Report on FOREST LIVING LABS network equipped with virtual tool and solutions for knowledge transfer

MOSAIC – Managing protective forest facing climate change compound events

WP3 – FORCE: Forest labs for raising awareness on resilience of protective forest coping with climate change

Activity 3.1: Establishment of network of forest living labs equipped with virtual tool and solutions for knowledge transfer

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Deliverable 3.1: Report on forest living labs network equipped with virtual tool and solutions for knowledge transfer

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MOSAIC, Interreg, Alpine Space

The main goal of the project MOSAIC is to support the Alpine Space program objective: Promoting climate change adaptation and disaster risk prevention, resilience, taking into account ecosystem-based approaches.

Therefore, MOSAIC focuses on hazard-resilient and sustainable protective forest management coping with climate changes' multiple dimensions, which is essential for managing climate-related risks. In order to support regional and alpine climate action plans, the project aims to collect, harmonize and share data, model alpine climate-related disasters trends, and protective forest effects. The project partners strive to raise awareness among foresters, risk managers, decision makers and the public through a network of forest living labs in the European Alps.

Activity 3.1 Establishment of forest living labs network equipped with virtual tool and solutions for knowledge transfer

Forest living labs (FLLs) are established in hotspot areas identified in WP1 in each project partner country and will serve as a research, training and awareness tool. A virtual tool (app) and a common educational concept for training of adaptive and integrated measures in forests with protective functions, which are potentially at risk due to climate change compound events, will be produced.

Deliverable 3.1: Report on forest living labs network equipped with virtual tool and solutions for knowledge transfer

This report presents the process used for establishing a FLLs network, virtual tool and educational concept for training, including feedback from various users. All FLLs created in this project are presented together with brief descriptions of case studies, research areas, best practice examples and stakeholder involvement process.

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1. INTRODUCTION:

A report on forest living labs (FLLs) network equipped with virtual tool and solutions for knowledge transfer is a deliverable within the MOSAIC project. Forest living labs are set up in each project partner country in hotspot areas identified in WP1, and serve as a research, training and awareness-raising tool. We present the theory and knowledge related to the process of FLLs establishment, together with stakeholder involvement and a description of educational concepts for training with Marteloscope plots, using a virtual tablet-based tool for tree selection and thinning management decision making. All FLLs created in this project are described together with case studies, research, test areas, best practice examples and stakeholders' involvement.

2. GLOSSARY

Living labs: Living labs are defined as user-led open innovation ecosystems, which engage stakeholders in the form of a public-private-people partnership (PPPP) to co-create products, services, social innovations. They are set in real-life environments (e.g., forest, campus, city, region).

Forest living lab: Forest living lab is an open-innovation ecosystem set in a forest area. It is used for research and development, innovation processes and knowledge transfer in field of forestry. It involves different stakeholders and active users to help co-create products, services and innovations related to forestry practices.

Marteloscope: Silvicultural training site typically one hectare in size in which all trees are numbered, their position mapped and mensuration data (e.g., height, diameter at breast height, tree condition) are recorded. In combination with evaluation and simulation software, virtual tree selection and thinning exercises can be performed.

Integration forum: Formal or informal exchange formats where actors meet in order to exchange science-based information. They enable direct or indirect interaction between science and practice and can be of a material or conceptual nature (e.g., expert panels, workshops, practice-oriented journal articles).

Protective forest: Forests that mitigate or prevent the impact of a natural hazard, including rockfall, snow avalanches, erosion, landslides, debris flows or flooding against people, infrastructure, settlements, forests and soil. Two types of protective forest have to be distinguished:

1. The term ***site protective forest*** is used for forest areas in which the preservation of the forest itself is the main objective.
2. The term ***object protective forest*** is used for forest areas that protect identified objects in developed areas against natural hazards.

3. LIVING LAB METHOD

Climate change is imposing increasing stress on ecosystems, leading to significant changes. Managing these complex changes can be a challenge, especially when many diverse interest groups are involved. In order to find solutions to these complex problems, one helpful approach is using a Living Lab. Therefore, the Living Lab Method is now utilized in many projects that are funded by the European Union. Living Labs are defined as followed:

"Living Labs (LLs) are open innovation ecosystems in real-life environments (e.g. cities, forest, campus) using iterative feedback processes throughout a lifecycle approach of an innovation to create sustainable impact. They focus on co-creation, rapid prototyping & testing and scaling-up innovations & businesses, providing (different types of) joint-value to the involved stakeholders" (ENOLL, 2023).

Thereby, the commonality among most Living Labs lies in their engagement with real-life problems and their endeavors to devise solutions (LUPP et.al., 2021).

Living Labs generally undergo **three main-phases:**

1. ***Defining a problem in depth with all stakeholders***, which involves a risk-evaluation and situation analysis.

2. The second phase involves ***collecting existing data*** from previous research and experiences of stakeholders, as well as analyzing what aspects of the problem can be solved with that data, but also where a lack of knowledge exists and which new innovative solutions can be implemented. This can be achieved through experiments, case studies and workshops.

3. After a solution is found, there should be an ***implementation and evaluation*** of this solution. This feedback can help identify unresolved issues or areas where the solution can be improved. (LUPP et.al., 2021).

Stakeholders of all four groups of the Quadruple Helix should be present in the Living Lab co-creation, including industry, academia, state and public (CARAYANNIS, 2009). All sectors have different views, experiences, competences and knowledge that can be included in the Living Lab process (LUPP et.al., 2021). Furthermore, every person or each group has slightly different risk perceptions (SANTORO S. et.al., 2019). Having this represented in the Living Lab is quite helpful, in order to individualize innovative solutions for the specific situation. Bringing the public via non-governmental organizations (NGOs), public initiatives as well as users and owners into the Living Lab, supports the public-private relationship as it provides validation of their struggles and can support the implementation of the solution needed (PONSARD, 2020).

Establishing many forms of communication between stakeholders is a key factor in a Living Lab, which can happen through engagement events, meet & greets, trainings, online platforms and workshops. This helps foster co-creative and open innovation processes within the Living Lab (ENOLL, 2023), as well as enhancing knowledge transfer for everybody involved (STÅHLBRÖST/HOLST, 2013).

