost protection practices. Conventional protection measures such as heaters, wind machines and sprinklers, mist or surface irrigation may require high energy consumption and substantial financial resources. Farmers often need to apply emergency protection measures under uncertain climatic conditions, increasing operational risks and production costs.

Frost-related damages also affect agricultural cooperatives, local markets and agri-food supply chains. Reduced production volumes may impact product availability, processing activities and export capacity, particularly in regions where citrus production constitutes an important component of local economic activity. Indirect economic impacts may therefore extend to employment, transportation, packaging and commercial activities associated with agricultural production.

At regional level, climate-related agricultural losses may increase pressure on compensation and insurance mechanisms. In Greece, ELGA plays a central role in assessing and compensating agricultural damages caused by extreme weather events, including frost. Increasing frequency and severity of climate-related damages may create additional economic burdens for both producers and public support mechanisms.

The LIFE-FROSTDEFEND project aims to contribute to the reduction of these socioeconomic impacts through improved preparedness, better targeting of protection measures and enhanced decision-making support. The implementation of the FROSTDEFEND tool is expected to help farmers optimize frost protection interventions, reduce unnecessary operational costs and improve the efficiency of adaptation responses. In addition to direct economic benefits, the project supports broader climate resilience objectives by strengthening stakeholder awareness, improving access to climate-risk information and promoting sustainable adaptation practices. The long-term objective is to support the continuity and sustainability of frost-sensitive agricultural production systems while enhancing the resilience of local agricultural economies under changing climatic conditions.

Overall assessment. Based on the above, early-warning and decision-support systems are considered a priority adaptation option because they improve both economic and environmental performance. They do not necessarily replace all existing frost protection systems, but they increase their efficiency by ensuring that they are used only when needed and under appropriate conditions. Table 7 provides a summary of the identified threats and corresponding adaptation measures.

Table 7. Summary of Threats and Adaptation Measures

Threat / Climate hazard	Main potential impacts	Proposed adaptation measures

Frost and late spring frost	Flower damage, young fruit loss, reduced yield, tree tissue damage	Early-warning system, frost-risk alerts, optimized activation of protection measures
Radiative frost and cold-air accumulation	Localized severe damage in lowland orchards	Mapping of frost-prone zones, wind machines where inversion exists, soil and vegetation management
Severe frost below critical thresholds	Major production losses and possible tree damage	Emergency response protocols, sprinkler/micro-sprinkler systems where feasible, targeted protection
Increased climatic variability	Earlier flowering and higher exposure to late frost	Phenological monitoring, cultivar/rootstock selection, adaptive farm planning
High operating cost of conventional protection	Increased production costs and reduced profitability	Decision-support tools, reduced unnecessary activation, cost-benefit monitoring
Environmental burden from frost protection	Fuel use, CO_2 emissions, water demand	Low-emission practices, efficient timing, monitoring of CO_2 savings

8. Stakeholder Engagement and Capacity Building

8.1 Stakeholder Mapping and Participation

The successful implementation and long-term sustainability of the LIFE-FROSTDEFEND Adaptation Plan depend fundamentally on the active involvement, cooperation and coordination of a broad network of stakeholders operating across the agricultural, scientific, institutional and policy sectors. Frost-risk management and climate adaptation in agriculture are inherently multidisciplinary challenges requiring continuous interaction among farmers, agricultural cooperatives, scientific institutions, public authorities, advisory services, environmental organizations and agricultural risk-management bodies. The LIFE-FROSTDEFEND project therefore adopts a participatory and multi-level stakeholder engagement approach (Figure 23) aiming to strengthen climate resilience through knowledge sharing, operational cooperation and collective adaptation planning.

The stakeholder engagement strategy has been designed to support not only the implementation of the project itself but also the broader integration of climate adaptation into local agricultural governance and operational decision-making processes. Particular emphasis is placed on strengthening communication between scientific institutions and end-users, improving accessibility of climate-risk information, enhancing local preparedness and fostering long-term ownership of adaptation measures among agricultural stakeholders.

The stakeholder mapping process identified a wide range of actors directly or indirectly associated with frost-risk management and agricultural resilience within the pilot and replication regions. These stakeholders differ in terms of responsibilities, operational roles, institutional capacities and levels of influence, yet all contribute to the overall effectiveness and sustainability of the adaptation framework.

Farmers and Agricultural Producers

Farmers constitute the principal target group and the primary end-users of the LIFE-FROSTDEFEND adaptation framework. The project focuses especially on producers cultivating frost-sensitive perennial crops such as citrus and additional temperate fruit-tree cultivations exposed to spring frost events and temperature variability. In the participating regions of Achaia, Argolida and Laconia, citrus production represents a major component of local agricultural economies and a critical source of income for rural communities. Agricultural producers are directly exposed to the impacts of climate variability and constitute the first operational level of response during frost events. Their participation is therefore essential not only for the practical implementation of adaptation measures but also for the operational evaluation and continuous improvement of the FROSTDEFEND system. Farmers contribute through the use of the early-warning platform, implementation of frost protection interventions, provision of field observations and recording of operational practices and crop losses. Their experiential knowledge regarding local climatic conditions, crop behaviour and effectiveness of protection measures constitutes a particularly valuable component of the adaptation process.

Special emphasis is placed on the participation of small and medium-sized farms, which frequently present higher vulnerability to climate-related risks due to limited financial resources, reduced access to technological infrastructure and dependence on highly sensitive cultivation systems. Through targeted dissemination, training and technical support activities, the project aims to strengthen the adaptive capacity of these producers and support the gradual transition from reactive to preventive frost-risk management approaches.

The project additionally seeks to promote behavioural and operational changes among producers by encouraging the use of evidence-based decision-making, optimized timing of interventions and more environmentally sustainable frost protection practices. In this context, farmers are not treated merely as recipients of technical information but as active participants in the co-development of operational adaptation strategies.

Agricultural Cooperatives and Producer Organizations

Agricultural cooperatives and producer organizations represent one of the most important stakeholder groups within the LIFE FROSTDEFEND framework due to their

central role in local agricultural governance, communication and operational coordination. In the participating regions, cooperatives act as key intermediaries connecting farmers with scientific institutions, authorities, advisory bodies and agricultural markets.

Particularly in Achaia, Argolida and Laconia, citrus cooperatives possess extensive operational networks and longstanding relationships with local producers. Their participation significantly enhances the dissemination potential and practical applicability of the project. Cooperatives contribute to the communication of frost-risk alerts, dissemination of operational recommendations, organization of stakeholder meetings and facilitation of training and awareness activities. They also support the collection of field data and feedback regarding adaptation practices and intervention effectiveness.

The involvement of cooperatives is especially important for ensuring the long-term sustainability and transferability of the adaptation framework beyond the duration of the LIFE project. Due to their organizational structure and local presence, cooperatives are expected to play a major role in the continuation of operational monitoring, communication of early-warning information and promotion of adaptation practices during the After-LIFE implementation phase.

Producer organizations additionally contribute to strengthening collective preparedness and coordinated operational responses during frost-risk periods. The project therefore promotes the development of stronger local cooperation mechanisms capable of improving both adaptation effectiveness and regional resilience.

The project consortium includes the Agricultural Cooperatives Union Aeghion S.A. (ACUA) as a project partner. The Union comprises 44 agricultural cooperatives representing approximately 6,000 active producers and will play a key role in disseminating and promoting the FROSTDEFEND Tool.

Scientific and Research Institutions

Scientific and research institutions constitute the technical and scientific foundation of LIFE FROSTDEFEND. The participating organizations provide expertise in climate science, atmospheric monitoring, frost forecasting, agricultural vulnerability assessment, environmental analysis, adaptation planning and digital tool development.

The project consortium includes major scientific partners such as:

- the National Centre for Scientific Research “Demokritos” (NCSR-D),
- the Agricultural University of Athens (AUA),
- the French National Research Institute for Agriculture, Food and Environment (INRAE).

NCSR "Demokritos" contributes advanced expertise in atmospheric sciences, environmental monitoring and climate-risk assessment, supporting the development of the monitoring and forecasting components of the FROSTDEFEND tool. The Agricultural University of Athens supports agricultural monitoring activities, crop vulnerability analysis, stakeholder engagement and agronomic evaluation of frost impacts. INRAE contributes scientific expertise related to agricultural resilience, climate adaptation and implementation of replication activities within the French pilot region.

The scientific institutions participating in the project are responsible for:

- development and operation of the FROSTDEFEND early-warning system,
- processing and analysis of meteorological and operational datasets,
- preparation of adaptation guidelines and technical recommendations,
- vulnerability and risk assessment,
- scientific validation of forecasting methodologies,
- support for dissemination and capacity-building activities,
- evaluation of transferability and replication potential.

Beyond their technical role, research institutions also act as intermediaries between scientific knowledge and operational agricultural practice, facilitating the translation of climate adaptation policies into practical field-level applications.

Public Authorities and Institutional Stakeholders

Public authorities and institutional stakeholders play a critical role in supporting climate adaptation governance, agricultural resilience planning and long-term policy integration. The LIFE-FROSTDEFEND Adaptation Plan has been developed in close alignment with European, national and regional adaptation strategies and therefore maintains strong relevance for competent authorities operating in the fields of environment, agriculture and climate policy.

Key institutional stakeholders include:

- the Ministry of Environment and Energy of Greece,
- the Ministry of Rural Development and Food,
- regional authorities and local municipalities,
- environmental and agricultural agencies,
- French climate adaptation and agricultural authorities,
- regional and local public administrations.

