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MOSAIC

# MOSAIC

## Deliverable Report

# D.2.2.1

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## Executive Summary

Deliverable D.2.2.1 reports on the analysis and use of quantitative data and on the involvement of target groups within Work Package 2 (WP2) of the MOSAIC project, focusing on the **NAZCA *modelling platform for climate change (CC)–driven compound events affecting Alpine Space (AS) protective forests***. Building on the datasets and models documented in **Deliverable D.2.1.1**, this report demonstrates how enhanced empirical information and upgraded modelling tools are translated into actionable knowledge for climate adaptation and disaster risk reduction.

The deliverable is structured in two complementary parts. **Part 1** presents **quantitative data analysis** carried out under Activity 2.2, illustrating how field- and lab-based data are used to upgrade, calibrate, and apply hazard and risk models in contexts affected by CC-related compound and cascading events. A central element is a **collective case study on post-fire forest regeneration**, which exemplifies transnational data harmonisation, analysis, and upscaling under climate scenarios. **Part 2** provides a **qualitative assessment of actor involvement**, drawing on documented engagement with a wide range of target groups, including public authorities, practitioners, infrastructure managers, NGOs, researchers, students, and the general public. **Three case studies** at different spatial scales (local, national, transnational) illustrate how scientific results are co-produced, communicated, and used to support decision-making and capacity building.

Together, these components highlight how MOSAIC operationalises the science-policy interface by linking quantitative modelling with stakeholder engagement to support evidence-based climate action and **ecosystem-based disaster risk reduction** (**Eco-DRR**) in the Alpine region.

# 1. Introduction

## 1.1 Purpose of Deliverable

This deliverable documents the outcomes of quantitative data analysis and qualitative actor involvement activities conducted under **WP2: NAZCA – *NaturAl haZards modelling platform for analysing climate change (CC) compound events on Alpine Space (AS) protective forests***. In particular, it addresses **Activity 2.2**, which focuses on upgrading, calibrating, and validating existing hazard, vulnerability, and risk models using enhanced information derived from field and laboratory experiments (Activity 2.1 – Deliverable D.2.1.1) and complementary datasets from WP1.

The purpose of this deliverable is twofold. First, it demonstrates how empirical data and modelling tools are **operationally used to analyse CC-driven compound events** affecting forest ecosystems and their protective functions. Second, it documents how these results are discussed, interpreted, and co-produced with **relevant target groups** to support informed decision-making, adaptive forest management, and ecosystem-based disaster risk reduction (**Eco-DRR**). The deliverable therefore explicitly adopts a **science-policy interface perspective**, bridging scientific analysis with stakeholder engagement.

## 1.2 Deliverable Overview

Climate change (CC) is intensifying the frequency and severity of climate-related hazards (Seidl et al. 2017, IPCC 2022), often through compound and cascading events (Cutter 2018) involving the interaction of multiple disturbances such as droughts, wildfires, windthrows, pest outbreaks, and snow-related hazards. In the Alpine Space, these processes directly affect forest composition, structure, and resilience, with major implications for the capacity of protective forests to reduce risks to people, infrastructure, and economic activities (Moos et al. 2023).

This deliverable builds on the harmonised datasets and models presented in Deliverable D.2.1.1 and focuses on their application for stakeholders and target groups within **WP2 Activity 2.2**. The report is organised into two main parts.

***Part 1***. *Quantitative Data Analysis* illustrates how empirical data from field surveys, laboratory experiments, and spatial datasets are integrated into hazard and risk models to assess CC-driven compound events. Particular attention is given to post-disturbance dynamics and to the upscaling of results under climate scenarios. A **collective case study** on post-fire forest regeneration serves as a concrete example of transnational data collection, harmonisation, and analysis, providing inputs for model calibration and application.

***Part 2***. *Qualitative Assessment of Actor Involvement* examines how scientific knowledge generated within WP2 is shared, discussed, and co-produced with a broad range of target groups. These include local, regional, and national public authorities, sectoral agencies, infrastructure and forest service providers, NGOs, higher education and research organisations, students, and the general public. Three case studies at different spatial scales (i) a **local Forest Living Lab** (Mompantero) through dedicated focus groups, (ii) a national-scale **choice experiment** for Italy, and (iii) a **transnational summer school** illustrate complementary modes of engagement, ranging from consultation and co-design to capacity building.

By combining quantitative analysis with qualitative insights on actor involvement, the deliverable demonstrates how MOSAIC supports the **translation of scientific evidence into policy-relevant knowledge and practical action** for climate adaptation and disaster risk reduction in the AS.

## 1.3 Related Documents

This deliverable is closely linked to **Deliverable D.2.1.1**, which documents the datasets and models used as input for the analyses presented here. Additional supporting information on target group involvement is drawn from official project reporting, ensuring consistency with documented stakeholder engagement across the MOSAIC project.

# PART 1 - Quantitative Data Analysis

## 2. Overview of Quantitative Data and Analytical Framework

### 2.1 Overview of the Chapter

This chapter provides an overview of the quantitative data used within WP2 Activity 2.2 to upgrade, calibrate, and apply natural hazard and risk models under climate change (CC) and compound event conditions. Building on the datasets and models documented in Deliverable D.2.1.1, the chapter clarifies the data needs, describes the datasets currently available, and outlines how these data support model development and application within the NAZCA platform. The focus is on operational use of data for assessing the impacts of CC-driven compound events on Alpine Space protective forests, rather than on exhaustive technical documentation. Detailed metadata and data curation procedures are reported in D.2.1.1 and are therefore not repeated here.

### 2.2 Data needs

Activity 2.2 requires quantitative data that enable the integration of forest dynamics, disturbances, and natural hazards into upgraded risk models, with particular attention to compound and cascading events and future climate scenarios. Key data needs include:

- **Forest structural and mechanical properties**, including tree stability, resistance, and post-disturbance conditions, to parameterize and calibrate hazard models (e.g. rockfall, avalanche).
- **Disturbance-specific data** related to wildfires, windthrows, drought stress, and post-disturbance regeneration, to assess changes in forest protective functions over time.

- **Disturbance detection and attribution data** are a critical requirement for Activity 2.2. Robust identification of the timing, spatial extent, and recurrence of disturbances is necessary to: (i) distinguish pre-disturbance, disturbance, and post-disturbance phases, (ii) identify areas affected by compound events (e.g. wildfire followed by erosion or rockfall), (iii) provide spatially explicit inputs for model calibration, validation, and scenario analysis.
- **Hydro-geomorphic and terrain data** (e.g. DEMs, orthophotos, LiDAR) to represent topography, flow paths, and interaction between forests and hazards at several spatiotemporal scales.
- **Climate-related indicators** and proxies to evaluate current hazard conditions and explore future scenarios under climate change.
- **Forest dynamics** and **species distribution models** to simulate long-term forest development, regeneration, and shifts in species suitability under CC.

Together, these data are required to support model calibration, validation, and application across different disturbance types and temporal horizons (pre-disturbance, post-disturbance, recovery), and to enable upscaling from local experiments to broader spatial scales.

## 2.3 Data obtained

The quantitative data used in this deliverable originate primarily from **datasets and models compiled under D.2.1.1**, complemented by additional records that are being integrated as WP2 activities progress. The available resources cover multiple hazard types, disturbance processes, and modelling approaches, with a strong emphasis on **rockfalls and wildfires**, two key drivers of compound risk in Alpine forests.

***Forest–Hazard Interaction and Rockfall Modelling*.** Several datasets and models focus on quantifying the protective role of forests against rockfall and its evolution under disturbance and climate change, including:

- Measurements of **mechanical properties of healthy and burned/unburned trees** obtained through pull-and-release experiments, supporting calibration of rockfall impact models.
- Modelling of **protective forest effects against rockfall and soil erosion**, primarily using **RockyFor3D**, with applications under current and CC-altered conditions (e.g. increased drought stress).
- Integrated approaches combining **expert knowledge, forest dynamics models (TreeMig)**, and rockfall simulations to assess future protective capacity under CC-related risk and hazard increase.

These datasets provide critical inputs for evaluating how forest structure and condition influence hazard propagation and risk mitigation considering forests as Eco-DRR.

***Wildfire and Post-Fire Dynamics*.** Wildfire-related datasets address both changing hazard conditions and post-disturbance forest functionality, including:

- **Fire danger assessment** using **Fire Weather Index (FWI)** and **Cosmic Ray probes**.
- Evaluation of the **decay and recovery of protective forest effects after fire**, quantifying changes in the capacity of standing and lying trees to mitigate hazards over time.

These data are essential for understanding post-fire trajectories and informing adaptive management strategies.

***Disturbance Detection and Dynamics*.** A key component of the quantitative framework is the integration of **remote-sensing based disturbance detection**, which enables consistent identification of forest disturbances across space and time. Within MOSAIC, this role is fulfilled by **HILANDYN**, which provides spatially explicit information on forest disturbance occurrence, extent, and temporal dynamics derived from Earth observation data (i.e., Landsat timeseries). HILANDYN supports the detection of major forest disturbances relevant to CC-driven compound events, including wildfires and windthrows, and enables the analysis of disturbance interactions and recurrence. These disturbance layers are essential for linking empirical field data with modelling activities, identifying compound-event hotspots, and distinguishing different disturbance phases used in hazard and risk assessments.