Key elements of living labs *(ENOLL, 2023):*

- ***Multi-stakeholder participation***

  Taking a holistic view on society and involving stakeholders from the quadruple helix model (government, academia, private sector and citizens).

- ***Co-creation***

  In a living lab, values are bottom-up co-created not only for but also by all relevant stakeholders, ensuring a higher adoption in the end.

- ***Active user involvement***

  A living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation.

- ***Real life setting***

  A living lab operates in the real-life setting of the end users, infusing innovations into their life instead of moving the users to test sites to explore the innovations.

- ***Multi-method approach***

  Each living lab activity is problem driven. Therefore, the methodological approach towards every individual activity will be selected based on the expected outcomes of the activity and the stakeholders who need to be involved.

- ***Orchestration***

  The living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders.

The European LL concept is an approach, a movement, and a tool that is ever growing and evolving. Since this concept was defined in the early 2000s and following the launch of the ENOLL network, it has grown membership and spread over a broad geographical range. We can conclude, that LLs are described as innovation environments where citizens, public authorities, private enterprises and research institutions collaborate in the creation of new products, services and systems (Schuurman et al. 2025).

As a proposition, SWOT analysis (strengths, weaknesses, opportunities and threats) can be used at both the beginning and end of the FLL process to assess and reflect on challenges and capacities. Initially, it can help to define key problems and identify areas for enhancement or development. Following research activities and practical training - such as exercises using the Marteloscope, the SWOT analysis can be repeated to evaluate changes, improvements or newly emerged issues. This comparative approach allows stakeholders to measure the impact of applied methods and to refine their strategies. The final SWOT results can then serve as a foundation for proposing concrete, transferable solutions that address the identified challenges, with potential to be scaled to other regions or integrated into national-level planning.

3.1. FOREST LIVING LABS

In order to address the challenges of climate change and their impact on forestry, the MOSAIC project has been focusing on finding innovative solutions to promote climate change adaptation, disaster risk prevention and increasing forest resilience, while taking into account ecosystem-based approaches. To address this issue, living labs (LLs) have been recognized as a suitable methodological approach. According to the ENOLL (2023), LLs are not a simple or linear concept; their broad and flexible definition allows for adaptations across diverse environments and thematic areas. For the purposes of this project, we adopt ENOLL (2023) definition, while incorporating the specific characteristics of the MOSAIC forest living labs (FLLs) where needed.

At the moment, there is no universally established definition of a FLL[1], despite the fact that the broader LL concept has been successfully applied in various forest environments. Several initiatives (e.g., Ponsard and Nihoul 2020; REFOREST 2022-2025; ANDORRA 2023; FoResLab 2025) demonstrated the applicability of LLs in addressing several topics like sustainable forest management, agroforestry, urban forestry, forest soils, and tropical forest ecosystems.

Forest Living Labs can be understood as LLs where the co-creation, testing and scaling-up of adaptive forest management strategies aim to address various challenges occurring within forest ecosystems (IUFRO, 2025). In this context, the MOSAIC FLLs represent a specific application of the FLL concept in protective forests aiming to implement integrated and adaptive management approaches in the Alpine space, with a particular focus on climate change mitigation.

LLs aim to facilitate the transfer of scientific research into marketable innovations (Alhajj Ali et al. 2025, ENOLL, 2023). Within the MOSAIC project, this objective has been developed within the Work Packages (WP) 1 and 2. WP1 has focused on data mining and developing projections of climate change (CC) effects on the Alpine Space (AS), while WP2 has worked on a natural hazards modeling platform for the analysis of CC compound events and AS protection forests.

WP3 has played a key role in stakeholder identification and engagement, employing the methodology described in chapter 4 as well as in the facilitation of their active involvement, an essential foundation for the establishment of the FLLs.

Throughout the entire MOSAIC project, particular emphasis was on the research, training and awareness-raising dimension of the LL framework. To this end, the marteloscope (see chapter 5) was adopted as a central tool for shaping the FLL. Rather than serving solely as a training plot, the concept of marteloscope within MOSAIC has been enhanced with elements of innovation, co-creation and stakeholder engagement, transforming it into a fully functioning FLL utilizing already existing functionalities.

It is important to highlight that the transferability of Living Lab innovations to other areas is enhanced when the LL is placed in an environment that represents broader regional characteristics (Alhajj Ali et al., 2025). To address this concern, we have established our FLLs across a broad geographical area of the Alps, extending from Slovenia in the east to France in the west. The network includes sites in Italy, Austria, France, Slovenia and Switzerland, and

[1] Task Force T52 at IUFRO is currently working on creating a uniform definition (see https://www.iufro.org/task-forces/forest-living-labs-for-sustainable-climate-adaptation-forlivs)

was designed to capture a wide range of forest types, tree species, natural hazards and varying geological, climatic and topographical conditions.

Figure 1 presents the key elements of an effective FLL that were selected by Mosaic partners during the project meeting workshop.