These authorities contribute to the project through support for regional adaptation planning, dissemination of climate adaptation information, facilitation of stakeholder

coordination and integration of project outputs into broader policy frameworks. Their participation strengthens the institutional legitimacy and policy relevance of the adaptation framework while enhancing opportunities for future operational implementation and replication. Regional authorities are particularly important due to their responsibility for the implementation of Regional Climate Change Adaptation Plans (PeSPKA) and regional agricultural resilience policies. The project may support these authorities through the provision of localized climate-risk information, operational adaptation experience and evidence-based recommendations for agricultural adaptation planning.

Municipal authorities also represent important local stakeholders because frost-related damages frequently generate broader socioeconomic consequences affecting local economies, employment and rural development. Their participation contributes to strengthening local preparedness and improving communication among communities and agricultural actors.

Agricultural Insurance and Risk-Management Organizations

Agricultural insurance bodies and climate-risk management organizations constitute another important stakeholder category due to the increasing economic impacts associated with frost-related agricultural damages. In Greece, the Hellenic Agricultural Insurance Organization (ELGA) represents a particularly significant stakeholder because of its central role in agricultural compensation and risk assessment processes.

The LIFE-FROSTDEFEND project may support agricultural insurance and compensation mechanisms through:

- improved frost-risk monitoring,
- localized meteorological information,
- documentation of intervention practices,
- seasonal crop-loss observations,
- operational datasets regarding frost protection effectiveness.

The availability of more detailed and spatially targeted climate-risk information may contribute to future improvements in agricultural risk assessment methodologies, climate-related compensation procedures and development of more adaptive agricultural insurance mechanisms.

The project additionally creates opportunities for stronger cooperation between adaptation planning and agricultural risk-management systems, contributing to more integrated approaches for managing climate-related agricultural losses.

Agricultural Advisory Services

Agricultural advisors and technical consultants represent an essential link between scientific knowledge and agricultural practice. Their participation is particularly important for facilitating the operational implementation of adaptation measures and supporting farmer capacity building.

Advisory bodies contribute through:

- transfer of technical and scientific knowledge,
- communication of operational recommendations,
- support for implementation of adaptation practices,
- organization of training activities,
- facilitation of adoption of innovative tools and methodologies.

The integration of advisory services into the LIFE-FROSTDEFEND framework enhances the long-term sustainability and practical applicability of the proposed adaptation measures. Advisors may continue supporting dissemination and operational use of the FROSTDEFEND tool after the completion of the LIFE project, thereby strengthening the continuity of adaptation activities during the After-LIFE phase.

Civil Society, Local Communities and Environmental Stakeholders

In addition to institutional and agricultural stakeholders, the project recognizes the importance of broader community participation and environmental awareness. Local communities, environmental organizations and civil society actors may contribute to strengthening climate adaptation awareness, promoting environmentally sustainable agricultural practices and supporting wider dissemination of project results.

The LIFE FROSTDEFEND project also seeks to strengthen public awareness regarding the relationship between climate change, atmospheric conditions, frost occurrence and agricultural resilience. Through dissemination campaigns, workshops, training sessions and communication activities, the project promotes greater understanding of climate adaptation challenges and encourages wider societal engagement in resilience-building processes.

Stakeholder Participation as a Pillar of Long-Term Sustainability

Overall, stakeholder participation constitutes a central pillar of the LIFE FROSTDEFEND adaptation framework. The project adopts a collaborative governance approach, recognizing that successful agricultural adaptation cannot be achieved through technological solutions alone, but also requires continuous communication, institutional coordination, stakeholder trust and local participation. By bringing

together scientific institutions, public authorities, cooperatives, producers, advisors and local communities within a common adaptation framework, LIFE FROSTDEFEND enhances the operational relevance, policy applicability and long-term sustainability of its outputs, while supporting the development of more resilient agricultural systems under changing climatic conditions.



Figure 23. LIFE FROSTDEFEND STAKEHOLDERS engagement scheme

8.2 Awareness Raising and Training

The LIFE-FROSTDEFEND project recognizes that effective climate adaptation in agriculture requires substantial improvement of awareness, knowledge transfer, behavioral change and long-term capacity building among all stakeholders involved in agricultural production and climate-risk management. Increasing climatic variability and the growing complexity of frost-related risks require farmers and agricultural actors to progressively adopt more informed, preventive and scientifically supported adaptation approaches. In this context, awareness-raising and training activities constitute a fundamental pillar of the LIFE FROSTDEFEND adaptation framework and contribute directly to the long-term sustainability and operational effectiveness of the project.

The project therefore adopts a comprehensive participatory communication and capacity-building strategy targeting:

- farmers and agricultural producers,

- agricultural cooperatives and producer organizations,
- advisory services and extension bodies,
- local and regional authorities,
- scientific institutions,
- environmental stakeholders,
- the wider agricultural and rural community.

The overall objective of the awareness and training strategy is to strengthen the adaptive capacity of local agricultural systems through improved understanding of frost-risk dynamics, climate change impacts and operational adaptation measures. Particular emphasis is placed on promoting a transition from reactive and experience-based responses towards proactive, data-driven and climate-smart agricultural practices.

The LIFE-FROSTDEFEND communication approach additionally seeks to strengthen long-term climate adaptation culture within agricultural communities by improving accessibility to climate-risk information and increasing familiarity with operational adaptation tools and sustainable frost protection methodologies.

Dissemination and Communication Activities

Dissemination and communication activities are implemented mainly through Actions E1 and E2 of the LIFE-FROSTDEFEND project and constitute one of the principal mechanisms for transferring scientific knowledge and operational experience to end-users and relevant stakeholders.

The dissemination framework includes a broad range of communication and outreach activities designed to maximize the visibility, accessibility and practical applicability of project outputs. These activities include:

- stakeholder workshops and consultation meetings;
- technical seminars and scientific presentations;
- farmer training sessions;
- local and regional awareness events;
- participation in agricultural exhibitions;
- pilot demonstrations;
- dissemination campaigns through digital and printed media;
- networking activities with agricultural and environmental stakeholders.

Particular emphasis is placed on dissemination activities within the pilot and replication regions of Achaia, Argolida, Laconia and Puy-de-Dôme, where agricultural stakeholders directly affected by frost-related climate risks may benefit from practical guidance and operational support. Local dissemination activities facilitate direct

interaction between farmers, researchers and authorities, improving trust, communication and acceptance of adaptation measures.

The LIFE-FROSTDEFEND project additionally promotes transnational exchange of experience and best practices between Greece and France, strengthening the European dimension of the project and supporting transferability of adaptation approaches under different agricultural and climatic conditions.

Communication tools developed within the project include:

- the project website and digital communication platforms;
- newsletters;
- technical manuals and operational guidance documents;
- awareness leaflets;
- scientific and technical reports;
- social media and online communication activities.

These dissemination tools are intended to ensure broad accessibility of project outputs and facilitate the practical uptake of adaptation recommendations by different stakeholder groups.

Farmer Engagement and Participatory Adaptation

Farmer engagement represents one of the central pillars of the LIFE-FROSTDEFEND adaptation framework. The project adopts a strongly participatory approach recognizing that successful agricultural adaptation requires active involvement of end-users in all implementation stages, including monitoring, evaluation and refinement of adaptation measures.

The project therefore aims not only to provide technical information but also to support behavioral and operational changes regarding frost-risk management and climate adaptation practices. Particular emphasis is placed on encouraging:

- proactive rather than reactive operational responses;
- use of localized climate-risk information;
- optimized timing of frost protection interventions;
- reduction of unnecessary operational practices;
- environmentally sustainable and resource-efficient adaptation measures;
- improved preparedness and operational planning.

Participating farmers are actively involved through:

- surveys and structured questionnaires;
- pilot implementation activities;

- operational testing of the FROSTDEFEND tool;
- provision of field observations;
- seasonal evaluation of intervention effectiveness;
- recording of crop damages and operational practices;
- participation in workshops, meetings and training activities.

This participatory approach allows adaptation recommendations and operational thresholds to be continuously refined according to:

- local climatic conditions,
- crop-specific characteristics,
- operational realities,
- farmer experience,
- stakeholder needs and expectations.

The direct involvement of producers significantly improves the practical applicability and acceptance of the adaptation framework while strengthening local ownership and long-term sustainability of project outputs.

Capacity-Building Activities

Capacity building constitutes a key component of the LIFE FROSTDEFEND stakeholder engagement strategy. The project recognizes that many agricultural stakeholders have limited access to specialized climate-risk information and operational forecasting tools. Its capacity-building activities are therefore designed to strengthen the technical knowledge and practical skills of farmers and local stakeholders in relation to frost-risk preparedness and adaptation planning.

The main areas addressed include:

- interpretation of frost-risk forecasts and early-warning information;
- operational use of the FROSTDEFEND Tool;
- understanding of the meteorological conditions associated with frost formation;
- identification of critical crop phenological stages;
- selection and implementation of efficient and cost-effective frost protection measures;
- assessment of the effectiveness of operational interventions;
- evaluation of the environmental impacts of frost protection practices; and
- application of sustainable and climate-smart adaptation approaches.

Practical demonstrations and pilot applications complement theoretical instruction by familiarizing participants with operational procedures and increasing confidence in the use of scientific forecasting and decision-support systems. Field-based activities also

encourage the direct exchange of experience among farmers and support the dissemination of effective practices within local agricultural communities.