**Forest Dynamics and Species Distribution Modelling**

To support long-term assessments and upscaling under climate scenarios, the database includes:

- **Species Distribution Models (SDMs)** developed by multiple partners.
- **Forest landscape and individual-based models**, such as **SAMSARA2**, which simulate regeneration, growth, and mortality in mixed and uneven-aged mountain forests.
- Combined modelling frameworks (e.g. SDMs and FLAM) to explore forest responses under future climate and disturbance regimes.

***Spatial and Remote Sensing Data*****.** High-resolution spatial datasets, including **LiDAR and orthophotos** from UAV (Unoccupied Aerial Vehicles, e.g., drones), are used to characterise forest structure and terrain in selected case study areas, supporting both empirical analysis and model parameterisation (e.g., avalanche and rockfall risks, windthrow predisposition).

Overall, the datasets obtained provide a comprehensive and complementary basis for analysing CC-driven compound events, linking empirical measurements, spatial data, and modelling tools within the NAZCA platform.

## 2.4 Metadata and data harmonisation

Detailed metadata, including information on spatial reference systems, resolutions, temporal coverage, and data access, are documented in **Deliverable D.2.1.1**. For the purposes of this deliverable, all quantitative analyses rely on harmonised datasets curated according to the FAIR principles, ensuring consistency, traceability, and interoperability across partners and modelling applications.

# 3. Activities Carried out within WP2

## 3.1 Overview of WP2 Activity 2.2 Analytical Framework

Within WP2, Activity 2.2 focuses on the **upgrading, calibration, and application of hazard, vulnerability, and risk models** by integrating enhanced empirical information from field and laboratory experiments (Activity 2.1), disturbance detection products, and complementary datasets from WP1. The overarching objective is to improve the assessment of **CC–driven compound events** affecting AS protective forests.

Quantitative analyses conducted under WP2 are organised according to their **functional role in the risk assessment cycle**, rather than by PP or discipline. This application-oriented structure supports decision-making by explicitly linking data and models to different phases of disturbance and management, including pre-disturbance conditions, disturbance occurrence and interactions, and post-disturbance recovery and adaptation.

## 3.2 Pre-Disturbance and Post-Disturbance Hazard Assessment

Pre-disturbance and post-disturbance analyses provide essential inputs for anticipating changes in hazard dynamics and forest protective functions under CC and compound/cascading-event conditions. Within MOSAIC, wildfire and windthrow hazards represent key applications of this approach, each requiring dedicated quantitative data and modelling workflows.

***Wildfire Hazard Assessment*.** Several MOSAIC analyses focus on wildfire risk by linking empirical weather data with hazard indices. Fire danger has been consistently assessed using the **Fire Weather Index (FWI)** (Fosberg 1981) combined with meteorological observations and climate projections (led by PP5 – DPC/SPL). A tailored workflow was developed to estimate future FWI trends using a reduced set of robust climate variables (maximum temperature and precipitation), enabling consistent projection of future shifts in fire-prone seasons and the frequency of high and very high fire danger conditions under alternative climate scenarios.

At the local and regional scales, calibration of fire danger thresholds was performed by relating historical fire occurrences to station data, improving the spatial relevance of FWI classes for operational risk assessment (Figure 1). These calibrated indices support wildfire risk mapping and early warning, offering information directly usable by forest managers and fire response agencies to anticipate hazard emergence and prioritise preparedness measures.

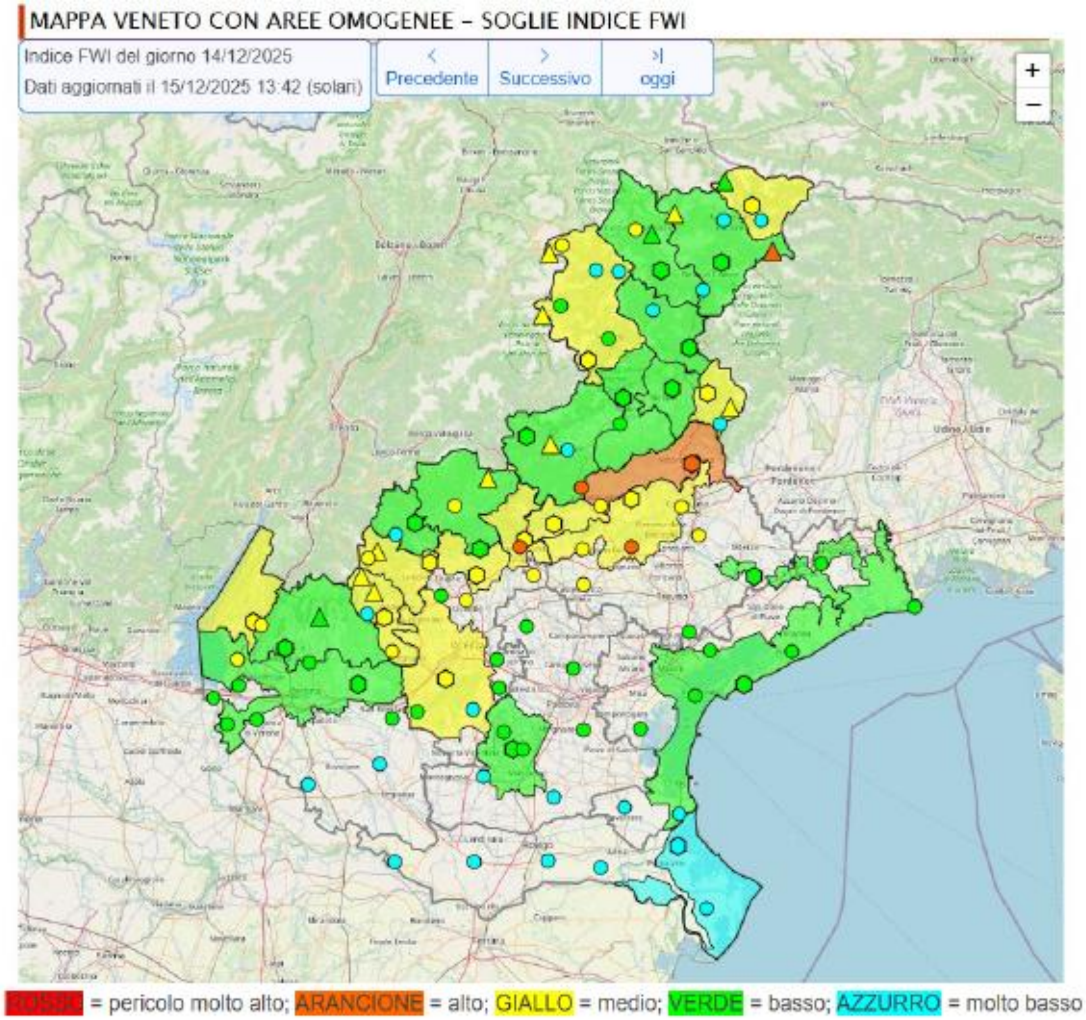


*Figure 1. Example of calibrated Fire Weather Index (FWI) danger classes derived through the integration of meteorological data and Cosmic Ray soil moisture probes. The map shows homogeneous fire-danger areas in the Veneto Region for 15 December 2025, with locally calibrated FWI thresholds improving the spatial consistency and operational relevance of wildfire hazard assessment. Colours indicate fire danger classes from very low (azure) to very high (red); symbols represent meteorological stations used for calibration.*

***Windthrow Hazard Assessment and ForestGALES Updating*.** Windthrows constitute another major disturbance agent with important implications for forest structure and protective functions. It is the first cause of timber loss in Europe, and many studies expect future conditions to exacerbate this trend (Patacca et al. 2023). This is particularly true for steep, storm-prone Alpine terrains of the Northern and Eastern Alps, as Vaia demonstrated in 2018 (Chirici 2019). Within MOSAIC, quantitative efforts have advanced both empirical characterisation and model development for this hazard.

Notably, the **ForestGALES model** (Hale et al. 2015) – originally designed to simulate wind conditionality and tree stability at limited spatial extents – was updated and extended to calculate Critical Wind Speed (CWS) over large areas by incorporating LiDAR-derived canopy height model (CHM) (led by PP4 – UNIPD). Baggio et al. 2025 reports on these updates, showing how ForestGALES integrates stand-level attributes (e.g. height, density, species composition) and site characteristics with mechanistic assessments of wind exposure to predict the probability and severity of windthrow events across large landscapes (Figures 2, 3).

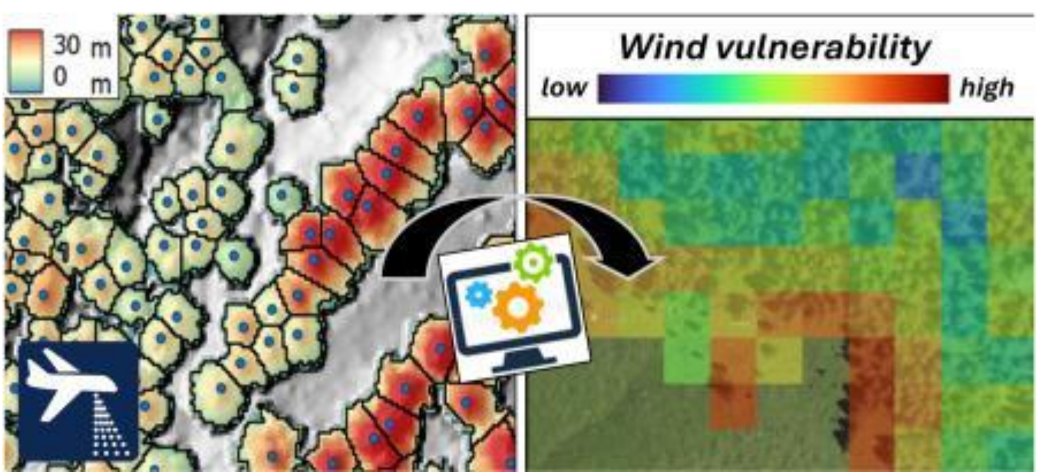

*Figure 2 – A graphical abstract briefly summarizing the core message of Baggio et al. (2025): from RS-LiDAR data and canopy height model (CHM) to the wind vulnerability calculation through the critical wind speed.*

In particular, a raster CHM was used to detect treetops, which were classified into species (from species distribution polygons). The resulting tree dataset made of information such as diameter at breast height (DBH) from allometric equations, height from CHM, and species abundance was then provided to the model to obtain the CWS (Figure 3).