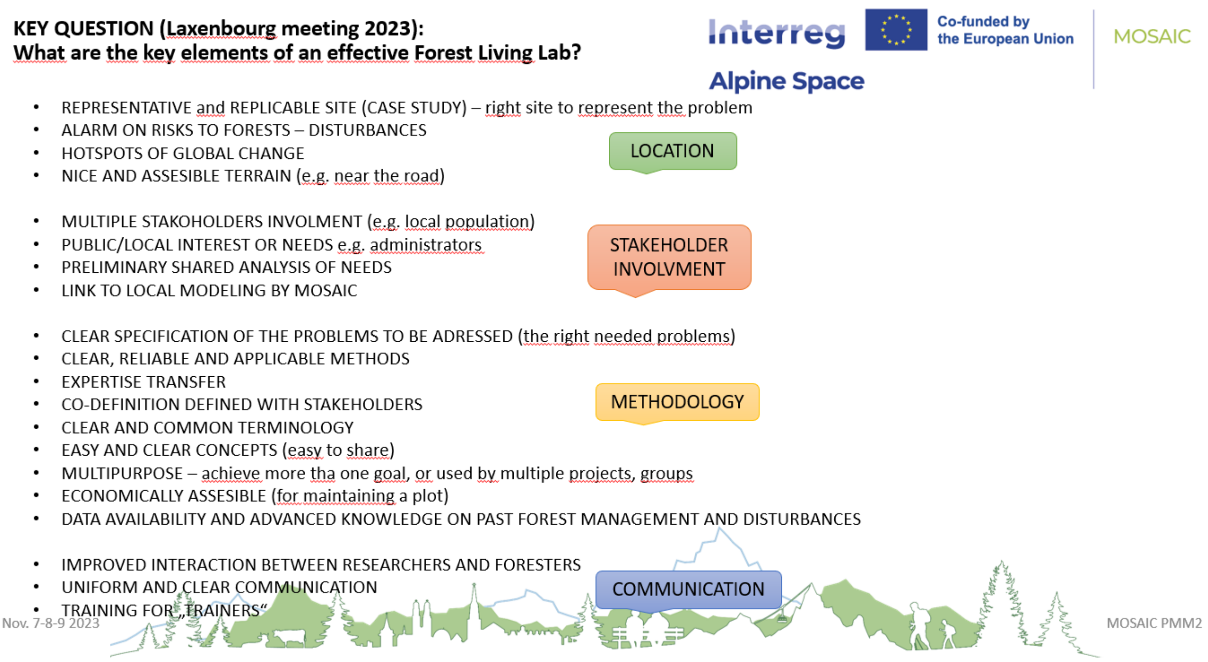


Figure 1: The results of a workshop within Mosaic project partners on what are key elements of an effective forest living lab

4. METHODOLOGY FOR STAKEHOLDER IDENTIFICATION and INVOLVMENT

The MOSAIC project recognizes different categories of stakeholders distributed across a wider area of the Alpine space. There are many possibilities on how to identify and engage stakeholders, each of which may vary depending on the project's objectives, the timing of stakeholder involvement, and their motivation to participate. In MOSAIC, active stakeholder input has been considered as a central element in establishing the FLLs.

Several methods for identifying relevant stakeholders and tools to foster their motivation and engagement during the project can be used. Some of these approaches and tools are outlined below.

4.1. VENN DIAGRAM

The Venn diagram is a valuable method used to identify stakeholders based on their relevance and relationship to a central component of interest – in this case, the FLL. The process of creating a Venn diagram for the stakeholder's identification involves four steps:

1. compiling a comprehensive list of stakeholders;

2. identifying stakeholders with the greatest relevance to the project;
3. prioritizing the most significant stakeholders by representing them with larger circles;
4. assigning each circle to a specific stakeholder.

Stakeholders can be categorized into groups, each represented by a circle of a distinct colour. The size of each circle indicates the stakeholder's relative importance, influence and potential contribution to the central component. The distance of the circles from the centre reflects the strength of the relationship between the stakeholders and the component of interest. Determining circle placement should be a participatory process, involving a discussion among stakeholders and should ensure that the diagram reflects real-world dynamics. An example from stakeholder identification workshop in Slovenia is presented in figure 2.

In the MOSAIC project, the Venn diagram was used to visually illustrate the relationships—existing and missing—between stakeholders. Through the analysis of the Venn diagram, we obtained a deeper understanding of the stakeholder relevance, influence and proximity to the project's goal, supporting a more strategic engagement in the design and implementation of the FLL.

Figure 2: Venn diagram for stakeholder recognition and their relationship definition (example from FLL Soteska, Slovenia)

4.2. PERSONIFICATION OF STAKEHOLDERS

The personification of stakeholders is a tool to help better identify and understand the motivation and needs of stakeholders. It synthesises broad knowledge about a particular target group. The project team, who deals with the ad hoc problems initialy identifies different stakeholders who are or might be beneficial in the course of the project. It is possible to include already associated stakeholders or non-existent stakeholders. Data is then used to create a personification of existing stakeholders, while an idealized stakeholder is created for those who are yet to be identified. To identify new stakeholders, we use information that is crucial to the project's needs, while ensuring that the same criteria is applied to each stakeholders' profile. (Barov et al. 2021; Ortbal et al. 2016).

4.3. INTEGRATION FORUMS

Described methods are optional, other methods for stakeholders' identification can be used as well. For stakeholder involvement and knowledge transfer we decided to use a method called Integration Forums, where we were searching for already established integration forums and organising new ones when necessary.

Integration forums serve the targeted transfer of scientific knowledge into practice (Kirchner and Krott, 2020). They are formal or informal formats where actors meet in order to exchange science-based information. These formats can be of a material or conceptual nature (e.g. expert panels, workshops, practice-oriented journal articles).

Unlike other knowledge transfer models, the "research – integration – utilization" (RIU) model developed by Böcher and Krott (2016) explicitly takes into account the different functional logics in the fields of science (empirical evidence and logic) and practice (power and interests) for successful knowledge transfer. The RIU model aims to bridge these "different worlds" of science and practice through an additional "integration phase.

Integration forums represent key formats for actor compositions within this integration phase. Through bi-directional exchange between the involved actors, they contribute to

- informing scientific actors about the practical needs for scientific solutions, and
- providing practitioners with scientific information tailored to their needs and interests.

Thus, integration forums function as starting points for generating practical relevance for practitioners. To ensure this relevance, the concept aims to bring together actors who share similar practical challenges and interests. This enables scientific information to be tailored to these interests and actively utilized by the participants.

Integration forums may consist of diverse actor constellations. For successful knowledge transfer, the composition of actors should be considered when selecting an appropriate integration forum.

From the perspective of a research project, integration forums can be classified into the types "existing," "hybrid," and "new" forums (Kirchner and Krott, 2022; see Table 1). Moreover, different actor roles within an integration forum—such as "key actor," "target actor," and "participating actor"—can be distinguished. Identifying and classifying both the type of integration forum and the actor roles can help optimize the organization of targeted scientific knowledge transfer. *Further information on the concept of integration forums will be provided in Deliverable 3.2.1.*

Table 1: Types and examples of integration forums and actor roles.