In addition, the project promotes the establishment of local adaptation knowledge networks to support long-term preparedness, peer learning and the continuous improvement of frost-management practices beyond the duration of the LIFE project.

Long-Term Capacity Building and Sustainability

Overall, awareness raising, training and stakeholder engagement activities are designed not only to support the implementation of the LIFE-FROSTDEFEND project during its operational phase but also to establish long-term adaptive capacity within local agricultural systems.

By strengthening technical knowledge, operational preparedness, institutional cooperation and climate-risk awareness, the project contributes to:

- improved resilience of agricultural communities;
- stronger cooperation among stakeholders;
- increased adoption of sustainable adaptation practices;
- enhanced preparedness for future climate-related risks;
- long-term sustainability of operational adaptation mechanisms.

The project therefore supports the gradual development of a climate adaptation culture within the agricultural sector, capable of improving resilience, reducing vulnerability and strengthening the capacity of local communities to respond effectively to future climatic challenges.

8.3 Transferability, Replication and After-LIFE Sustainability

Transferability, replication and long-term sustainability are central to the LIFE FROSTDEFEND project and align with the LIFE Programme's objectives for demonstration, scalability and policy uptake. The project was designed not only as a pilot initiative for selected agricultural regions, but also as an adaptable climate-risk management framework for frost-prone agricultural systems across Europe.

LIFE FROSTDEFEND integrates localized meteorological monitoring, frost forecasting and early-warning systems, crop-specific vulnerability thresholds, sustainable protection measures and evidence-based decision support. Its structure allows the methodology and the FROSTDEFEND Tool to be adapted to different climatic conditions, crops, farm structures, technological capacities and institutional settings without major structural changes. The use of widely available meteorological data and compatibility with existing advisory systems further support broader implementation.

The pilot area in Achaia (Aigio) and the replication regions in Argolida (Argos), Laconia (Sparti) and Puy-de-Dôme (Clermont-Ferrand) enable the framework to be tested under diverse agroclimatic and operational conditions. Achaia provides the main testing environment because of the economic importance and frost sensitivity of its citrus production, particularly lemon cultivation. Argolida and Laconia represent additional Mediterranean citrus-growing areas exposed to cold-air accumulation and localized frost, while Puy-de-Dôme provides a contrasting climatic and agricultural context in central France, characterized by cooler conditions. This multi-regional approach strengthens the scientific validity and European replication potential of the project.

The methodology may subsequently be transferred to other frost-prone regions and adapted to citrus crops, vineyards, orchards, perennial crops, high-value horticultural systems and protected cultivation. Its flexibility is particularly relevant as changing flowering periods and increasing climatic variability create new frost vulnerabilities in areas previously considered less exposed.

The After-LIFE strategy focuses on maintaining the operational use and institutional integration of project outputs through continued cooperation among research institutions, public authorities, agricultural advisors, cooperatives and producers. Long-term activities may include frost-risk monitoring, seasonal forecasting, regular updating of recommendations, dissemination of alerts and collection of intervention data.

Agricultural advisory services and cooperatives will be important for ensuring continued access to forecasting information and operational guidance. Their established communication networks can support farmer preparedness, local coordination and the practical application of project results. The project's datasets, methodologies and recommendations may also contribute to regional adaptation planning, agricultural risk assessment, insurance mechanisms and climate-resilience policies.

The framework is compatible with future research and innovation activities in climate adaptation, digital agriculture and climate-smart farming and may be incorporated into national and European funding initiatives. By supporting transferable climate services, sustainable agricultural practices and evidence-based adaptation planning, LIFE FROSTDEFEND contributes to wider European climate adaptation priorities.

Overall, LIFE FROSTDEFEND provides a scalable, operational and transferable framework that can support the long-term resilience of frost-prone agricultural systems under changing climatic conditions.

9. LIFE-FROSTDEFEND Action Plan

The LIFE-FROSTDEFEND Adaptation Plan aims to support the gradual transition from reactive frost management practices towards a more preventive, coordinated and climate-resilient agricultural adaptation framework. The proposed Action Plan translates the strategic objectives of the project into a structured set of operational

measures, implementation priorities and coordination actions targeting frost-sensitive agricultural systems.

The Action Plan is designed to:

- reduce frost-related crop losses where technically and economically feasible;
- improve preparedness before frost-risk periods;
- strengthen operational response capacity during frost events;
- support farmer decision-making through the FROSTDEFEND tool;
- promote more targeted and resource-efficient frost-protection practices;
- improve the collection and use of frost-risk, crop-damage and intervention data;
- enhance the resilience of local agricultural systems;
- support transferability and replication to other frost-prone regions.

The implementation framework combines technological, agronomic, institutional and participatory measures. It is designed to remain operational beyond the project lifetime through continued stakeholder engagement, integration with advisory services, cooperation with local and regional authorities, and identification of suitable financing pathways.

The Action Plan is based on the following principles:

1. **Prevention and preparedness**: frost-risk management should start before the occurrence of damaging frost events.
2. **Localisation**: warnings and adaptation recommendations should be based on local monitoring, crop conditions and site-specific exposure.
3. **Evidence-based decision-making**: actions should rely on measured data, validated indicators, field observations and user feedback.
4. **Crop sensitivity**: frost risk should be interpreted in relation to crop type, phenological stage, exposure duration and local conditions.
5. **Resource efficiency**: frost-protection measures should be applied only when justified by risk level and operational feasibility.
6. **Stakeholder participation**: farmers, cooperatives, advisors and public authorities should be involved in the implementation and refinement of adaptation actions.
7. **Sustainability and transferability**: project results should be maintained and further developed after the project end, with potential replication in other frost-prone agricultural areas.

Strategic Objective 1: Strengthening Frost-Risk Monitoring and Early Warning

Rationale

Timely and reliable frost-risk information is essential for reducing uncertainty and supporting farm-level decision-making. The FROSTDEFEND tool provides a basis for operational early warning by combining local monitoring, meteorological data and frost-risk indicators.

Priority actions:

Action	Description	Timing	Responsible actors	Expected output
1.1 Maintain monitoring stations	Maintain and operate the existing monitoring points in pilot and replicate areas.	Short-term and continuous	Project partners, local stakeholders and end users	Operational monitoring network
1.2 Monitor frost-risk indicators	Collect and analyse the available meteorological data and other relevant indicators	Continuous during frost-risk periods	Project partners	Seasonal frost-risk datasets
1.3 Complete and document Tool operation	Communicate tool functions and operational limitations.	Short-term and continuous	Project partners	Tool status
1.4 Operate the FROSTDEFEND warning tool	Generate and communicate frost-risk levels to end uses.	Short-term and continuous	Project partners	Operational frost alerts
1.5 Review and improve alert calibration	Collect and Compare alerts with field observations, reported damage and user feedback.	Medium-term and after-LIFE	Technical partners, farmers	Improved model performance
1.6 Establish warning communication channels	Use appropriate channels such as the platform, email, cooperative networks	Short-term and continuous	Cooperatives, project partners, advisors	Improved dissemination

	or advisory services where available.			

Implementation indicators

Indicator	Unit	Evidence source
Operational monitoring points	Number	Station records, maintenance logs
Frost-risk alerts generated	Number	FROSTDEFEND platform records
Farmers/users registered or reached	Number	User database, cooperative records
Forecast performance	Qualitative / quantitative	Comparison with observations
User feedback	Qualitative / score	Interviews, platform records

Indicative timeline:

- **Short-term:** installation, testing, and operational deployment during the project implementation period;
- **Medium-term:** continued use, refinement, and possible expansion of the approach during the After-Life period, based on operational experience and identified needs;
- **Long-term:** potential integration into regional advisory services may be explored, subject to future needs and resources.

Verification method: platform logs, monitoring records, seasonal reports, user feedback, and assessment of forecast performance against observed frost events.

Strategic Objective 2: Improving Farm-Level Preparedness and Adaptation Capacity

Rationale

The adaptation framework emphasizes the importance of strengthening farmer preparedness and improving operational response capacity before and during frost events. Many frost-protection practices are activated under time pressure and may depend on local experience rather than structured decision protocols. The Action Plan

promotes preparedness before frost and clearer operational response during frost events.

Priority actions

Action	Description	Timing	Responsible actors	Expected output
2.1 Finalize frost-response guidance	Develop simple protocols for farmers.	Short-term	Project partners, cooperatives, advisors	Practical frost-response guidance
2.2 Deliver training and capacity building activities	Organize workshops, seminars and demonstrations for farmers and cooperatives.	Short-term and medium-term	Project partners, cooperatives, regional actors	Trained end users
2.3 Promote and integrate crop-stage awareness	Include phenology and crop sensitivity in guidance and interpretation of frost-risk information.	Medium-term	Project partners, advisors, farmers	Better crop-stage-based response
2.4 Strengthen local coordination	Encourage communication among farmers, cooperatives and authorities before high-risk periods.	Continuous	Cooperatives, local authorities	Improved operational coordination
2.5 Collect feedback after frost events	Record whether warnings were received, whether action was taken, and whether damage occurred.	After each relevant event	Farmers, cooperatives, project partners	Event feedback records

Implementation indicators

Indicator	Unit	Evidence source
Training events organized	Number	Agendas, attendance lists
Stakeholders reached	Number	Attendance records
Frost-response protocols prepared	Number	Technical material

Post-event feedback forms collected	Number	User feedback records

Indicative timeline

- Continuous implementation throughout the project duration and after-life period.