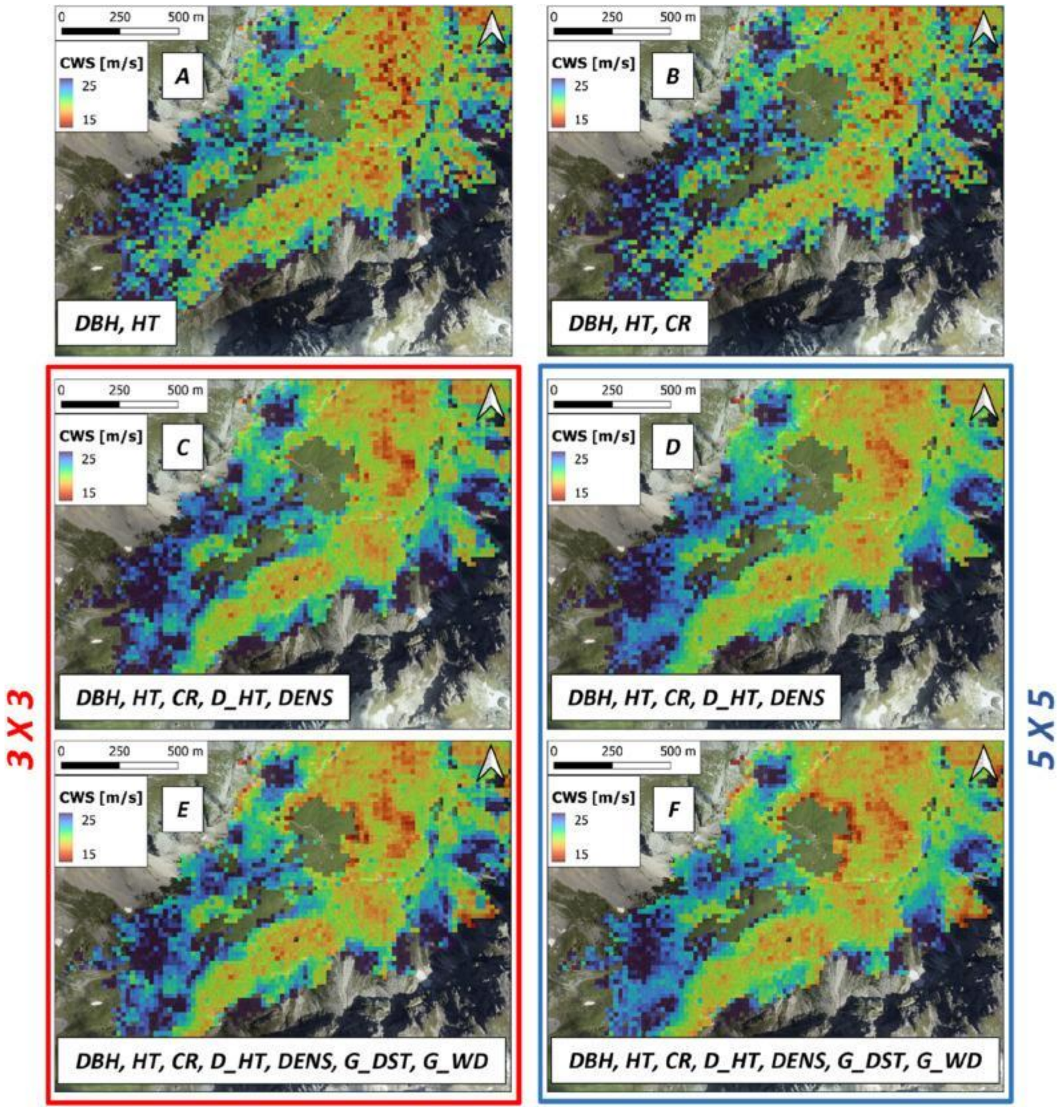


*Figure 3 – Critical wind speed of damage computed with Baggio et al. (2025) algorithm for six Scenarios (A to F) of increasing input complexity. Results are shown for a portion of the Rocca Pietore municipality study area. In Scenario A, the inputs only include DBH and tree height (HT); in Scenario B, tree crown width (CR) is added to the inputs. In Scenarios C and D, stand density (DENS) and dominant height (D_HT) are added, after being calculated with a 3x3 and a 5x5 moving window, respectively; In Scenarios E and F, the distance to the closest gap (G_DST) and its relative width (G_WD) are included in the inputs for the calculation of the CWS. From Baggio et al. (2025).*

This updated ForestGALES framework may support both **pre-disturbance risk mapping** (identifying stands at high windthrow risk under current and future climate conditions) and **post-disturbance characterisation** (estimating the spatial distribution of damage and its effects on subsequent hazard dynamics, such as increased susceptibility to rockfall). By providing spatially explicit windthrow risk surfaces compatible with other hazard layers, this model enhances MOSAIC's capability to account for **compound and cascading interactions** – for example, how windthrow-induced canopy openings alter snowpack stability or slope hydrology.

Other activities related to this topic include the assessment of avalanche probability in sites disturbed by windthrows (cascading effect) in several Alpine countries (led by PP6 – BFW, Austria) and the application of FLAM (wildFire cLimate impacts and Adaptation Model) model to the AS (led by PP7 – IIASA).

## 3.3 Disturbance Detection and Cascading Effects

A central element of Activity 2.2 is the explicit consideration of **compound and cascading events**, where multiple disturbances interact over time and space. Robust disturbance detection and attribution are therefore essential. RS-based disturbance detection, notably through **HILANDYN (High-dimensional detection of Landscape Dynamics)**, enables the identification of forest disturbances such as wildfires and windthrows and their spatial overlap with hazard-prone areas (Morresi et al. 2024; Figure 4). These products allow the definition of **compound/cascading-event hotspots**, where sequential or interacting disturbances amplify risk. This wall-to-wall AS coverage provides a crucial basis for (i) the quantification of historical hazards pathways and (ii) for defining hotspots of compound/cascading disturbances.

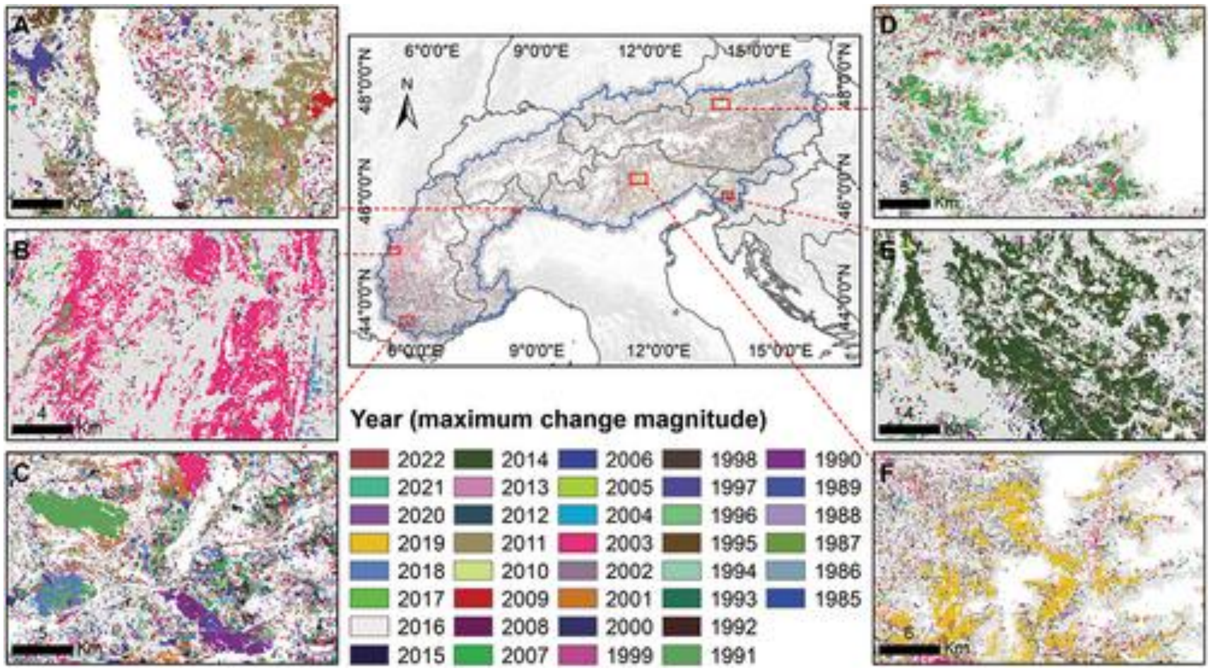


*Figure 4. Examples of stand-replacing and non-stand-replacing forest disturbances detected by HILANDYN in the study area between 1985 and 2022. Panels A-F depict the following disturbance events: (a) dieback induced by defoliating insect outbreak (Asian chestnut gall wasp, Dryocosmus kuriphilus) in 2011; (b) dieback caused by a severe drought and heatwave in 2003; (c) wildfires in 1990, 1991, 2003, and 2017; (d) windthrow in 2007; (e) ice storm in 2014; (f) windthrow in 2018. The grey background in the central panel indicates the presence of forest cover either in 1990 or 2018 according to the Corine Land Cover within the European Alps borders (blue line). From Morresi et al. (2024).*

Quantitative analyses within MOSAIC have demonstrated how **disturbances can alter cascading hazard and risk dynamics**, for example by modifying rockfall susceptibility following windthrows. On one hand, rockfall protection can increase due to surface roughness linked to biological legacies (Costa et al. 2021; PP4 – UNIPD), on the other hand empirical and modelling studies show that forest damage caused by windstorms or fires can significantly reduce protective capacity, leading to increased rockfall risk and altered impact patterns (Moos et al. 2025; PP10 – HAFL). Other activities carried out to assess cascading effects include the assessment of rockfall susceptibility in post-fire environments (PP1 – INRAE; PP10 – HAFL), in eroded sites (PP8 – UL), and of avalanche susceptibility in post-windthrows areas (PP6 – BFW).