Type of integration forum		*Examples of integration forums*	*Actor roles*		
			Key actors (gatekeeper function)	***Participating actors*** (part of the forum)	***Target actors*** (should be reached by the forum)
Existing	• forum **exists** • has a link to science • is **known by** the project	• Advisory boards	• Federal ministry	Actors selected by forum or key actor	Actors selected by forum, key actor or participating actor
Hybrid	• forum might **exists** • link to science may exist or might be yet established • is **unknown** to the project yet	• Bilateral discussion	• Professional authorities • Decision makers		Actors selected by key actor
		• Expert rounds • Ad-hoc task forces	• Responsible authorities • Internal/ex-ternal experts	Actors selected by key actor	Actors selected by key actor or participating actor
New	• forum **does not exist** but **might be established** by the project • might develop a link to research by the project	• Workshops • Round tables	• Researcher	Actors selected by researcher	Actors selected by researcher or unspecified entity

5. EDUCATIONAL CONCEPT FOR TRAINING WITHIN THE MOSAIC PROJECT

The MOSAIC project aims to enhance the competencies of forest practitioners, decision-makers, and forestry professionals by developing a targeted training curriculum. The training will focus on protective forest management using marteloscope plots and I+ Trainer in combination with the Samsara growth model. The purpose is to foster better decision-making in complex forest ecosystems, particularly in protective forests, by improving understanding of silvicultural interventions, forest dynamics, and multifunctional forest management.

The curriculum follows the structured nine-step curriculum development process, enriched with five practical training principles.

5.1. NINE-STEP CURRICULUM DEVELOPMENT PROCESS

<u>Step 1: Determine Training Needs</u>

This step involves identifying the gap between the current knowledge, skills, and attitudes of the target group and the desired competencies. In the context of the MOSAIC project, the training must address this gap by providing practical, scenario-based education focused on sustainable and risk-informed decision-making.

<u>Step 2: Specify Training Objectives</u>

Clear objectives are essential to guide both trainers and participants. For this training, the objectives can include:

- Understand the ecological, protective, and societal functions of protective forests.
- Recognize site-specific limitations and risks.
- Develop management and sylviculture strategies that maintain or enhance the protective function of the forest.
- Evaluate and justify silvicultural decisions in the context of real forest stands.

Step 3: Organise Training Content

Content should align with the defined objectives. For Mosaic training, it may include:

- Silvicultural measures for improving forest structure and resilience (e.g. thinning, other).
- Introduction to tools for decision support: I+ Trainer and marteloscope exercises (tree selection) and Samsara simulations (long-term stand development).
- The role and classification of protective forests in forest policy and planning.
- Site conditions and limitations (e.g. slope, soil stability, natural hazards).

Step 4: Select Training Methods and Techniques

The training should be interactive, field-based, and rooted in problem-solving. A trainer should provide trainees with learning activities that effectively present the training content and help them accomplish training objectives.

Training methods can include:

- Guided training on marteloscope plots to explore tree selection and structural evaluation.
- Group discussion of case studies, including historical examples of protective forest failures and successes.
- Use of simulations (e.g., Samsara) to visualize long-term consequences of different interventions.
- Participatory planning exercises where participants develop and present management strategies.

The aim is active learning, critical thinking, and peer learning.

Step 5: Identify Needed Training Resources

Identification of the resources you will need to conduct the training, like facilities, equipment, and materials, administrative and personnel support. Comprehensive preparation ensures high-quality delivery.

For successful implementation, the training should require:

- Access to equipped marteloscope plots with recorded data.
- Equipment (tablets and laptops for using I+ Trainer and Samsara model).
- Visual aids, maps, sylvicultural and management plans and datasheets to support field exercises.

- Trainers with experience in protective forest management.
- Local forest professionals who know the area.
- Facilities for indoor sessions and group work, coffee breaks and lunch.

Step 6: Assemble and Package Lesson Plans

A structured lesson plan will ensure smooth implementation. It includes a schedule, detailed session objectives, content outlines, required materials, and instructional strategies, ensuring clarity and consistency across trainers.

Each training day or module should be clearly planned. Lesson plans should include:

- Learning goals for each session.
- Key points to deliver.
- Field and classroom activities.
- Timing and materials.
- Safety protocols for fieldwork.

This allows for smooth delivery, clear structure, and flexibility for adaptation

Step 7: Develop Training Support Materials

Training materials should be practical, relevant, and easy to use. These may include printed manuals, field guides, data sheets, and digital resources for I+ Trainer and Samsara usage.

Support materials will serve both during and after training for reinforcement.

Step 8: Develop Tests for Measuring Trainee Learning

Knowledge checks, peer assessments, group presentations and practical tests (e.g., tree selection exercises, simulation tasks) will evaluate learning outcomes. Participants' feedback should also be collected to improve future sessions.

These allow trainers to adjust the content and evaluate learning outcomes.

Step 9: Try Out and Revise the Training Curriculum

Before conducting a training, a pilot session should be organized to test a curriculum with a small group of participants. This pilot will help identify:

- Clarity and relevance of content.
- Engagement of participants.
- Technical or logistical issues.
- Timing and workload balance

Feedback will inform revisions, ensuring the curriculum is robust, applicable, and well-received.

5.2. FIVE PRACTICAL TRAINING PRINCIPLES

Integration of Training Principles:

0. ***Invitation for participants***

   Clear invitations will specify the training goals, agenda, trainers, location, and required equipment.

1. ***Effective start of training***

   The training should begin by introducing goals, structure, logistics, and expected outcomes.

2. ***Put your knowledge into a wider frame***

   Trainees will connect new knowledge with broader forest policy and climate adaptation goals.

3. ***Digestible content***

   Content will be divided into small, practical segments with time for reflection and discussion.

4. ***Practice, practice, practice***

   Emphasis will be placed on active, hands-on learning—participants will apply, simulate, and reflect.

5. ***Evaluation***

   Evaluation is embedded throughout and after the training to ensure learning effectiveness and improve future delivery. For evaluation the evaluation questionnaire can be used.

5.3. MARTELOSCOPES AND I+ TRAINER VIRTUAL TOOL FOR KNOWLEDGE TRANSFER

The central tool for knowledge transfer used in MOSAIC FLLs is the marteloscope – a silvicultural training site typically covering an area of 1 ha. Within each marteloscope, all trees are individually numbered, mapped and recorded with attributes such as species, diameter at breast height (dbh) and height. Additional metrics like basal area, volume, habitat value and economic value are calculated. Habitat value is assessed based on the presence of tree microhabitats assessed from a comprehensive survey, while economic value is determined by tree quality and current local wood market prices.