Verification method

Evidence should include attendance sheets, training material, feedback forms, stakeholder meeting minutes and examples of operational communication before or during frost-risk events.

Strategic Objective 3: Promoting Efficient and Sustainable Frost Protection Practices

Rationale

The adaptation plan promotes more targeted and environmentally sustainable frost protection practices in order to reduce operational costs and environmental impacts.

Priority actions

Action	Description	Timing	Responsible actors	Expected output
3.1 Link warnings to intervention decisions	Present risk levels and guidance as decision-support information for preparing or considering measures, rather than as automatic activation instructions.	Short-term and continuous	Project partners, Farmers, advisors, cooperatives	More informed interventions
3.2 Avoid unnecessary interventions	Explain how local risk information may help users avoid costly actions when risk appears low, while noting forecast uncertainty.	Medium-term	Project partners and cooperatives	Reduced unnecessary actions, proportionate response

3.3 Promote efficient use of active protection	Support better timing of active protection systems where available and feasible.	Medium-term	Farmers, advisors	Targeted use of resources
3.4 Promote passive and agronomic measures	Encourage practices such as site-specific planning, canopy and soil management, pruning strategies and maintenance of monitoring equipment, where relevant to crop and site.	Medium-term and long-term	Farmers, advisors, cooperatives	Improved preventive capacity
3.5 Record intervention data	Collect information on actions taken, timing, duration, resources used and perceived effectiveness.	Continuous during frost-risk periods	Farmers, cooperatives, project partners	Intervention database

Implementation indicators

Indicator	**Unit**	**Evidence source**
Recorded protection interventions	Number	Farmer logs, survey forms
Interventions linked to FROSTDEFEND alerts	Number / %	User feedback and platform data
Avoided or unnecessary interventions identified	Number	Farmer reports, event comparison
Estimated emissions reduction	CO_2e	Only where input data are available and method is documented

Indicative timeline

Before project closure, priority will be given to documenting tested practices, implementation experience, and practical recommendations. During the After-Life period, the developed tool and proposed best practices can be applied in subsequent frost-risk periods by farmers, agronomists, and advisory bodies, supporting their continued practical use and allowing experience to be gathered under a wider range of frost conditions.

Verification method

Operational, economic or environmental benefits should be reported only where supported by sufficient data and a documented assessment method. Where quantitative assessment is not possible, qualitative findings may be presented with a clear description of the evidence and limitations.

Strategic Objective 4: Supporting Data Collection, Knowledge Generation and Policy Integration

Rationale

The adaptation framework supports the systematic collection and analysis of frost-risk and intervention data in order to improve adaptation planning and policy support.

Priority actions

Action	Description	Timing	Responsible actors	Expected output
4.1 Establish seasonal data records	Maintain datasets for frost-risk indicators, alerts, observations and user feedback.	Continuous	Project partners	Seasonal data archive
4.2 Record crop-damage information	Gather damage observations where available, using consistent templates/platform records.	After frost events	Farmers, cooperatives, advisors	Damage records
4.3 Assess seasonal performance	Compare alerts, observations, interventions and damage reports at the end of each frost season.	Annual / seasonal	Project partners	Seasonal assessment reports
4.4 Document recommendations for future updates	Identify changes that could be considered if new observations, feedback or	Medium-term and after-LIFE	Project partners, advisors	Updated recommendations

	resources become available			
4.5 Share relevant findings with interested bodies and support policy uptake and transferability	Share aggregated results with competent authorities and agricultural risk-management bodies, where appropriate.	Medium-term and long-term	Project partners, authorities, ELGA and relevant bodies	Improved evidence base for risk management

Implementation indicators

Indicator	**Unit**	**Evidence source**
Datasets documented	Number	Data archive
Damage observations collected	Number	Field forms, cooperative records
Seasonal assessment reports prepared	Number	Technical reports
Future updates recommendations documented	Number	Revised guidelines/Recommendation note
Meetings with authorities or risk-management bodies	Number	Minutes, attendance records

Indicative timeline

Before project closure, available datasets, observations and recommendations should be documented. Further updating or seasonal assessment after closure may be undertaken if data collection mechanisms, responsible organizations and resources remain available.

Verification method

Evidence may include archived datasets, metadata, event summaries, available damage observations, technical notes, meeting records and stakeholder feedback. Any reference to policy, advisory or insurance use should be described as a potential contribution unless formal uptake is documented.

Strategic Objective 5: Strengthen stakeholder engagement, communication and capacity building

Rationale

The effectiveness of the adaptation plan depends on whether farmers and local stakeholders understand, trust and use the information provided. Continuous engagement is therefore essential.

Priority actions

Action	Description	Timing	Responsible actors	Expected output
5.1 Maintain stakeholder networks	Continue cooperation with farmers, cooperatives, advisors, public authorities and technical partners.	Continuous	Project partners	Active stakeholder network
5.2 Disseminate practical material	Produce and distribute user-friendly guidance, leaflets, platform instructions and seasonal messages.	Short-term and medium-term	Project partners	Dissemination material
5.3 Organize local demonstration activities	Present the tool and adaptation measures in pilot/replication areas.	Medium-term	Cooperatives, project partners	Demonstrations and field events
5.4 Collect user feedback	Gather feedback on usability, alert clarity, operational relevance and barriers to adoption.	Continuous	Project partners, cooperatives	User feedback dataset
5.5 Preserve access to key public outputs	Continue website updates, layman communication and dissemination of project outcomes.	After-LIFE	Project partners	Continued visibility

Implementation indicators

Indicator	Unit	Evidence source
Stakeholders or contact records	Yes/No	Contact records
Demonstration events completed	Number	Agendas, photos
Stakeholders reached	Number	Attendance, website analytics
Feedback responses received	Number	Surveys
Core public outputs archived or accessible	Number	Website, dissemination materials produced,

Strategic Objective 6: Support replication and transferability

Rationale

Frost risk affects many European fruit-growing regions. The LIFE-FROSTDEFEND approach can be transferred to additional areas if local monitoring, crop sensitivity, farmer needs and institutional capacity are considered.

Priority actions

Action	Description	Timing	Responsible actors	Expected output
6.1 Define transferability requirements	Identify minimum technical and institutional requirements for replication.	Medium-term	Project partners	Transferability checklist
6.2 Identify candidate regions	Explore additional frost-prone fruit-growing areas through stakeholder networks.	Medium-term and after-LIFE	Project partners, authorities, cooperatives	Candidate replication areas

6.3 Define a local adaptation pathway/Adapt the tool to local conditions	Outline steps needed to calibrate and interpret the tool for local climate, crops, phenology and monitoring; Calibration monitoring and alert interpretation to local climate, crops and phenological conditions.	Long-term	Project partners, local stakeholders	Locally adapted warning service
6.4 Support exploratory cooperation/Promote cooperation agreements	Engage in preliminary discussions with interested cooperatives, advisory services or authorities where appropriate.	Long-term	Project partners	Replication partnerships
6.5 Explore business and service models	Assess options for maintenance, hosting, technical support and user services.	Long-term	Project partners, cooperatives, potential operators	Sustainability pathway

Implementation indicators

Indicator	**Unit**	**Evidence source**
Transferability checklist	Yes/No	Technical note
Candidate replication areas identified	Number	Technical note
Stakeholder meetings	Number	Meeting minutes
Cooperation agreements or letters of interest	Number	Signed documents
Funding or service-model options assessed	Number	Business/market analysis

9.1 Governance and Coordination

Effective governance and coordination are considered essential for the successful implementation of the LIFE FROSTDEFEND Adaptation Plan. Due to the cross-sectoral nature of climate adaptation and frost-risk management, implementation

requires cooperation among scientific institutions, farmers, cooperatives, regional authorities and national stakeholders.

The governance framework is based on:

- collaboration among project partners,
- continuous stakeholder engagement,
- coordination with competent authorities,
- integration of scientific and operational knowledge,
- support for participatory adaptation planning.

Project partners serve as the main scientific and technical coordinators of the adaptation framework. Their role includes:

- coordination of monitoring and forecasting activities;
- technical support and data analysis;
- preparation of adaptation guidelines;
- stakeholder communication and dissemination;
- support for policy integration and transferability.

Agricultural cooperatives and participating farmers play a central role in the implementation process through:

- operational use of the FROSTDEFEND tool;
- participation in monitoring activities;
- provision of field observations and feedback;
- implementation of adaptation practices.

Competent authorities, including regional administrations and agricultural organizations, contribute through:

- institutional support,
- dissemination of adaptation information,
- integration of adaptation planning into broader agricultural resilience policies.

Particular importance is given to cooperation with agricultural insurance and risk-management bodies, including ELGA, in order to support improved understanding of climate-related agricultural risks and operational losses.

9.2 Financing and Sustainability Considerations

The long-term sustainability of the adaptation framework depends on the availability of operational support, institutional cooperation and continued stakeholder participation.

The LIFE Programme provides the initial implementation framework for:

- development of the early-warning tool,
- pilot testing and validation,
- monitoring and data collection,
- stakeholder engagement and dissemination.

After-LIFE financing needs

To maintain and expand the adaptation framework after the project, financing will be needed for:

- maintenance and replacement of monitoring equipment;
- hosting, operation and technical support of the platform;
- seasonal data analysis and model calibration;
- stakeholder training and advisory support;
- communication and dissemination;
- replication in additional areas.