## 3.4 Post-Disturbance Recovery and Adaptive Management

Post-disturbance analyses within Activity 2.2 focused on understanding **recovery trajectories and management options** that influence long-term forest protective functions. Within MOSAIC, several quantitative approaches address this phase.

Fine-scale **Species Distribution Models (SDMs)** have been applied to assess post-fire regeneration potential and guide restoration strategies under current and future climate conditions. These models support the identification of species and management options that enhance forest resilience and protective capacity after disturbance.

In parallel, **forest dynamics models**, including individual-based and spatially explicit approaches such as SAMSARA 2 and landscape-scale models (e.g. FLAM), are used to simulate long-term forest development under interacting climate and disturbance pressures. These tools enable the exploration of alternative management scenarios and support the upscaling of local observations to regional and transnational assessments.

By linking post-disturbance data with dynamic modelling, WP2 analyses contribute to **adaptive forest management** strategies that integrate climate change adaptation and ecosystem-based disaster risk reduction.

## 3.5 Contribution to NAZCA Platform and Policy-Relevant Outputs

The quantitative analyses presented in this chapter directly contribute to the development of the **NAZCA modelling platform** by providing calibrated inputs, validated modelling workflows, and spatially explicit outputs relevant for decision-making. By structuring analyses around disturbance phases and compound-event dynamics, WP2 supports the translation of complex scientific information into actionable knowledge for public authorities, risk managers, and forest practitioners.

Pre-disturbance and post-disturbance hazard assessment within WP2 Activity 2.2 relies on the coordinated **use** and **upgrading** of a suite of **complementary models**, addressing forest dynamics, disturbance processes, and natural hazards under CC and compound/cascading-event conditions. The following modelling tools and indices were used or updated within MOSAIC:

- ***Correlative Species Distribution Models (SDMs)***. Updated to assess post-disturbance regeneration potential and shifts in species suitability following disturbances such as wildfire and windthrow, supporting restoration planning and adaptive management. Applied to measure potential of species shifts and turnovers for the AS by several PPs, providing important foundations for hotspots.
- ***DEM Pull-and-Release experiments and DEM-based rock–tree impact modelling*****.** Uploaded to quantify tree mechanical stability and resistance to rock impacts, providing empirical inputs for calibrating rockfall hazard models of healthy (unburned) and burned trees after wildfires.
- ***RockyFor3D.*** Employed to simulate rockfall trajectories and forest protective effects under different forest structures and disturbance conditions, including post-fire and post-windthrow scenarios.
- ***ZEMOKOST and DEBFLOW*****.** Used to model debris flows and torrential processes, supporting assessments of forest regulation functions and interactions between hydrological and geomorphic hazards.
- ***ForestGALES.*** Updated to assess windthrow risk by integrating stand-level forest characteristics, site exposure, and climate drivers at a large spatial scale through the

integration of RS-derived LiDAR data, supporting both pre-disturbance risk mapping and post-disturbance impact assessment.

- ***TreeMig.*** Used to simulate long-term forest dynamics and species composition changes under climate change, providing inputs for assessing future protective forest capacity at the landscape scales.
- ***SVH (Stored Volume Height) and ATP (Adapted Tree Parameters)***. Derived indicators used to represent forest structure and mechanical properties relevant for hazard modelling and for linking empirical measurements with simulation outputs.
- ***Fire Weather Index (FWI).*** Applied and locally calibrated to assess wildfire danger, including integration with Cosmic Ray soil moisture probes to improve operational relevance and spatial consistency of fire danger classes.

In addition, several **process-based and landscape-scale models** are used to support longer-term assessments and upscaling under CC scenarios:

- ***SAMSARA2*****.** Process-based, individual-based stand model simulating regeneration, growth, and mortality in mountain forests.
- ***FLAM***. Regional-scale forest dynamics and wildfire disturbance modelling framework.
- ***LandClim.*** Spatially explicit model for forest landscape dynamics under climate and disturbance regimes.
- ***FlowPy***. Modelling tool for simulating flow paths and gravitational hazard propagation. Updated within WP2 in French Alps.

Together, these models provide a coherent analytical framework linking empirical data, disturbance detection, and simulation tools to support integrated assessments of CC-driven compound events and their impacts on protective forests and society (Table 1).

*Table 1. Models used and updated within WP2 Activity 2.2, their purpose, a reference, operational phase of application, and main target groups.*

| Model or Tool | Main purpose | References | Operational phase | Main Target Group(s) |
|---|---|---|---|---|
| **Correlative SDMs** | Assess post-disturbance regeneration potential at local scale and shifts in species suitability under climate change (at the regional scale) | Miller 2010, Mantero et al. 2024, Anselmetto et al. 2025 | Post-disturbance; Recovery and restoration; CC-related risks | Forest managers; Policymakers; Restoration planners; Scientists; Society |
| **DEM Pull&Release + DEM rock–tree impact** | Quantify tree mechanical stability and resistance to rock impacts; calibrate rockfall models in post-disturbance environments | Dorren and Berger 2006 | Post-disturbance; Compound and cascading effects | Risk managers; Infrastructure authorities; Researchers |
| **RockyFor3D** | Simulate rockfall trajectories and forest protective effects under different forest and disturbance conditions | Dorren and Berger 2010 | Post-disturbance; Compound and cascading effects | Risk managers; Forest services; Civil protection |
| **ZEMOKOST + DEBFLOW** | Model debris flows and torrential processes; assess forest regulation functions | Geobrugg 2007, Kohl 2010 | Pre-disturbance; Risk mitigation | Risk managers; Water authorities; Policymakers |
| **ForestGALE S** | Assess windthrow risk based on stand structure, exposure, and climate drivers | Hale et al. 2015, Baggio et al. 2025 | Pre-disturbance; Risk mitigation | Forest managers; Risk managers; Policymakers |
| **TreeMig** | Simulate long-term forest dynamics and species composition under climate change at the landscape scale | Lischke et al. 2006 | Post-disturbance; Long-term adaptation; CC-related risks | Forest planners; Policymakers; Researchers |
| **SVH & ATP indicators** | Represent forest structure and mechanical properties relevant for hazard modelling | - | Pre-disturbance; Post-disturbance; Risk mitigation | Modellers; Forest services; Risk analysts |
| **FWI (calibrated with Cosmic Ray probes)** | Assess and locally calibrate wildfire danger for operational use using advanced cosmic ray probes | Fosberg 1981 | Pre-disturbance; Disturbance | Civil protection; Fire services; Policymakers |
| **SAMSARA2** | Simulate stand-scale forest dynamics (regeneration, growth, | Courbaud et al. 2015 | Post-disturbance; Long-term adaptation; CC- | Forest managers; Researchers; Society; Students |

| Model or Tool | Main purpose | References | Operational phase | Main Target Group(s) |
|---|---|---|---|---|
| | mortality) | | related risks | |
| **FLAM** | Explore landscape-scale forest dynamics and disturbance interactions | Krasovskii et al. 2018 | Pre-disturbance; Post-disturbance; Risk mitigation; CC-related risks | Policymakers; Landscape planners; Researchers |
| **LandClim** | Model forest landscape dynamics under climate and disturbance regimes | Schumacher 2004 | Long-term adaptation | Policymakers; Strategic planners; Researchers |
| **FlowPy** | Simulate flow paths and gravitational hazard propagation | D'Ambroise et al. 2022 | Disturbance; Post-disturbance | Risk managers; Infrastructure planners |

# 4. Case Study – Collective Quantitative Data Analysis of Post-Fire Regeneration

## 4.1 Rationale and Objectives of the Collective Post-Fire Regeneration Effort

Post-disturbance forest regeneration represents a critical phase in the **disturbance-recovery cycle** of Alpine forests, with direct implications for ecosystem resilience and the provision of protective functions against natural hazards (Wohlgemuth et al. 2017). In the context of CC, wildfires are expected to increase in frequency, intensity, and spatial extent, often interacting with other disturbances such as drought, windthrow, erosion, and rockfall even in previously unaffected areas (Seidl et al. 2017). These interactions can generate **compound and cascading** risk conditions, particularly in steep mountain environments where forests play a key role in reducing hazard impacts (Mantero et al. 2023, 2024).