The marteloscope is integrated with a virtual tree selection tool called I+ trainer (figure 3 and 4) developed by the European Forest Institute (EFI). This tool will be used for a knowledge transfer to our designated stakeholders. The I+ software tool allows users to simulate forest management decisions and immediately visualize their future ecological and economic consequences. Results from these exercises are intended to stimulate discussion and collaborative learning among the participants (INFORMAR; Krause et al. 2018), making it an effective tool for participatory forest management within the FLL framework.

Additionally, a growth simulation model - Samsara for predicting the future development of stands following silviculture treatments (in our case one ha marteloscopes) will be used for 50+ year prediction.

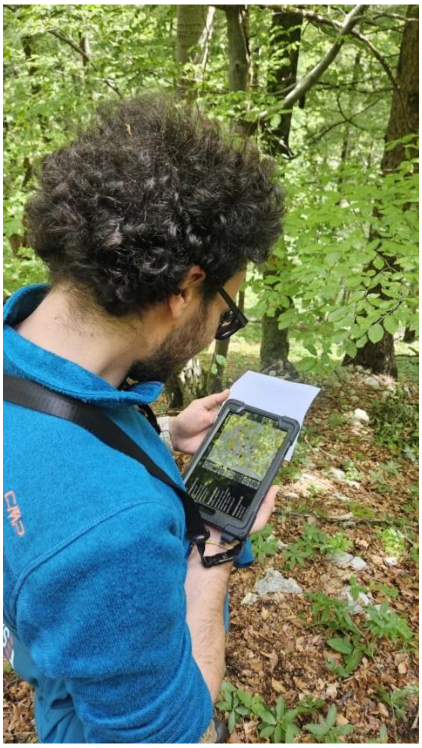


Figure 3: Use of the I+ Trainer on Marteloscope

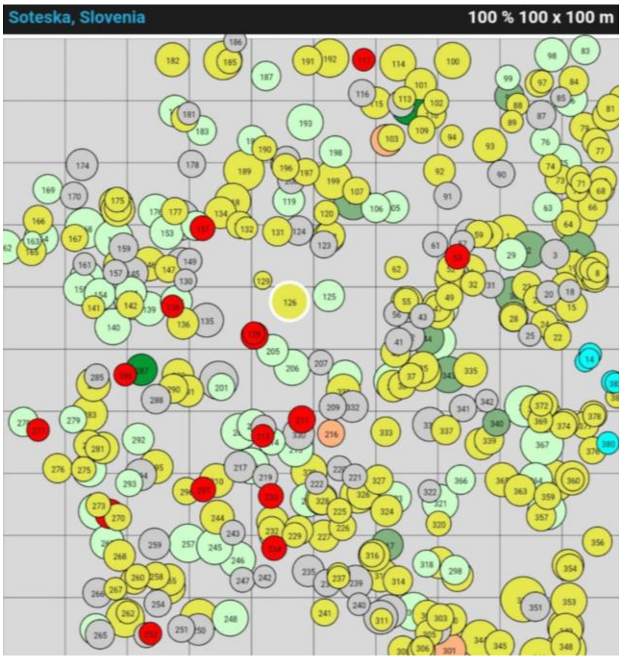


Figure 4: Map of trees on I+ trainer app

5.3.1. Development of the Protective Module in the MOSAIC Project

As part of a deliverable for the MOSAIC project, the I+Trainer is being further developed and upgraded with a protective module to be used in protective forests, where providing protection against natural hazards (e.g. rockfall, landslides, snow avalanches) is more important than wood extraction.

The new module will allow users to assess how different silvicultural measures affect the protective function of the forest, whether they increase or decrease it. This will form part of an educational tool for transferring knowledge on protective forest management to forestry practitioners and other stakeholders.

The development of the protective module is being carried out jointly by MOSAIC project partners and EFI. The following steps outline the process so far:

1. **Definition of protective indicators:** Fifteen protective indicators important for evaluating the forest's protective function were defined by MOSAIC partners (Figure 7).
2. **Expert evaluation:** The indicators were assessed by 27 SFS forestry experts and 8 MOSAIC project partners according to their importance for stand stability and slope-process prevention.

3. **Data analysis:** The evaluation results were analyzed and ranked (Figures 5 and 6).
4. **Partner discussion:** A follow-up evaluation with MOSAIC partners was held to discuss the importance of indicators and decide which should be included in the protective module, based on the analysis results (figure 7).
5. **Coordination with EFI:** Meetings with EFI will follow to explore the technical possibilities of integrating the selected indicators into the module.
6. **Integration:** The most relevant selected indicators will be incorporated into the I+Trainer.
7. **Testing:** The protective module will be tested in Marteloscope plots.
8. **Revision:** The module will be updated and refined if necessary.

Evaluation Results of Protective Indicators

PROTECTIVE FOREST INDICATORS FOR STAND STABILITY

RATE	INDICATORS
1	h/d ratio
2	Root system
3	Crown asymmetry
4	Tree compositon
5	Stand structure
6	Regeneration
7	Stem inclination
8	Gaps
9	Tree distribution
10	Stand density
11	Stand basal area
12	Crown closure
13	Distance between trees
14	Lying deadwood biomass
15	Stem injuries

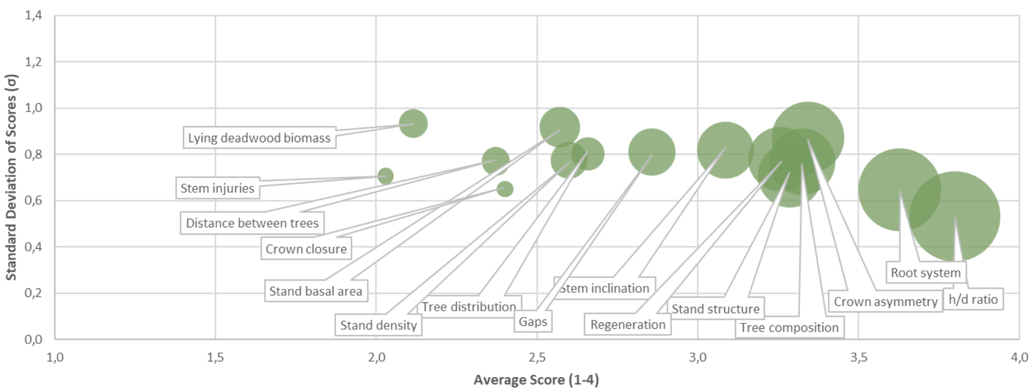


Figure 5: The results of evaluation of protective forest indicators for stand stability