Potential financing sources

Long-term sustainability may be supported through:

- integration of the tool into agricultural advisory systems;
- adoption of the tool by national agricultural insurance agencies;
- contributions from cooperatives or producer organisations;
- regional or national agricultural adaptation programmes;
- climate adaptation and innovation funding;
- agricultural advisory service budgets;
- future EU or national funding opportunities;
- service-based models for platform maintenance and support;
- incorporation into agricultural risk-management frameworks;

The adaptation framework promotes cost-efficient measures that can be gradually adopted according to local capacities and operational needs. Particular emphasis is placed on scalability and transferability in order to facilitate wider implementation beyond the pilot areas.

9.3 Monitoring, reporting and evidence requirements

Implementation of the Action Plan should be monitored through a set of operational, environmental, socioeconomic and governance indicators.

Core monitoring indicators

Category	Indicator examples	Evidence
Operational performance	Monitoring stations, alerts, lead time, system availability	Platform logs, station records
User uptake	Registered users, active users, trained farmers, feedback responses	User database, attendance lists
Preparedness	Use of protocols, actions taken before frost events	Surveys, cooperative records
Environmental/resource efficiency	Fuel, energy or water use where available	Farm records, intervention logs
Socioeconomic impact	Avoided losses, reduced costs, improved preparedness where documented	Farmer reports, economic records
Replication	New areas interested, cooperation agreements, follow-up actions	Meeting records, letters
Policy uptake	Use of results by authorities/advisors	Official correspondence, meeting minutes

Reporting principles

- Quantitative results should be reported only when supported by data.
- Qualitative results should clearly state the evidence source.
- Significant deviations from expected outcomes should be explained.
- Damage reduction, cost savings or emission reductions should not be claimed unless a transparent method and supporting data are available.
- All monitoring data should be archived in a form suitable for project reporting and after-LIFE evaluation.

9.4 Risks and mitigation measures

Risk	**Potential effect**	**Mitigation measure**
Equipment malfunction or data gaps	Reduced warning reliability	Preventive maintenance, backup checks, data-quality control

Low farmer uptake	Reduced impact of the tool	Training, simple messages, cooperative involvement, user feedback, adjustment of subscription and equipment prices
Limited protection resources	Farmers may not be able to act despite warnings	Promote preparedness, prioritisation and feasible measures
High cost of active protection	Limited adoption	Support targeted interventions and avoid unnecessary activation
Limited post-project financing	Reduced long-term sustainability	Develop mixed financing and institutional cooperation
Uncertainty in crop damage thresholds	Risk of over- or under-warning	Combine thresholds with phenology, duration and field observations
Extreme frost beyond protection capacity	Residual damage despite warning	Communicate limitations and improve risk preparedness

9.5 Indicative implementation roadmap

Phase	**Period**	**Main focus**	**Key outputs**
Phase 1: Operational deployment	During project implementation	Tool deployment, monitoring, stakeholder engagement	Operational platform, pilot alerts, training
Phase 2: Validation and refinement	During project implementation and first after-LIFE period	Calibration, user feedback, seasonal evaluation	Improved alerts, event reports
Phase 3: Institutional anchoring	After project end	Link with cooperatives, advisors and authorities	Continuation pathway
Phase 4: Replication and scaling	After project end	Transfer to other frost-prone areas	Replication checklist, new partnerships
Phase 5: Long-term sustainability	Long-term	Maintenance, financing and policy uptake	Sustained operational framework

9.6 Expected results and contribution to climate adaptation

The Action Plan is expected to support:

- improved frost-risk anticipation;
- better preparedness of farmers and cooperatives;
- more timely and targeted activation of frost-protection measures;
- stronger evidence on frost exposure, crop vulnerability and operational response;
- improved stakeholder cooperation;
- increased awareness of climate-related agricultural risks;
- improved basis for replication in additional frost-prone regions.

The Action Plan does not eliminate frost risk. Instead, it strengthens the capacity of agricultural systems to anticipate, prepare for and respond to damaging frost events in a more coordinated, evidence-based and climate-resilient way.

10. Monitoring Strategy

Given that climate-risk assessment and adaptation constitute a continuous short-term and medium-term process, and considering that scientific knowledge and climate-related datasets are rapidly evolving, a monitoring strategy for the adaptation of the LIFE-FROSTDEFEND project to climate change is proposed. The monitoring strategy aims to support the continuous evaluation of climate-related frost risks, the effectiveness of adaptation measures and the possible implementation of additional measures where necessary based on actual climatic, meteorological and operational conditions observed in the project implementation areas.

The previous sections of the Adaptation Plan presented the assessment of climate vulnerability, frost-related risks, crop sensitivity and proposed adaptation measures based on current climate knowledge, operational data and scientific literature. Some of the proposed measures constitute structural or operational measures, including the development of the FROSTDEFEND early-warning system, deployment of meteorological monitoring infrastructure and implementation of frost protection practices. Other measures constitute non-structural actions, including development of operational procedures, training and awareness activities, improvement of advisory services and integration of climate-risk information into agricultural planning and insurance-related processes.

Within this context, an environmental and operational monitoring framework is proposed as a means of supporting the assessment and possible improvement of climate resilience and adaptation capacity in frost-sensitive agricultural systems. The proposed framework could be applied by project partners and, where relevant, by agricultural cooperatives, farmers, competent authorities or other interested stakeholders.

The proposed monitoring strategy could contribute to:

- evaluate the effectiveness of adaptation measures;
- improve preparedness and operational response capacity;
- support continuous improvement of the FROSTDEFEND tool;
- strengthen evidence-based adaptation planning;
- improve understanding of frost-risk dynamics under climate variability;
- support long-term agricultural resilience.

The monitoring approach could integrate procedures related to:

A. Methodology for Monitoring Climate Change Evolution and Frost-Risk Conditions

Monitoring of climate-related risks and frost conditions could be based on the continuous evaluation of official climate and meteorological information sources, regional adaptation plans and operational datasets relevant to the participating regions.

The monitoring process could consider information derived from:

- Copernicus Climate Change Service datasets (ERA5-Land) and climate indicators;
- the Greek National Climate Change Adaptation Hub and available climate diagnostic tools;
- Regional Climate Change Adaptation Plans (PeSPKA) of Western Greece and Peloponnese;
- climate data and meteorological bulletins provided by the Hellenic National Meteorological Service (HNMS);
- Météo-France climate and meteorological datasets for the French replication area;
- climate-related agricultural information provided by competent authorities and agricultural organizations;
- future revisions of national and regional adaptation frameworks.

Special attention could be given to:

- changes in minimum air temperatures;
- frequency and severity of frost events;
- occurrence of late spring frost episodes;
- climatic variability and temperature anomalies;
- changes in crop phenology associated with warmer winter conditions;
- local meteorological conditions affecting frost formation.

The monitoring process may include:

- collection of seasonal frost-event data;
- comparison between historical and current climatic conditions;
- analysis of frost-event trends;
- evaluation of climate-risk evolution;
- identification of emerging climate-related threats affecting frost-sensitive cultivations.

The results of climate monitoring could be incorporated into annual and seasonal review procedures. Updated information may help determine whether:

- new climate-related threats may affect the agricultural systems;
- existing frost risks are intensifying;
- additional adaptation measures may be required;
- operational thresholds or procedures should be revised.

Particular attention could be given to the evolution of frost risk in:

- citrus- and temperate- fruit growing areas;
- lowland agricultural areas prone to cold-air accumulation;
- regions experiencing increasing climatic variability;
- areas with a history of repeated frost-related crop damage.

B. Methodology for Monitoring and Evaluating Adaptation Measures

The effectiveness of the proposed adaptation measures could be evaluated through the use of operational and environmental indicators corresponding to each category of frost-related risk and adaptation response.

Monitoring activities could focus on:

- operational performance of the FROSTDEFEND tool;
- effectiveness of frost protection measures;
- implementation of preparedness procedures;
- environmental performance of adaptation practices;
- operational costs and resource use;
- stakeholder participation and engagement.

The monitoring framework could include the following procedures and indicators:

Frost Events and Crop Protection Measures

- Continuous monitoring of meteorological forecasts and frost-risk alerts in order to improve preparedness for frost episodes;
- Collection of warning bulletins and meteorological observations from official meteorological services;
- Recording of frost events, including minimum temperatures, duration and affected cultivation areas;
- Documentation of operational responses and implemented frost protection measures;
- Evaluation of intervention timing and effectiveness;
- Recording of observed crop damages and estimated production losses.

The collected information could support the identification of:

- effective protection practices;
- operational limitations;
- areas requiring additional adaptation support;
- opportunities for optimization of intervention timing.

Monitoring of Protection Practices and Operational Performance

The monitoring framework could include systematic recording of:

- number of interventions and sprayings;
- activation of heaters, sprinklers or wind machines;
- operational duration of protection systems;
- type of protection compounds or measures used;
- geographical location of interventions;
- operational costs and resource consumption.

The monitoring process could evaluate:

- whether interventions were activated under appropriate risk conditions;
- whether protection measures successfully reduced crop damage;
- whether operational procedures require improvement;
- whether unnecessary or premature interventions occurred.

Special emphasis could be placed on reducing unnecessary activation of energy-intensive frost protection systems.

Environmental Performance and Sustainability Monitoring

The monitoring strategy could also assess the environmental performance of adaptation measures, particularly regarding:

- energy consumption;
- fuel use;
- water use associated with sprinkler systems;
- greenhouse gas emissions;
- operational efficiency of targeted interventions.