Within WP2 Activity 2.2, the **collective post-fire regeneration effort** was designed to address a key knowledge gap: how forest regeneration dynamics unfold across the AS following wildfire, and how these dynamics affect the temporal evolution of protective forest functions. Understanding regeneration trajectories is essential to identify periods of heightened vulnerability, during which the loss or delay of forest cover may reduce slope stability, increase sediment connectivity, or amplify gravitational hazards.

The objectives of this collective effort are threefold:

1. To **quantify post-fire regeneration patterns** across a broad range of environmental, climatic, and wildfire conditions in the AS;

2. To **identify the main drivers of regeneration success**, composition, and speed, including climate, topography, fire severity, and time since fire;

3. To provide **quantitative inputs for hazard and forest dynamics models**, supporting post-disturbance risk assessment, model calibration, and adaptive forest management strategies.

By adopting a **transnational** and harmonised approach, this case study directly supports the NAZCA modelling platform and contributes actionable knowledge for policymakers, risk managers, and forest practitioners dealing with CC-driven wildfire risk and its cascading effects.

## 4.2 Transnational Data Collection and Harmonisation

To meet these objectives, a coordinated, transnational data collection effort was implemented across the AS, building on both newly collected field data and harmonised existing datasets. The collective dataset includes post-fire regeneration surveys from **14 wildfire events** distributed across **five Alpine countries**, spanning a wide gradient of environmental conditions and **time since fire** (approximately 1 to 20 years).

A **common field protocol** was defined and shared among partners to ensure consistency in data collection and interpretation. Field surveys were conducted using a standardised plot-based design, recording information on tree regeneration abundance, species composition, size classes, and associated environmental variables. Where available, existing datasets were harmonised to match the common structure and variable definitions, enabling their integration into a unified database.

Data **harmonisation** focused on (i) standardising regeneration metrics and species codes, (ii) aligning spatial references and plot metadata, (iii) ensuring consistency in fire-related variables (e.g. time since fire, qualitative fire severity), (iv) applying quality control procedures to ensure comparability across countries and sampling campaigns.

The resulting dataset represents **the most comprehensive transnational collections** of post-fire regeneration data currently available for Alpine forests. Its harmonised structure enables robust comparative analyses and supports integration with other spatial layers and modelling tools developed within WP2, including disturbance detection products, hazard models, and forest dynamics simulations.

By consolidating empirical observations across administrative and ecological boundaries, this collective effort provides a strong empirical basis for assessing post-fire recovery trajectories and their implications for protective forest functions under current and future climate conditions.

### 4.3 Quantitative Analysis and Key Results

Quantitative analyses were conducted on the harmonised post-fire regeneration dataset to identify **general patterns and key drivers of forest recovery** across the Alpine Space. The analytical framework was designed to balance statistical robustness with interpretability, in order to support both scientific understanding and decision-making in post-disturbance management. Analyses focused on three main dimensions: (i) regeneration abundance and composition, (ii) temporal trajectories of recovery following fire, and (iii) the relative influence of climatic, topographic, and disturbance-related drivers.

The collective dataset was analysed using a combination of **regression-based models and machine-learning approaches**, allowing the exploration of both linear and non-linear relationships between regeneration metrics and explanatory variables (i.e., drivers). Predictor variables included climatic conditions, elevation and terrain characteristics, fire-related attributes, and time-since-disturbance.

To account for the hierarchical structure of the data and the transnational sampling design, models explicitly considered variability among fire events and regions. This approach enabled the identification of generalizable patterns while preserving sensitivity to local conditions.

Results show that **post-fire regeneration trajectories are highly variable**, but follow consistent patterns across the Alpine Space when analysed in relation to time since fire and environmental gradients (Figures 5-7). Time-since-fire emerged as a primary driver of regeneration dynamics (Figure 5), with early post-fire phases characterised by high regeneration density of pioneer and early successional species but with high variability among sites, followed by a progressive increase in regeneration abundance of late successional species and a recovery of structural complexity (Figure 6). This temporal signal highlights a **critical window of reduced protective function** in the first years following fire, during which forests provide limited mitigation against gravitational and erosion-related hazards due to limited dbh and structural complexity.

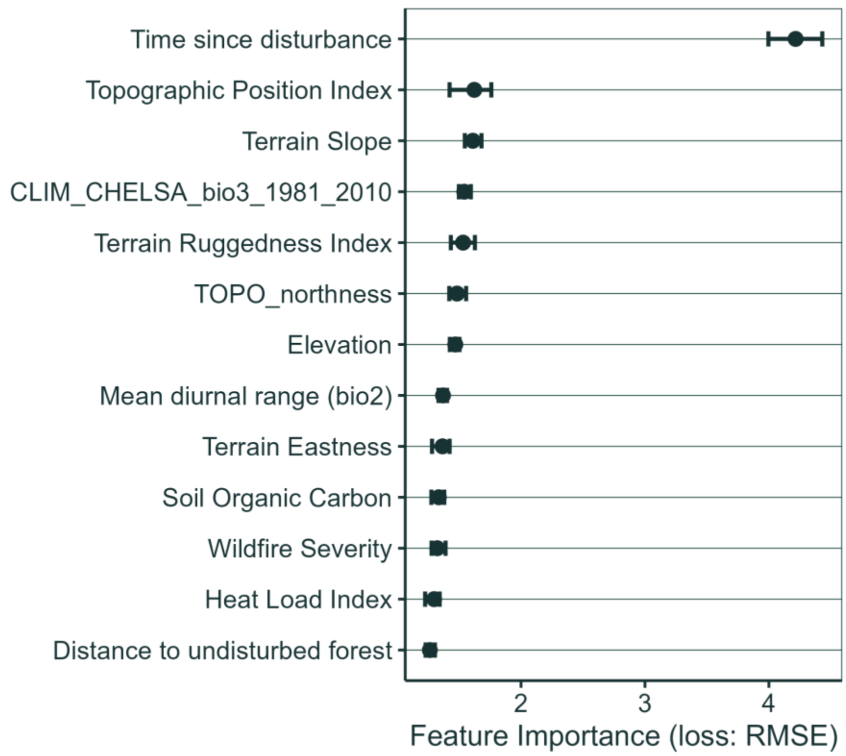


*Figure 5. Relative importance of environmental and disturbance-related predictors driving post-fire forest regeneration across the Alpine Space, expressed as the increase in model prediction error (RMSE) when each variable is permuted. Time since disturbance emerges as the dominant driver, followed by topographic position and climatic seasonality, highlighting the combined role of recovery time, terrain, and climate in shaping post-fire regeneration trajectories.*

Species composition analyses revealed **distinct successional pathways**, with early regeneration often dominated by pioneer or disturbance-tolerant species, followed by gradual diversification over time. These shifts have important implications for long-term forest structure and stability, influencing how quickly and effectively protective functions can be restored (Figure 6).

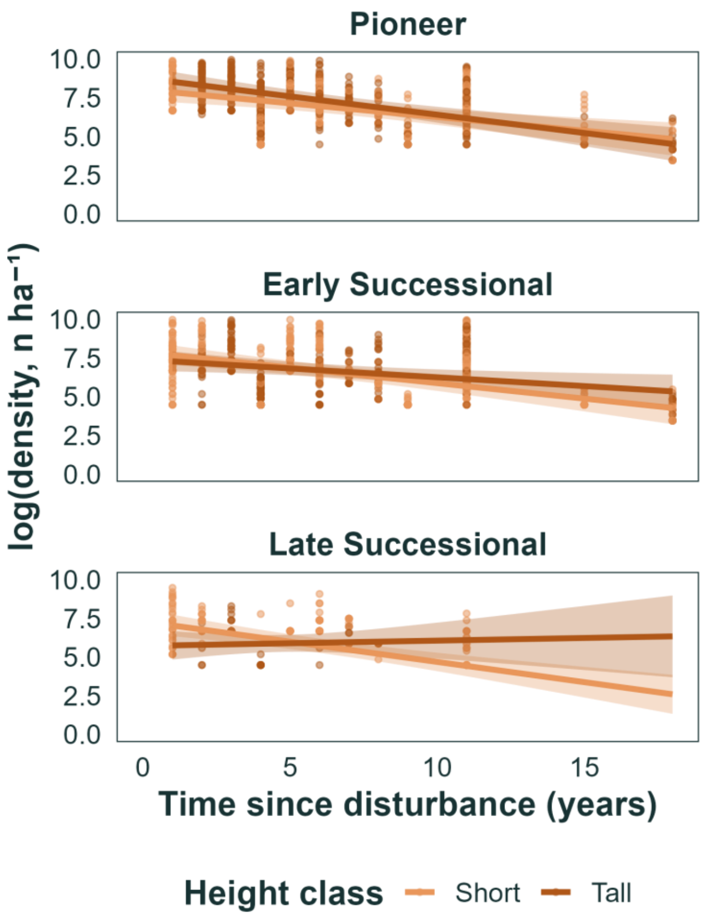


*Figure 6. Post-fire regeneration trajectories for pioneer, early successional, and late successional tree groups as a function of time since disturbance. Points represent plot-level observations across the Alpine Space, while lines show fitted relationships with confidence bands, differentiated by regeneration height class (short vs. tall). Results indicate contrasting successional dynamics, with declining densities of pioneer and early successional species over time and increasing dominance of late successional species, highlighting shifts in forest structure relevant for the recovery of protective functions.*