PROTECTIVE FOREST INDICATORS FOR SLOPE PROCESSESS PREVENTION

RATE	INDICATORS
1	Root system
2	Gaps
3	Stand density
4	Tree distribution
5	Distance between trees
6	Stand structure
7	Regeneration
8	Tree composition
9	Lying dead wood biomass
10	Stand basal area
11	h/d ration
12	Stem inclination
13	Crown closure
14	Crown asymmetry
15	Stem injuries

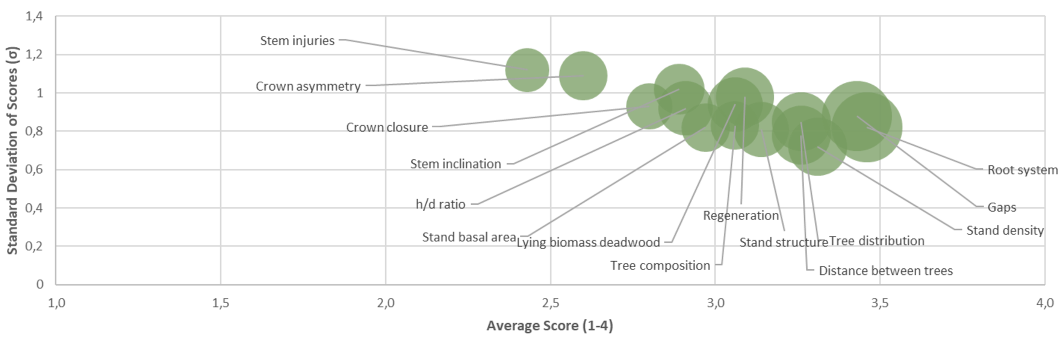


Figure 6: The results of evaluation of protective forest indicators for slope processess prevention

The graphs in Figures 5 and 6 show the evaluation results (scores) provided by 27 SFS forestry experts and 8 MOSAIC project partners for each of the defined protective indicators. The evaluators received a list of indicators (Figure 7) and rated each one on a scale from 1 to 4, based on its importance for forest stand stability and slope process prevention.

Results and Interpretation

Based on the scores given by all 35 evaluators, the following parameters were calculated:

- **Average score** (x-axis): Indicates how important each protective indicator is on average.
- **Standard deviation** (y-axis): Shows how consistent the evaluators' opinions were. A lower value (closer to 0) means stronger agreement, while a higher value (closer to 1) indicates more variation in responses.
- **Frequency distribution**: Represents the number of evaluators who assigned a specific score to an indicator (e.g. for Crown asymmetry, 17 evaluators gave a score of "4", 6 gave a "3", etc.).
- **Frequency distribution in %:** Shows the percentage of evaluators assigning a particular score to an indicator (e.g. 81 % of evaluators gave a score of "4" for the indicator H/D ratio).

Visualization and Insights

The results are displayed in a bubble chart that combines all parameters described above.

The horizontal axis shows the average score, and the vertical axis shows the standard deviation (ranging from 0 to 1 or higher).

The size of each bubble corresponds to the frequency distribution — the number of evaluators who gave the highest score ("4").

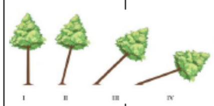
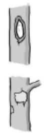
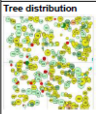
The most important protective indicators are those that:

a) have the largest bubbles (most evaluators assigned the highest score),

b) are positioned furthest to the right on the chart (indicating the highest average score), and

c) are lowest on the chart (indicating the lowest standard deviation and highest agreement among evaluators).

Finally, based on the bubble chart analysis, the protective indicators were ranked from most to least important and presented in a summary table (Figures 5 and 6).