Where appropriate data are available, the FROSTDEFEND tool could support the estimation of indicative eCO2 emission reductions through comparison between:

- conventional frost protection practices involving continuous or precautionary activation;
- optimized intervention timing supported by operational forecasting and localized frost-risk information.

The environmental monitoring process could contribute to:

- improvement of resource efficiency;
- reduction of unnecessary operational emissions;
- promotion of environmentally sustainable adaptation practices.

Monitoring of Farmer Participation and Adaptive Capacity

The monitoring framework could also consider stakeholder participation and behavioural adaptation through:

- recording of participation in training and dissemination activities;
- evaluation of farmer engagement with the FROSTDEFEND tool;
- collection of feedback regarding operational usability and effectiveness;
- assessment of adoption of recommended adaptation practices.

Where available, information could be collected from participating farmers and cooperatives regarding:

- perceived usefulness of frost alerts;
- effectiveness of protection measures;
- operational challenges;
- adaptation needs and priorities;
- economic impacts of frost events.

This participatory approach supports the continuous improvement of the adaptation framework and strengthens local ownership of adaptation measures.

C. Seasonal Review and Continuous Improvement Process

The results of monitoring activities could be incorporated into annual and seasonal review procedures coordinated by the project partners.

The review process could consider:

- evolution of frost-risk conditions;
- effectiveness of adaptation measures;
- operational performance of the FROSTDEFEND tool;
- environmental and economic performance indicators;
- stakeholder feedback and operational experiences.

Based on the results of the review process, decisions may be taken regarding:

- revision of operational procedures;
- updating of intervention thresholds;
- implementation of additional adaptation measures;
- improvement of forecasting methodologies;
- enhancement of stakeholder support mechanisms.

The monitoring strategy therefore establishes a dynamic and adaptive framework capable of evolving according to:

- new scientific knowledge;
- updated climate projections;
- operational experience;
- changing agricultural conditions;
- stakeholder needs.

Through continuous monitoring, evaluation and periodic updating, the LIFE-FROSTDEFEND Adaptation Plan aims to support the long-term resilience and sustainability of frost-sensitive agricultural systems under changing climatic conditions.

11. Consistency with Climate Adaptation Strategies and Plans

The LIFE-FROSTDEFEND project is fully aligned and synergistic with European, national and regional climate adaptation strategies, policies and action plans related to climate resilience, agricultural adaptation and sustainable development (Figure 24).

The project contributes to the implementation of adaptation priorities through the development of operational frost-risk management tools, climate monitoring systems and sustainable agricultural adaptation measures targeting frost-sensitive cultivation systems.

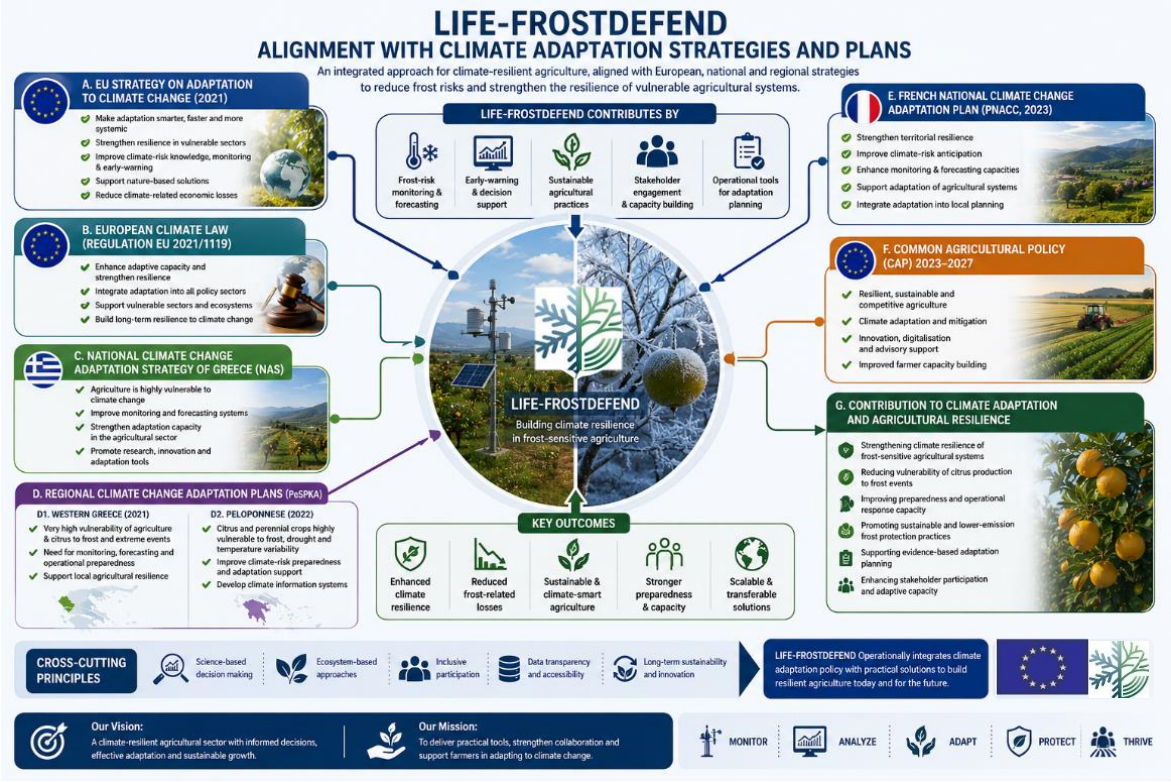


Figure 24. LIFE FROSTDEFEND alignment with Climate Adaptation Strategies and Plans

In particular, the project contributes to the following strategies and policy frameworks:

A. EU Strategy on Adaptation to Climate Change

The LIFE-FROSTDEFEND project is fully consistent with the objectives of the EU Strategy on Adaptation to Climate Change, adopted by the European Commission in 2021 (European Commission, 2021). The Strategy emphasizes the need to make adaptation "smarter, faster and more systemic" through improved climate-risk knowledge, data-driven decision-making, enhanced resilience and integration of adaptation into sectoral policies.

The Strategy specifically highlights the importance of:

- strengthening climate resilience in vulnerable sectors such as agriculture;
- improving climate-risk assessment and monitoring;

- enhancing early-warning systems and preparedness mechanisms;
- supporting nature-based and ecosystem-based adaptation approaches;
- reducing climate-related economic losses;
- improving access to climate-related information and operational tools.

LIFE-FROSTDEFEND directly contributes to these objectives through:

- development of the FROSTDEFEND early-warning and decision-support system;
- implementation of frost-risk monitoring and forecasting procedures;
- support for climate-resilient agricultural practices;
- promotion of targeted and environmentally sustainable frost protection measures;
- strengthening stakeholder preparedness and adaptive capacity.

The project also supports the Strategy's objective of integrating adaptation into local and regional planning processes by providing practical operational tools and adaptation recommendations for frost-prone agricultural regions in Greece and France.

B. European Climate Law – Regulation (EU) 2021/1119

The LIFE-FROSTDEFEND project is also aligned with Regulation (EU) 2021/1119 establishing the European Climate Law (European Union, 2021).

Article 5 of the Regulation states that:

"The relevant Union institutions and the Member States shall ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change."

Furthermore, the Regulation emphasizes that adaptation policies should:

- improve integration of climate adaptation into all policy sectors;
- support vulnerable sectors and populations;
- promote ecosystem-based adaptation approaches;
- strengthen long-term resilience under future climate conditions.

The agricultural sector is identified as one of the sectors highly exposed to climate-related risks due to its direct dependence on climatic conditions and sensitivity to extreme weather events.

LIFE-FROSTDEFEND contributes to these objectives through:

- enhancement of climate resilience in frost-sensitive agricultural systems;

- reduction of vulnerability of citrus cultivation to frost-related hazards;
- promotion of sustainable and ecosystem-oriented adaptation approaches;
- development of operational adaptation tools supporting local resilience;
- integration of adaptation into agricultural decision-making processes.

The project further contributes to the practical implementation of climate adaptation requirements by supporting the development of monitoring, evaluation and operational preparedness mechanisms for climate-related agricultural risks.

C. National Climate Change Adaptation Strategy of Greece (NAS)

The LIFE-FROSTDEFEND Adaptation Plan is fully aligned with the National Climate Change Adaptation Strategy of Greece (Ministry of Environment and Energy of Greece, 2016), which establishes the national framework for climate adaptation planning and implementation.

The Strategy identifies agriculture among the sectors with the highest climate vulnerability due to:

- increasing climatic variability;
- exposure to extreme weather events;
- dependence on water availability and temperature stability;
- sensitivity of agricultural production systems to changing climatic conditions.

The Strategy emphasizes the importance of:

- strengthening adaptation capacity of the agricultural sector;
- improving climate-risk monitoring systems;
- enhancing preparedness and operational planning;
- supporting research and innovation related to adaptation;
- integrating adaptation into regional and sectoral planning.

LIFE-FROSTDEFEND contributes directly to these priorities through:

- implementation of localized frost-risk monitoring systems;
- development of operational forecasting and early-warning tools;
- support for adaptation planning in frost-prone agricultural regions;
- strengthening of stakeholder awareness and preparedness;
- promotion of sustainable and efficient frost protection practices.

The project also supports the Strategy's emphasis on scientific research, innovation and development of adaptation-support tools capable of improving resilience under future climatic conditions.