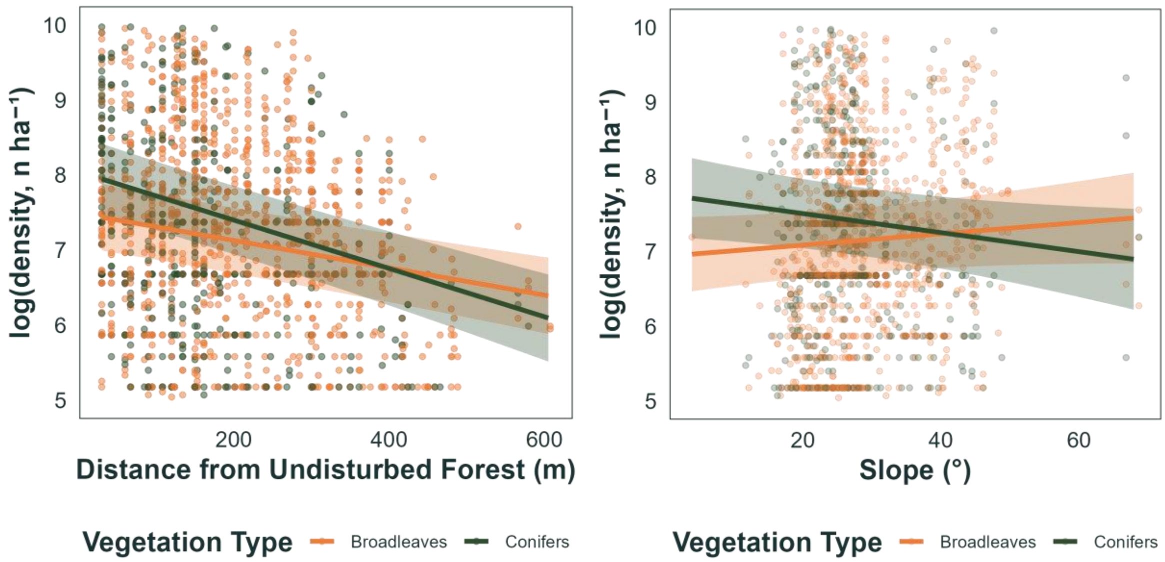


*Figure 7. Relationship between post-fire regeneration density and (a) distance from undisturbed forest and (b) slope steepness for broadleaves and conifers across the Alpine Space. Points represent individual plots, while lines and shaded areas indicate fitted relationships with confidence intervals. Results highlight contrasting responses of vegetation types to topographic and disturbance constraints, with implications for post-fire recovery and the restoration of protective forest functions on steep slopes.*

Climatic and topographic factors significantly modulated regeneration success. Sites in steeper slopes generally showed lower conifer density but higher abundance of broadleaves (Figure 7). Distance from forest edges represents a constraint for conifers more than broadleaves.

The quantitative results provide **empirical baselines** for calibrating and validating hazard and forest dynamics models used within WP2. In particular, the identified recovery timelines and driver relationships can inform assumptions on post-fire forest structure in rockfall, erosion, and debris-flow modelling. By quantifying the duration and variability of post-fire recovery phases, the analysis supports **risk-informed prioritisation of management interventions**, helping identify where and when restoration or protective measures are most urgently needed (see for instance

Mantero et al. 2024). At the same time, the transnational nature of the dataset allows results to be generalised beyond individual case studies, strengthening their relevance for AS-wide CC adaptation strategies.

## 4.4 Implications for Protective Forests and Risk Management

The collective analysis of post-fire forest regeneration provides clear insights into how wildfire alters the **temporal continuity of protective forest functions** in the AS. Quantitative results highlight that post-fire recovery is neither immediate nor uniform, resulting in **time windows during which forests offer reduced protection** against gravitational, erosion-related, and hydro-geomorphic hazards (see the case study example in the Comba delle Foglie, Piedmont region, of 2018 in Vacha et al. 2023).

The early post-fire phase, characterised by limited structural complexity, represents a **critical period of heightened vulnerability**. During this phase, reduced canopy cover and root reinforcement can amplify slope instability, sediment mobilisation, and rockfall susceptibility, especially when fires interact with other disturbances such as heavy precipitation or windthrow. These findings reinforce the importance of explicitly considering **post-disturbance conditions** in hazard and risk assessments, rather than assuming static forest protective functions. On the other hand, disturbances such as fire may create important ecosystem conditions for diversifying species richness and increase future resilience under increasing CC-related risks and hazards like drought and pathogens (Seidl et al. 2017).

The strong influence of climatic and topographic drivers on regeneration dynamics indicates that recovery trajectories vary systematically across the AS. This variability can be used to **prioritise post-fire management actions**, focusing on areas where slow regeneration coincides with high exposure to hazards or the presence of critical infrastructure and settlements (Mantero et al. 2023). By integrating regeneration outputs into hazard models (e.g. rockfall, debris flow, erosion), risk managers can better identify locations where **temporary protective measures** or targeted restoration efforts are required to bridge the gap until forest functions recover.

Results from the collective dataset support **adaptive forest management strategies** that account for future climate conditions and disturbance regimes (Stritih et al. 2026). The observed shifts in species composition and recovery rates suggest that post-fire restoration should not aim solely at reinstating pre-fire forest states, but rather at promoting forest structures and species assemblages that are resilient to future climate stressors while maintaining protective functions. The empirical relationships derived from this analysis provide valuable inputs for forest dynamics models and decision-support tools used within WP2, enabling scenario-based evaluation of alternative management options.

By translating transnational empirical evidence into actionable insights, this case study exemplifies the **science-policy interface approach** of MOSAIC. The results inform policymakers, forest services, and civil protection authorities about the duration and variability of post-fire recovery, supporting more realistic planning horizons for climate adaptation and disaster risk reduction. Moreover, it can inform citizens on the natural dynamics of post-fire ecosystems (see Chapter 6.1). Overall, the collective post-fire regeneration effort demonstrates how harmonised data and quantitative analysis can directly support **risk-informed decision-making** and contribute to the sustainable management of protective forests under climate change.

# PART 2 – Qualitative Assessment of Actors Involvement

## 5. Framework for Actor Involvement

The development and application of the NAZCA modelling platform within WP2 were supported by an extensive and multi-level process of **actor involvement**, spanning local to transnational scales. Engagement activities were designed to ensure that quantitative data, models, and scenario analyses produced within WP2 were not only scientifically robust, but also **relevant, interpretable, and usable** by a plethora of actors including decision-makers, practitioners, and other stakeholders involved in the management of AS protective forests and CC-related risks - but also to the general public and society and the future generation of managers (Table 2). A key role of WP2 is to ensure **transferability of knowledge and supporting decision systems for Eco-DRR.**

Actor involvement followed a **graduated approach**, ranging from consultation and validation (e.g., focus groups) to co-production (e.g., forest living labs and marteloscopes) and capacity building (e.g., summer school). This approach allowed MOSAIC to address the diverse needs of target groups, including public authorities, forest managers, civil protection agencies, infrastructure operators, researchers, educators, and the general public. Engagement activities were closely aligned with WP2 Activity 2.2, supporting the upgrading, calibration, and application of hazard and risk models under CC and compound/cascading-event conditions.

At the **local scale**, Forest Living Labs (FLLs), particularly the Mompantero site, served as focal points for direct interaction with municipalities, local forest services, practitioners, and society (Chapter 6.1). These interactions enabled the discussion of post-disturbance dynamics, protective forest functions, and management options grounded in site-specific evidence. Local policymakers and practitioners were involved across all the design phases of the project - from pre-disturbance to post-disturbance management - and using different tools such as FLLs and Marteloscopes.

At **regional and national scales**, WP2 partners engaged with forestry administrations, meteorological agencies, civil protection authorities, and sectoral agencies to validate modelling approaches, discuss operational thresholds (e.g. wildfire danger), and explore integration of MOSAIC outputs into existing planning and risk-management frameworks. Notably, several regional and national territorial agencies are included in MOSAIC and WP2 as active project partners (PPs), granting a direct and continuous collaboration and exchange of data, processes, and outputs that well incarnate the spirit of NAZCA platforms. Ministers of France, Austria, and Slovenia have been contacted to share efforts and results of MOSAIC to the relevant policymakers.

At the **transnational scale**, MOSAIC results and methods were disseminated and discussed through Alpine-wide networks (e.g., EUSALP Action Groups 2, 6, 7, 8, 9; Alpine Convention) international conferences (e.g., SISEF, Padova; IMC, Innsbruck; IUFRO, Sweden; SER, United States; EGU, Austria), training activities (i.e., a dedicated summer school), and higher-education programmes (e.g., students exchange and training). These activities strengthened cross-border knowledge exchange and contributed to long-term capacity building beyond the project duration.

Table 2 provides a synthetic overview of the main actor groups involved, their level of engagement, the spatial scale of interaction, and their contribution to WP2 activities.