Indicators	Input	Indicator description	Output - how do we want to show it in the I+ Trainer	indicator SCORE for stand stability	indicator SCORE for prevention of slope processes	Include them in the I+ trainer?	
h/d ratio (slenderness) 	height, diameter	The height-to-diameter ratio (H/D ratio) is a key indicator in forestry used to assess the stability of trees. H/D = tree height (m) / diameter at breast height (m). Trees with a high H/D ratio are generally less stable and more prone to breaking or uprooting, especially in exposed areas. On the other hand, trees with a lower H/D ratio - i.e. the same height but a larger diameter at breast height - tend to be more stable, resilient and resistant to natural disturbances.	*average slenderness of the trees in the stand *spatial distribution of tree slenderness (map with circles) *distribution of slenderness by DBH classes choose the treshold dbh from where we will calculate h/d ration (not for small trees)			YES	
Crown asymmetry 	Crown asymmetry Symmetrical / asymmetrical crown Suggestion - 3 classes: 0 = none (symmetrical crown) 1 = slightly asymmetrical crown 2 = highly asymmetrical crown	Crown symmetry is important for the stability of trees, especially in forests on steep slopes. Evenly distributed mass reduces the risk of overturning or breakage during wind, snow or storms. Asymmetrical crowns cause uneven mechanical stress, which increases instability, especially on inclined terrain.	* percentage of trees with an asymmetrical crown			YES	
Stem inclination 	Stem inclination Suggestion - 3 classes: 0 = none – straight stem 1 = slightly inclined 2 = highly inclined	Stem inclination strongly affects tree stability. Trees with significantly inclined stems have their center of gravity shifted outside the vertical axis, which causes an unfavorable distribution of forces in the root system. Key impacts of stem inclination on stand stability: * Increased risk of tree uprooting * Asymmetrical mass distribution: During wind, snow or ice storms, the mass is greater and one-sided, making inclined trees more susceptible to mechanical damage. In a stable protective stand, it is therefore desirable for trees to have upright stems with minimal inclination, as this improves their static properties and increases resistance to natural disturbances.	* percentage of trees with an inclined stem			YES	
Root system 	Based on tree species Suggestion - 3 classes: * deep root system * medium-deep root system * shallow root system	The root system plays a key role in the stability of trees and stands. * A strong, well developed root system reduces the risk of uprooting during wind, snow, or on an unstable terrain. * A deep root system (e.g., in oak, pine) passes through deeper soil layers and provides better stability on dry, rocky, or steep soils. * A shallow, branched system (e.g., in spruce) ensures good soil coverage, but is more susceptible to uprooting, especially on moist or unstable soils. * Roots intertwine the soil, increasing its cohesion and thus preventing erosion and landslides. Note: We still need to consider the site and what is a natural composition of tree species. That doesn't mean that it is good to remove all spruce trees on their natural site, because their root system is shallow.	* percentage of trees with a deep root system			YES	
Tree composition (species diversity) 	tree species	Key impacts of species mixture: * Broadleaves intercept more energy from falling (even larger) rocks than conifers, due to their higher wood density – highlighting the importance of mixed forest stands. *Different tree species have root systems with varying depths and branching patterns. The combination of these systems improves the stability of the stand and soil, reducing the risk of erosion and landslides. * Different species respond differently to wind, ice storms, drought, diseases and pests. Mixed stands are less prone to windthrow or ice damage and enable faster forest regeneration if part of the stand is lost. * Increased ecosystem resilience.	*naturalness of tree composition qualitative assessment Shannon index			no (it will be in educational concept)	
Stem injuries (silent witnesses) 	injuries Suggestion - 3 categories: 1. fresh injury (healing process has not started yet) 2. medium-aged injury (already in the process of healing) 3. old injury (fully healed)	Injuries (e.g., bark loss, stem damage) indicate where and how often rockfall occurs. By observing the injuries, we can assess: 1) effectiveness of the stand in stopping the falling rocks; 2) vulnerability of individual trees or forest areas, and 3) potential direction of rock movement. Information about stem injuries can help in planning thinning and harvesting operations, in order to maintain the forest's protection function (should such trees be removed or not?), selecting species that are more resistant to damage (e.g., broadleaves with denser wood), locating regeneration areas, or constructing additional protection structures.	* spatial distribution of silent witnesses (map with circles) * distribution of dbh classes combination injurie and tree species? Just to show the state now and not for the prediction how to update it?			YES	Michaela: I don't think the injury itself is relevant for natural hazard protection, but rather for analyzing whether a hazard has occurred in the past and how frequently.
Tree distribution 	Tree location	Evenly distributed trees in a stand can reduce the speed or stop the movement of rocks, snow or landslides. A forest with densely spaced trees has a more intertwined root system, which increases soil cohesion and thus reduces the risk of erosion and landslides. The horizontal and vertical structure of the stand affects material retention — uneven-aged stands (with trees of different heights and ages) and randomly distributed tree groups retain debris and snow better, as they create more contact points.	* spatial distribution of trees (map with circles) already available in I+ Trainer			INDEX?	Michaela: I think that rather than the spatial distribution of trees, the resulting occurrence of forest gaps of a certain width or length is more important for assessing the protective effect.
Stand density	Number of trees / ha	Appropriate stand density means, that the forest has enough stems and crowns to intercept and slow down slope processes. Higher tree density results in a denser and more intertwined root system that holds the upper soil layers, reducing the risk of erosion or landslides, improving water infiltration and preventing surface runoff. Excessive stand density can reduce the stability of individual trees — due to competition for light and nutrients, it may come to development of taller and thinner trees, with less stable stems and reduced root systems, which means increased susceptibility to windthrow or ice damage.	* number of trees/ha already available in I+ Trainer			INDEX?	Fred: this indicator has to be crossed with the dbh distribution or the basal area. If it's use alone then it could generate a wrong perception in term of risk mitigation. Michaela: I agree with Fred's remarks regarding this indicator.
Distance between trees	Tree location	Optimal distance between trees can provide effective and stable protection against slope processes by creating a continuous vertical and horizontal structure, allowing crown and root development, improving the efficiency of intercepting falling material, and ensuring good soil protection against erosion. On steep slopes, the distance between trees must be shorter, because the speed and energy of falling material are greater.	* average distance between trees index for spatial distribution - calculate distance from each tree to closest neighbor, it tells you if trees are distribution randomly or not this index in combination with density			no	Fred: this indicator is a key one for evaluating the protective effectiveness of a stand. But for rockfall this distancece has to be calculated takinginto account the rock average "diameter" or for each of its 3 dimensions. Michela: I think that rather than the distance between individual trees, the occurrence of forest gaps of a certain width or length is more important for assessing the protective effect.
Stand basal area 	Basal area (tree diameter)	An appropriate (neither too high nor too low) basal area ensures a sufficient density of stems and roots for mechanical protection and soil stability. The optimal basal area in protective forests on steep slopes, which guards against falling rocks, should be higher (depending on slope gradient, rock size and stand characteristics). For example, for alpine and subalpine beech forests in the Soteska area (Bohinjska Bistrica, Slovenia), the optimal basal area ranges between 50 and 68 m²/ha. Based on: https://www.ecorisq.org/rockfor-net-en	* basal area/ ha * spatial distribution of basal area (map with circles) already available in I+ Trainer			YES	Fred: this indicator has to be crossed with the stem density. If it's use alone then it could generate a wrong perception in term of risk mitigation. Michela: I agree with Fred's remarks regarding this indicator.