D. Regional Climate Change Adaptation Plans (PeSPKA)

D.1 Regional Climate Change Adaptation Plan of Western Greece

The design and implementation of LIFE-FROSTDEFEND are fully compatible with the conclusions, priorities and adaptation measures proposed in the Regional Climate Change Adaptation Plan (PeSPKA) of Western Greece (Region of Western Greece, 2021).

The Regional Adaptation Plan identifies agriculture as one of the sectors with very high vulnerability to climate change impacts, particularly due to:

- increasing climatic variability;
- changes in temperature patterns;
- occurrence of extreme weather events;
- exposure of perennial cultivations to frost and heat stress.

The Plan specifically recognizes:

- the vulnerability of citrus crops to abrupt temperature changes;
- the importance of improving monitoring and forecasting systems;
- the need for operational adaptation measures and preparedness mechanisms;
- the importance of supporting local agricultural resilience.

The LIFE-FROSTDEFEND project directly addresses these priorities through:

- implementation of localized frost-risk assessment and forecasting;
- support for operational preparedness of farmers and cooperatives;
- development of targeted adaptation measures for citrus cultivation;
- strengthening of climate resilience at regional level.

The adaptation plan further incorporates the climate-risk conclusions and adaptation priorities identified in the PeSPKA regarding:

- frost events;
- temperature variability;
- agricultural vulnerability;
- need for climate-risk monitoring and adaptation planning.

D.2 Regional Climate Change Adaptation Plan of Peloponnese

The LIFE-FROSTDEFEND project is also fully aligned with the Regional Climate Change Adaptation Plan of Peloponnese (Region of Peloponnese, 2022).

The Plan identifies:

- citrus cultivation,
- perennial crops,
- irrigated agriculture,
- agricultural production systems in lowland areas

as highly vulnerable to climate-related risks including frost events, droughts and temperature variability.

The Plan emphasizes the need for:

- improved climate-risk preparedness;
- strengthening of agricultural resilience;
- operational adaptation support;
- development of climate information systems;
- reduction of vulnerability of sensitive crops.

The project contributes to these priorities through implementation activities in:

- Argolida,
- Laconia,
- frost-sensitive citrus cultivation zones.

The project further supports regional adaptation planning by generating operational data, frost-risk information and practical adaptation experience that may support future regional resilience policies.

E. French National Climate Change Adaptation Plan (PNACC)

The LIFE-FROSTDEFEND project is aligned with the French National Climate Change Adaptation Plan (PNACC) (French Ministry for Ecological Transition, 2023), which identifies agriculture as a priority sector requiring improved climate resilience and preparedness.

The French adaptation framework emphasizes:

- strengthening territorial resilience;
- improving climate-risk anticipation;
- enhancing monitoring and forecasting capacities;
- supporting adaptation of agricultural systems;
- integrating climate adaptation into local planning and agricultural policies.

The implementation of replication activities in the Puy-de-Dôme region contributes to these objectives through:

- evaluation of frost adaptation practices under different climatic conditions;
- support for climate-resilient agricultural management;
- promotion of operational adaptation tools and stakeholder participation.

The French pilot activities further strengthen the transnational and transferability dimension of the LIFE-FROSTDEFEND adaptation framework.

F. Common Agricultural Policy (CAP) 2023–2027

The LIFE-FROSTDEFEND project also contributes to the objectives of the Common Agricultural Policy (CAP) 2023–2027 (European Commission, 2023), which promotes:

- resilient agricultural production systems;
- climate adaptation and mitigation;
- sustainable resource management;
- innovation and digitalization in agriculture;
- improved advisory support and farmer capacity building.

The project supports climate-smart agriculture through:

- operational use of climate-risk information;
- improved decision-making for frost protection;
- promotion of sustainable and resource-efficient practices;
- support for innovation and digital adaptation tools.

G. Contribution to Climate Adaptation and Agricultural Resilience

Overall, LIFE-FROSTDEFEND contributes to the practical implementation of climate adaptation priorities at European, national and regional levels through:

- strengthening climate resilience of frost-sensitive agricultural systems;
- reducing vulnerability of citrus production to frost events;
- improving preparedness and operational response capacity;
- promoting sustainable and lower-emission frost protection practices;
- supporting evidence-based adaptation planning;
- enhancing stakeholder participation and adaptive capacity.

The project therefore acts as an operational bridge between climate adaptation policy and practical implementation in the agricultural sector, supporting both local resilience and broader European climate adaptation objectives.

12. Conclusions and Recommendations

12.1 Main Conclusions

The LIFE FROSTDEFEND Adaptation Plan identifies frost events, including late-spring frosts, as an important climate-related risk for frost-sensitive agricultural systems in Greece and France. Although average temperatures are increasing as a result of climate change, greater climatic variability, abrupt temperature fluctuations and changes in crop phenology may continue to influence frost exposure and crop vulnerability. These risks are particularly relevant for perennial and high-value crops, including citrus crops such as lemons and oranges, as well as temperate fruit crops.

Warmer winter conditions may accelerate flowering and vegetative development, potentially increasing crop exposure to damaging cold events during late winter and early spring. The vulnerability assessment indicates that the pilot and replication regions are affected by a combination of climatic exposure, crop sensitivity and limitations in adaptive capacity. In the Greek study regions, relevant factors include the concentration of frost-sensitive perennial crops, the economic importance of fruit production, fragmented agricultural holdings, increasing production costs and uneven access to climate-risk information and technical tools.

Conventional frost-protection methods remain important in many agricultural areas but may involve technical, economic and environmental constraints. Active protection measures, such as heaters, wind machines and irrigation systems, can require significant operating expenditure, energy or water use, and timely activation within relatively narrow operational windows. Their effectiveness may also vary according to the type and severity of the frost event. Where localized forecasts and field observations are limited, protection measures may be activated too early, too late or when they are not necessary.

Within this context, LIFE FROSTDEFEND provides an integrated adaptation framework combining localized meteorological monitoring, frost-risk forecasting, early-warning information, and guidance on sustainable protection practices. The approach is intended to support preparedness and informed decision-making by farmers, cooperatives, agricultural advisors and relevant authorities.

12.2 Recommendations for Farmers and Agricultural Cooperatives

Farmers and agricultural cooperatives are central to the practical application of frost-risk adaptation measures. Improved access to localized forecasts, early-warning information and practical guidance may support more timely and targeted preparedness.

Farm-level preparedness may include:

- monitoring localized weather and frost-risk information;
- combining forecasts with field observations;
- identifying plots and crops with higher frost exposure;
- inspecting available protection equipment before frost-risk periods;
- preparing simple procedures for action before, during and after a frost event;
- recording protection measures, operational conditions and observed crop damage; and
- consulting agricultural advisors when selecting or activating protection measures.

Active protection measures should be selected according to local conditions, crop sensitivity, available infrastructure, resource availability and the expected characteristics of the frost event. Localized risk information may assist farmers in avoiding unnecessary activation and improving the timing of interventions, but the final decision remains farm-specific.

LIFE FROSTDEFEND also encourages a gradual transition towards more sustainable and resource-efficient agricultural adaptation practices. This may include optimizing frost-protection spraying practices (copper-based spraying schemes), reducing dependence on fuel-intensive systems where suitable alternatives are available, and adopting agronomic measures that support crop resilience and microclimatic regulation. Where technically and economically feasible, farmers may also consider frost-tolerant cultivars and rootstocks, particularly in areas repeatedly affected by frost damage.

Farmer observations and feedback can provide useful information on forecast relevance, protection practices and crop response. Participation in data collection should remain voluntary and should use practical and proportionate reporting methods.

12.3 Recommendations for Authorities and Advisory Services

Effective adaptation to frost risk requires coordination among scientific institutions, agricultural authorities, cooperatives, advisory services, insurance bodies and regional administrations. Cooperation may support the exchange of available information, improve communication during frost-risk periods and facilitate the use of project results in agricultural planning.

Public authorities and relevant organizations may consider:

- supporting access to localized meteorological and climate-risk information;
- strengthening cooperation between monitoring services, agricultural advisors and producer organizations;
- considering frost risk in regional agricultural and climate-adaptation planning;
- facilitating access to practical guidance and capacity-building material;
- exploring appropriate financial instruments for technically justified adaptation investments; and
- improving the documentation of frost events, agricultural impacts and protection measures.

Particular attention may be given to agricultural areas with a high concentration of frost-sensitive crops, repeated frost-related losses, limited adaptive capacity or increasing climatic variability.

Financial assistance may be especially relevant for small and medium-sized farms with limited investment capacity. However, support mechanisms should reflect local needs, technical feasibility, environmental considerations and available public resources.

The project results may also provide supporting information for discussions on agricultural risk assessment and insurance. Any use of project data for compensation, insurance or regulatory purposes would require additional validation, appropriate data-quality procedures and agreement by the competent institutions.

12.4 Monitoring and Knowledge Development

Continued collection of meteorological observations, crop-development information and field feedback may improve understanding of local frost conditions. Where responsibilities and resources are available, future activities could include:

- archiving available meteorological and frost-risk data;
- documenting relevant frost events and observed crop impacts;
- comparing forecasts with recorded conditions;
- reviewing user feedback on the clarity and relevance of warnings; and
- updating technical guidance when supported by new evidence.

The continuation of these activities after project closure cannot be assumed. It will depend on data availability, technical capacity, institutional interest, maintenance arrangements and financial resources.

12.5 After-LIFE Sustainability and Transferability

The long-term value of LIFE FROSTDEFEND lies not only in the possible continued use of the Tool, but also in the preservation and dissemination of the project's methodology, datasets, technical guidance and practical experience.