*Table 2. Overview of actor involvement within WP2.*

| Actor group | Spatial scale | Level of engagement | Main WP2-related activities | Purpose / contribution |
|---|---|---|---|---|
| *Local public authorities (municipalities, local foresters)* | Local | Co-design / Co-production | Forest Living Labs (e.g. Mompantero), field validation, focus groups | Contextualisation of post-disturbance risk; feedback on management options; co-design of Eco-DRR |
| *Regional public authorities (forest services, meteorological agencies)* | Regional | Consultation / Validation / Co-production | Hazard assessment, wildfire danger calibration, workshops, site visits | Operational relevance; alignment with regional planning; involvement as Project Partners |
| *National public authorities (ministries, civil protection)* | National | Consultation / Strategic dialogue | Policy-oriented meetings, expert hearings, national workshops | Uptake into national risk and forest policies |
| *Sectoral agencies (forestry, water, hazard management)* | National / Regional | Technical collaboration | Model testing (e.g. debris flows, rockfall, wildfire), data exchange | Model calibration and validation |
| *Infrastructure and public service providers (railways, road operators)* | Local / National | Consultation / Knowledge transfer | Workshops, site-based discussions, training-oriented exchanges | Application of results to infrastructure protection |
| *Interest groups and NGOs* | National / Transnational | Awareness raising / Dialogue | Conferences, thematic workshops, excursions | Dissemination and societal engagement |
| *Higher education and research organisations* | Transnational | Co-production / Capacity building | Conferences, student involvement, joint analyses | Scientific integration and innovation |
| *Education and training centres* | National / Transnational | Capacity building | Summer schools, training hubs, | Long-term knowledge legacy |

| Actor group | Spatial scale | Level of engagement | Main WP2-related activities | Purpose / contribution |
|---|---|---|---|---|
| | | | practical demonstrations | |
| *SMEs and enterprises* | National | Information exchange | Presentations, exploratory contacts | Awareness of innovation potential |
| *Cross-border governance bodies (e.g. EUSALP Action Groups, Alpine Convention)* | Transnational | Strategic coordination | Task force meetings, policy workshops | Alpine-wide alignment |
| *General public* | National / Transnational | Awareness raising | Media outreach, public events, social media, focus groups | Broader societal understanding of risks |

# 6. Case Studies of Actor Involvement

## 6.1 Mompantero Forest Living Lab (Local scale)

The **Mompantero Forest Living Lab (FLL)** represents a local-scale implementation of MOSAIC's science-policy interface, designed to facilitate structured dialogue between scientists, forest practitioners, policymakers, and citizens in a wildfire-prone Alpine context. The FLL aimed to support shared understanding of post-fire risks, ecosystem services, and management options relevant to protective forests under climate change (Table 3).

*Table 3. Focus group design and implementation within the Mompantero FLL.*

| Element | Description |
|---|---|
| Objective | Increase social awareness and understanding of post-fire restoration practices and risks |
| Actor groups involved | (i) Forestry practitioners and wood-chain operators; (ii) Local citizens; (iii) Local and regional policymakers |
| Spatial scale | Local (Mompantero area) |
| Engagement format | Moderated focus groups with facilitated discussion |
| Core topics addressed | Ecosystem services at risk from forest fires; post-fire restoration options; trade-offs of deadwood management |
| Discussion tools | Visual material (photos of post-fire management scenarios) |
| Data collection | Audio recording and qualitative content analysis |
| Output | Identification of shared priorities, divergences in perception, and communication needs |

Engagement activities were organised through **three moderated focus groups**, each targeting a specific actor group (practitioners, citizens, and policymakers), following a common discussion protocol. The focus groups were conducted in dedicated settings to encourage interaction and were audio-recorded for subsequent qualitative analysis..

Discussions addressed three main themes: (i) **ecosystem services most affected by forest fires**; (ii) **preferred post-fire management strategies**, illustrated through visual scenarios (Figure 8); (iii) **perceived benefits and drawbacks of leaving deadwood on site**.

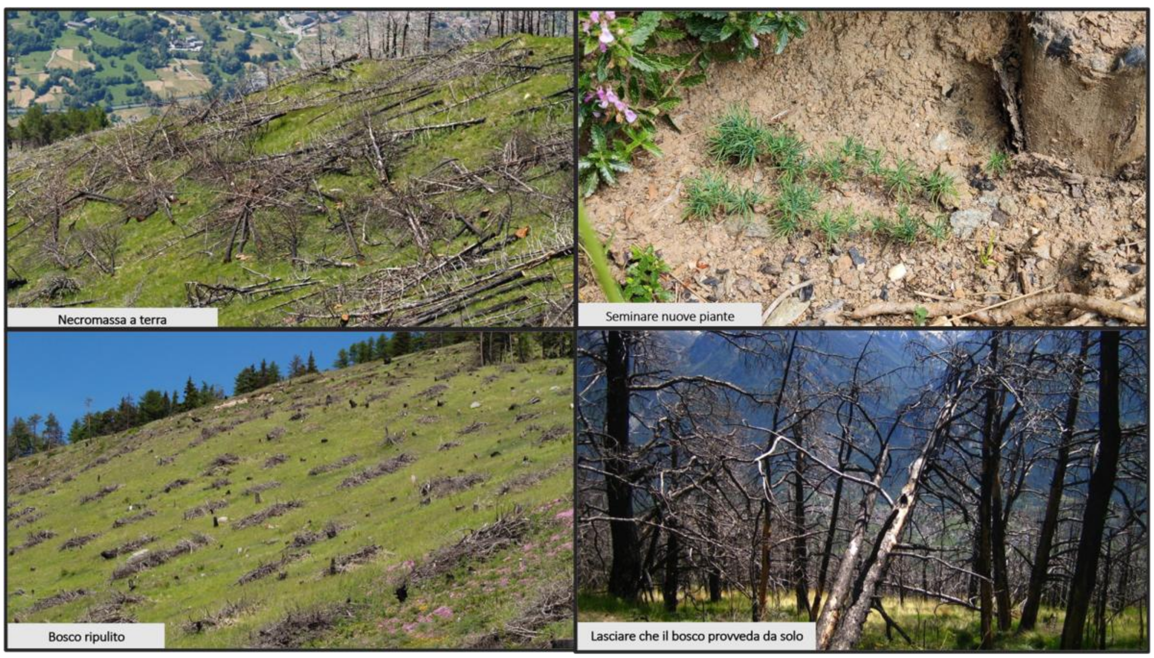


*Figure 8. Example of visual scenarios provided to the population related to post-fire management techniques.*

Across all actor groups, protection against hydrogeological hazards, biodiversity conservation, and long-term forest stability emerged as key concerns. However, priorities and framings differed. Practitioners emphasised operational feasibility, safety, and timing of interventions; policymakers focused on balancing risk reduction with regulatory and economic constraints; citizens highlighted landscape values, recreation, and the need for transparent communication.

These discussions revealed both converging and diverging perspectives on post-fire management, underscoring the importance of **context-specific, participatory approaches** when translating scientific evidence into locally accepted actions. Results show that when the different focus groups are considered jointly, **hydrogeological and territorial stability** emerge as the most relevant themes for ecosystem services, while **natural regeneration** is identified as the key issue for post-fire management.

## 6.2 Choice Experiment (National scale – Italian Alps)

To complement local qualitative engagement and quantitative biophysical analyses developed within WP2, MOSAIC implemented a **choice experiment (CE)** to assess societal preferences and willingness to pay for alternative **post-fire forest restoration strategies** in the Italian Alps. The CE was designed to support the science-policy interface by explicitly linking post-fire management options to public acceptance and economic trade-offs.

The primary objective of the choice experiment was to **quantify the social value** associated with different post-fire restoration measures and to explore how scientific evidence on forest dynamics and protective functions influences public preferences. The assessment was conducted at the **national scale**, targeting residents of Italian Alpine regions, and complements the modelling and regeneration analyses carried out within WP2.

The survey was administered to approximately **1,200 respondents**, providing a robust empirical basis for analysing preferences relevant to regional and national policy design

Respondents were presented with a series of **choice cards** (Figure 9), each describing alternative post-fire management scenarios characterised by a combination of attributes:

- **Deadwood management** (no intervention, partial or full salvage logging);
- **Reforestation strategies** (none, group planting, regular planting);
- **Protective infrastructure** (e.g. rockfall nets);
- **Annual cost per household**, framed as a regional tax contribution.

A **status-quo option** (no intervention, zero cost) was included in all choice sets, allowing respondents to opt out of active restoration. Follow-up questions captured motivations for nonpayment, distinguishing between lack of interest, scepticism about effectiveness, preference for prevention, or objection to new taxes.

Crucially, the experiment included two phases. In the second phase, respondents were provided with **scientific information** on post-fire forest dynamics, highlighting evidence that natural regeneration and deadwood retention can enhance microclimatic conditions, biodiversity, and long-term protective functions against rockfall and avalanches. This design allowed assessment of how **scientific knowledge influences preferences and acceptance of management options.**

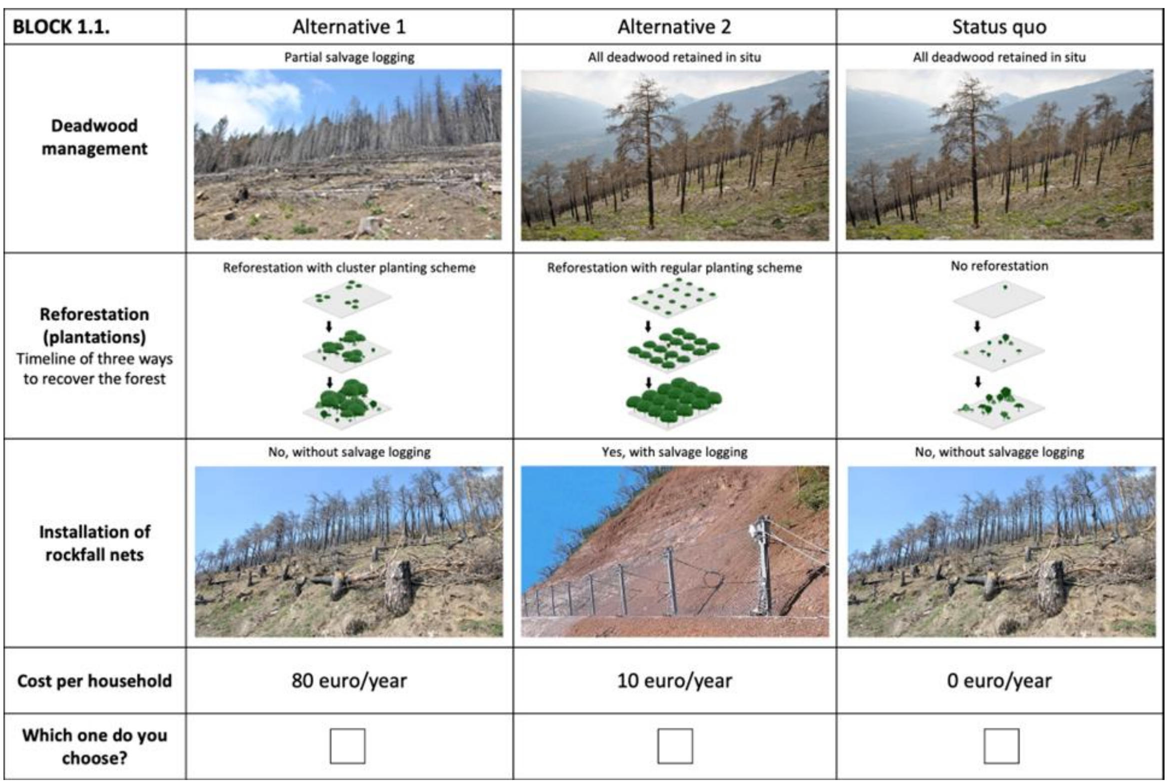


*Figure 9. A choice set example.*

The choice experiment demonstrates that public preferences for post-fire restoration are **heterogeneous** and sensitive to both costs and perceived effectiveness of interventions. Importantly, the provision of scientific information altered preferences, increasing acceptance of **nature-based and low-intervention strategies**, such as allowing natural regeneration and retaining deadwood, when these were framed in terms of long-term protective and ecological benefits.

These results directly support WP2 objectives by:

- Informing **policy-relevant trade-offs** between engineering-based and ecosystem-based solutions;
- Providing evidence on the **social acceptability of adaptive forest management strategies** under climate change;
- Supporting the integration of NAZCA modelling outputs into decision-making processes that account not only for hazard reduction, but also for societal preferences and legitimacy.

Overall, the choice experiment complements biophysical modelling and local engagement activities by embedding **societal values** into post-fire risk management and restoration planning at the Alpine scale.

## 6.3 Summer School (Transnational scale)

The MOSAIC Summer School, held in **Nevegal (Belluno, Italy) in October 2025**, represented the transnational-scale capacity-building component of WP2, with the explicit objective of transferring **NAZCA tools, compound/cascading-events concepts, and integrated disturbance-management approaches** to future professionals. The Summer School brought together students and early-career researchers from different disciplinary backgrounds, providing a structured environment to engage with real-world challenges related to CC, natural hazards, and protective forest management.

The Summer School was structured around the core idea of **multiple perspectives on disturbance management under CC-related risks**, combining lectures by different scientists of the PPs, field activities, and hands-on modelling exercises. The programme covered key disturbance agents affecting AS forests (wildfires, windthrows, rockfall), their cascading effects, and the role of forests as nature-based solutions for Eco-DRR.

A central component was the **marteloscope-based group exercise**, in which participants worked in small interdisciplinary teams to simulate forest management decisions with the explicit goal of **maximising protection against natural hazards**. Using the **SAMSARA2 forest growth model**, participants explored how different tree-selection strategies influenced forest structure, regeneration dynamics, and long-term protective capacity under changing climatic conditions. This exercise directly operationalised NAZCA concepts by linking stand-scale decisions to long-term risk outcomes.

Field excursions in the surrounding Alpine landscape complemented modelling activities, allowing participants to directly observe disturbance legacies, protective forest functions, and management constraints, and to relate empirical observations to model outputs.

Feedback collected through post-event questionnaires indicates **high overall satisfaction** with both the content and format of the Summer School. Participants particularly valued:

- the **hands-on modelling and marteloscope simulations**, which facilitated understanding of complex forest–hazard interactions;
- the integration of **quantitative models with field observations**;
- the opportunity to work in **small, multidisciplinary groups**, enhancing peer learning and problem-solving.

Respondents highlighted that the combination of theory, practice, and discussion improved their ability to understand **compound and cascading events**, uncertainty, and trade-offs in disturbance management. The explicit focus on protection against natural hazards was perceived as especially relevant for future professional applications in forestry, risk management, and spatial planning.

Beyond short-term training, the Summer School contributed to the **long-term legacy of MOSAIC** by embedding NAZCA tools and concepts into the skill set of future professionals. By engaging participants directly with SAMSARA2 simulations and marteloscope-based decision-making, the Summer School moved beyond awareness raising toward **practical competence** in using modelling tools to support adaptive forest management under CC.

The transnational composition of the teaching team and participants fostered cross-border exchange and the formation of professional networks, increasing the likelihood that MOSAIC approaches will be reused, adapted, and further developed beyond the project lifetime. In this sense, the Summer School represents a key mechanism through which **knowledge generated within WP2 is transferred sustainably**, supporting long-term capacity for managing CC-related compound risks in Alpine forests.

## 7. Cross-Cutting Insights from Actor Involvement

Part 2 of this deliverable demonstrates how **actor involvement activities complement quantitative analyses and modelling efforts** within WP2, strengthening the science-policy interface of the NAZCA platform. Engagement was deliberately structured across **multiple spatial scales** and through **diverse formats**, ensuring that scientific outputs addressing CC–driven compound/cascading events are relevant, understandable, and usable by different target groups within and outside the AS.

Section 5 highlighted the breadth of actor involvement, showing how local, regional, national, and transnational stakeholders were engaged through consultation, co-production, and capacity-building activities. This multi-level approach ensured continuous feedback between scientific development and practical needs, supporting the calibration, interpretation, and application of hazard and risk models.

Section 6 illustrated this approach through three complementary case studies. The **Mompantero Forest Living Lab** demonstrated how qualitative, place-based engagement enhances shared understanding of post-disturbance risks and management trade-offs at the local level. The **choice experiment** translated scientific evidence on post-fire forest dynamics into insights on societal preferences and policy acceptability at the national scale. The **Summer School** showcased how NAZCA tools and compound-events concepts are transferred to future professionals, supporting long-term capacity building beyond the project lifetime.

Together, these activities show that effective management of CC-related compound risks in Alpine protective forests requires not only robust data and models, but also **structured dialogue, social acceptance, and sustained knowledge transfer**. By integrating quantitative science with qualitative engagement, WP2 contributes to more legitimate, adaptive, and durable climate action strategies in the Alpine Space.

# 8. Conclusions and Outlook

Deliverable D.2.2.1 demonstrates how **quantitative data analysis and structured actor involvement** jointly support the development and application of the NAZCA modelling platform within WP2 of the MOSAIC project. By integrating empirical data, disturbance detection, and modelling tools with stakeholder engagement across multiple scales, the deliverable operationalises the science-policy interface needed to address **CC–driven compound events** affecting AS protective forests as Eco-DRR.

On the quantitative side, the deliverable shows how harmonised datasets and upgraded models can be used to assess **pre-disturbance, disturbance, and post-disturbance conditions**, with particular emphasis on wildfire and windthrow dynamics and their cascading effects. The collective post-fire regeneration case study illustrates the value of transnational, standardised field data for identifying recovery trajectories, critical windows of reduced protection, and key environmental drivers shaping forest resilience. These results provide empirical benchmarks for calibrating hazard and forest dynamics models and for supporting adaptive forest management under current and future climate scenarios.

Complementing these analyses, the qualitative component of the deliverable highlights the importance of **actor involvement** in translating scientific evidence into actionable knowledge. Engagement activities spanning local Forest Living Labs, national-scale preference assessments, and transnational capacity-building initiatives demonstrate how diverse target groups can be meaningfully involved in co-producing, interpreting, and applying project outputs. Together, these activities enhance the legitimacy, relevance, and usability of NAZCA tools for decision-makers, practitioners, and society at large.

A key added value of WP2 lies in its ability to connect **models, data, and people**. The integration of stakeholder perspectives with quantitative risk assessments supports more realistic and socially accepted climate adaptation and disaster risk reduction strategies, particularly in contexts where protective forests serve as critical ecosystem-based solutions. Importantly, the Summer School and training activities ensure that NAZCA concepts and tools are transferred to future professionals, contributing to a **long-term knowledge legacy beyond the project lifetime**.

Looking ahead, the approaches documented in this deliverable provide a robust foundation for further application and upscaling of NAZCA outputs. Continued integration of compound-event modelling, post-disturbance monitoring, and participatory processes will be essential to support Alpine-wide climate action plans and to enhance the resilience of protective forests in a changing climate. Deliverable D.2.2.1 thus contributes not only to the objectives of MOSAIC, but also to broader European efforts to promote evidence-based, inclusive, and adaptive responses to climate-related risks.

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