After the end of the funded period, priority may be given to feasible, low-resource activities such as:

- maintaining access to final reports, protocols and guidance material;
- using project results in advisory, educational or research activities;
- sharing the methodology with interested organizations and regions;
- responding, where possible, to requests for technical information; and
- exploring future cooperation or funding opportunities.

Ongoing monitoring, evaluation and operational feedback will remain essential for improving forecasting accuracy, refining adaptation recommendations and strengthening long-term resilience capacity.

The LIFE FROSTDEFEND approach may also be relevant to other frost-prone agricultural regions and crop systems. Before replication, local climatic conditions, crop sensitivity, phenology, monitoring capacity, stakeholder needs and institutional arrangements should be assessed. Additional calibration, testing and consultation may be required before the methodology or Tool can be applied operationally in a new area.

12.6 Overall Recommendation

LIFE FROSTDEFEND provides a practical framework for improving frost-risk preparedness by connecting scientific information with field-level decision-making. Its future contribution will depend on realistic implementation arrangements, stakeholder interest, available resources and continued evaluation of the evidence.

The project's main recommendation is therefore to promote a gradual and proportionate approach to frost adaptation that combines localized monitoring, informed preparedness, suitable protection practices, stakeholder cooperation and transparent assessment of results. This approach can support agricultural resilience while avoiding commitments or benefit claims that cannot be demonstrated or maintained beyond the project period.

References

Bank of Greece. 2011. The Environmental, Economic and Social Impacts of Climate Change in Greece. Climate Change Impacts Study Committee (CCISC). Bank of Greece, Athens, Greece. Available online. https://www.bankofgreece.gr/Publications/ClimateChange_FullReport_bm.pdf

Bourgeois, G., Snyder, R.L. & de Melo-Abreu, J.P. 2005. *Citrus Frost Protection*. University of California Agriculture and Natural Resources (UC ANR), Publication 8218. Oakland, California, USA. Available online: https://anrcatalog.ucanr.edu/pdf/8218.pdf

Climate-ADAPT. 2024. Agriculture and Climate Change Adaptation. European Climate Adaptation Platform. Available online. https://climate-adapt.eea.europa.eu/en/eu-adaptation-policy/sector-policies/agriculture/index_html

EU CAP Network. 2024. Insurance and Mutual Funds for Farm Resilience and Adaptation in the EU. Available online. https://eu-cap-network.ec.europa.eu/publications/insurance-and-mutual-funds-farm-resilience-and-adaptation-eu_en

European Commission. 2019. Communication on the European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2019) 640 final. Available online. https://commission.europa.eu/publications/communication-european-green-deal_en

European Commission. 2020. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Available online. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381

European Commission. 2021. *Technical Guidance on the Climate Proofing of Infrastructure in the Period 2021–2027*. Brussels, Belgium. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03)

European Commission. 2021. Forging a Climate-Resilient Europe – the New EU Strategy on Adaptation to Climate Change. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Available online. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0082

European Commission. 2021a. European Climate Law. Available online. https://climate.ec.europa.eu/eu-action/european-climate-law_en

European Commission. 2023. Approved 28 CAP Strategic Plans (2023–2027). Directorate-General for Agriculture and Rural Development, European Commission. Available online. https://agriculture.ec.europa.eu/system/files/2023-06/approved-28-cap-strategic-plans-2023-27.pdf

European Environment Agency (EEA). 2020. Climate Change Adaptation in the Agriculture Sector in Europe. Available online. https://www.eea.europa.eu/publications/cc-adaptation-agriculture

European Environment Agency (EEA). 2024. European Climate Risk Assessment. EEA Report No 01/2024. Available online. https://www.eea.europa.eu/publications/european-climate-risk-assessment

European Union. 2021. Regulation (EU) 2021/1119 Establishing the Framework for Achieving Climate Neutrality (European Climate Law). Available online. https://eur-lex.europa.eu/eli/reg/2021/1119/oj

FAO. 2005a. Frost Protection: Fundamentals, Practice and Economics, Volume I. Food and Agriculture Organization of the United Nations. Available online. https://www.fao.org/4/y7223e/y7223e00.pdf

FAO. 2005b. Recommended Methods of Frost Protection. In: Frost Protection: Fundamentals, Practice and Economics. Food and Agriculture Organization of the United Nations. Available online. https://www.fao.org/4/y7223e/y7223e08.htm

FAO. 2023. FAOSTAT – Crops and Livestock Products Database. Food and Agriculture Organization of the United Nations. Available online. https://www.fao.org/faostat/en/#data/QCL

FAO. 2023. *Climate-Smart Agriculture Sourcebook*. Food and Agriculture Organization of the United Nations. Rome, Italy. Available online: https://www.fao.org/climate-smart-agriculture-sourcebook

FranceAgriMer. 2023. Fruit Production Statistics and Agricultural Monitoring Reports. Available online. https://www.franceagrimer.fr/

French Ministry for Ecological Transition. 2020. National Low-Carbon Strategy (SNBC). Ministère de la Transition écologique. Available online. https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc

French Ministry for Ecological Transition. 2025. Third National Climate Change Adaptation Plan (PNACC-3). Ministère de la Transition écologique et de la Cohésion des territoires. Available online. https://www.ecologie.gouv.fr/politiques-publiques/adaptation-france-changement-climatique

Hellenic National Meteorological Service (HNMS). 2024. Climatic Data and Frost Event Records. Available online. https://www.hnms.gr/

Intergovernmental Panel on Climate Change (IPCC). 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Available online. https://www.ipcc.ch/report/ar6/wg2/

Lindow, S. E., Arny, D. C., & Upper, C. D. (1982). Bacterial ice nucleation: A factor in frost injury to plants. *Plant Physiology*, 70(4), 1084–1089. https://doi.org/10.1104/pp.70.4.1084

Luterbacher, J., Xoplaki, E., Casty, C., Wanner, H. & Pauling, A. 2006. Mediterranean climate variability over the last centuries: A review. In: Lionello, P., Malanotte-Rizzoli, P. & Boscolo, R. (eds.), Mediterranean Climate Variability. Elsevier, Amsterdam, pp. 27–148. Available online. https://doi.org/10.1016/S1571-9197(06)80003-7

Maki, L. R., Galyan, E. L., Chang-Chien, M.-M., & Caldwell, D. R. (1974). Ice nucleation induced by Pseudomonas syringae. Applied Microbiology, 28(3), 456–459. https://doi.org/10.1128/am.28.3.456-459.1974

Ministry of Environment and Energy of Greece (MEEN). 2016. National Climate Change Adaptation Strategy (NAS). Approved under Article 45 of Law 4414/2016. Athens, Greece. Available online. Adaptive Greece Hub – National Strategy for Adaptation to Climate Change

Ministry of Environment and Energy of Greece (MEEN). 2019. National Energy and Climate Plan (NECP). Athens, Greece. Available online. https://energy.ec.europa.eu/system/files/2020-01/el_final_necp_main_en_0.pdf

Ministry of Rural Development and Food of Greece. 2024. Citrus Cultivation Statistics and Agricultural Production Data. Available online. https://www.minagric.gr/for-farmer-2/crop-production/oporokipeytika/505-esperidoeidi/1713-stoixeia-esper-greece

Météo-France. 2023. Bulletin Climatique Régional – Auvergne-Rhône-Alpes. Available online. https://meteofrance.com/

Olesen, J.E., Trnka, M., Kersebaum, K.C., et al. 2011. Impacts and Adaptation of European Crop Production Systems to Climate Change. European Journal of Agronomy, 34(2), pp. 96–112. Available online. https://doi.org/10.1016/j.eja.2010.11.003

Region of Peloponnese. 2022. Regional Climate Change Adaptation Plan (PeSPKA) of the Peloponnese Region. Available online. https://adaptivegreecehub.gr/en/blog/library/perifereiako-schedio-gia-tin-prosarmogi-stin-klimatiki-allagi-tis-perifereias-peloponnisou/

Region of Western Greece. 2021. Regional Climate Change Adaptation Plan (PEPCCA) of Western Greece. Available online. https://adaptivegreecehub.gr/en/library/perifereiako-schedio-gia-tin-prosarmogi-stin-klimatiki-allagi-tis-perifereias-dytikis-elladas/

UC Agriculture and Natural Resources (UC ANR). 2005. Frost Protection for Citrus and Other Subtropicals. University of California Agriculture and Natural Resources. Available online. https://ucanr.edu/media/343878

Vautard, R. et al. (2023). Human influence on growing-period frosts like in early April 2021 in central France. Natural Hazards and Earth System Sciences, 23, 1045-1058. The study documents severe damage to grapevines and fruit trees in France after unusually warm March conditions advanced phenological development. Available at: https://nhess.copernicus.org/articles/23/1045/2023/

Vitasse, Y., Schneider, L., Rixen, C., Christen, D. & Rebetez, M. 2018. Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades. Agricultural and Forest Meteorology, 248, pp. 60–69. Available online. https://doi.org/10.1016/j.agrformet.2017.09.005

World Meteorological Organization (WMO). 2021. State of the Climate in Europe 2021. Available online. https://library.wmo.int/idurl/4/58971

Zittis, G., Hadjinicolaou, P. & Lelieveld, J. 2021. Projected changes in heat wave characteristics in the Eastern Mediterranean and the Middle East. Regional Environmental Change, 21, 121. Available online. https://doi.org/10.1007/s10113-021-01853-7



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