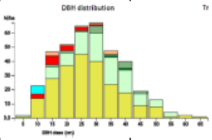
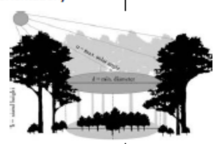
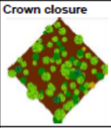
Stand structure 	Tree diameter distribution	The most desirable stands are structurally diverse: multiple layers, varying stem diameters, even distribution and presence of understory. The most ideal is an uneven-aged structure on suitable sites with apropriate species. Such a structure provides greater stand stability, without large gaps, that could pose a risk in terms of slope processes. The presence of understory and shrub species is also important, as it positively influences erosion prevention, reduces the speed of falling material (e.g., snow or rocks) and helps retain soil moisture.	* distribution of trees by diameter classes (graph) already available in I+ Trainer			YES
Gaps (size and orientation) 	gaps (polygon)	The size and orientation of gaps strongly influence the protective function of the forest. Excessively large gaps oriented downhill (in the direction of the slope) act as channels that accelerate slope processes and can pose a significant risk, whereas smaller, transversely oriented gaps present less danger, allow for regeneration, and do not significantly reduce the forest's protective effect.	* spatial distribution of gaps – map display (polygon) * orientation and size of gaps How this can change before and after the marking? Is it even possible? Discuss with EFI, how they do it in regeneration module?			YES
Regeneration 	Regeneration areas (polygons of regeneration gaps) Density, age and potential of seedlings development.	Properly planned regeneration areas enable continuous protection against slope processes and maintain stand stability. Regeneration of protective stands is important, because it contributes to structural diversity and supports the natural development of the forest. Small gaps positioned transversely to the slope are recommended, as well as gradual openings of the regeneration areas.	* Average density of regeneration and seedling age * regeneration areas on map (already available in I+ Trainer) How it works? Ask EFI.			YES
Crown closure 	crown size and shape	Crown closure directly influences several ecological and protective processes: * soil protection against erosion (crowns reduce the impact of precipitation and help regulate microclimate and soil moisture) * snow retention and reduction of avalanche risk * wind speed reduction and protection against windthrow	* spatial distribution – (map with circles) * % of crown-covered area proxy - estimation of tree crown related to dbh (Samsara) based on grid (also for regeneration and gaps) based on tree species - conifers and broadleaves			YES
Lying deadwood biomass 	Deadwood (location, orientation, diameter, length, decomposition rate)	Fallen logs and branches enhance the structural diversity of the terrain and can retain, direct and slow down falling rocks, snow, and soil material, preventing their sliding downhill. In relatively dense and stable stands, deadwood often acts as a natural barrier against avalanches and erosion. Moreover, decomposing wood retains moisture, influences stand biodiversity and positively affects regeneration. However, if there is too much deadwood biomass on the ground, it can become a hazard — by adding extra mass to the soil, it may cause landslides and erosion.	* volume (m^3/ha) *spatial distribution – map display			NO (in Samsara?)

Figure 7: An example of the evaluation form for protective indicators

5.4. SAMSARA - A GROWTH SIMULATION MODEL

The Samsara2 forest simulator (figure 5) is an individual-based and spatially explicit model (Courbaud & al., 2015) where individuals are classified as either saplings (diameter at breast height, DBH < 7.5 cm) or trees (DBH >7.5 cm). Tree and sapling demographic processes (recruitment, growth, mortality) are calculated for each year and for each individual. A key feature of the Samsara2 simulator is the integration of the SamsaraLight ray tracing model (Courbaud & al., 2003), which estimates the light intercepted by each tree and the light available on the forest floor for saplings. The Samsara2 model predicts the effect of forest management on the dynamics of several ecosystem services: wood production, biodiversity indicators based on tree microhabitats (Courbaud et al., 2021), protection against rock fall and snow avalanches (Dupire & aL., 2016). It is coupled to the Carbone balance model CAT (Pichancourt et al., 2018) and the economic library Economics2 (Ligot, 2021). These different simulation tools are modules of the software CAPSIS (Dufour-Kowalski et al., 2012).

An R package has been developed to connect the Samsara simulator to the field marking tool I+Trainer and simulate easily the consequences of the marking strategy (figure 6). It imports field marking data from the I+Trainer, launches Samsara simulations over 50 years with a first thinning intervention corresponding to the field marking and following interventions mimicking a similar strategy, and then produces a simulation report with projections of the evolution of the marteloscope and associated ecosystem services.

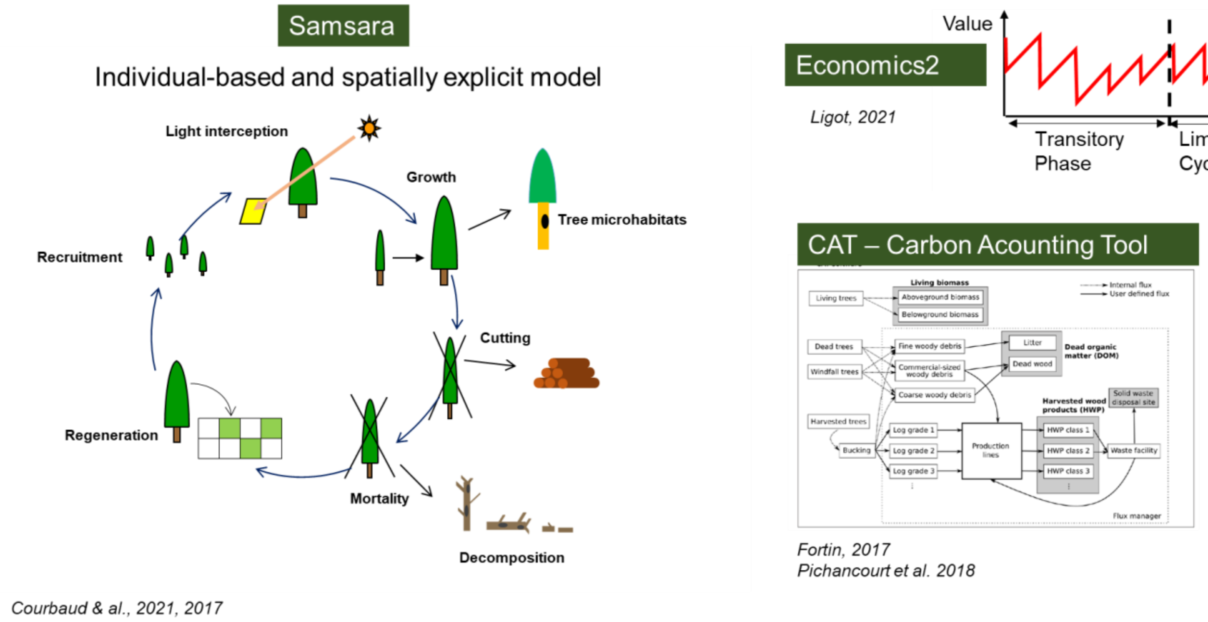


Figure 8: Principle of the Samsara model and of the associated libraries CAT and Economics2 in the software CAPSIS.

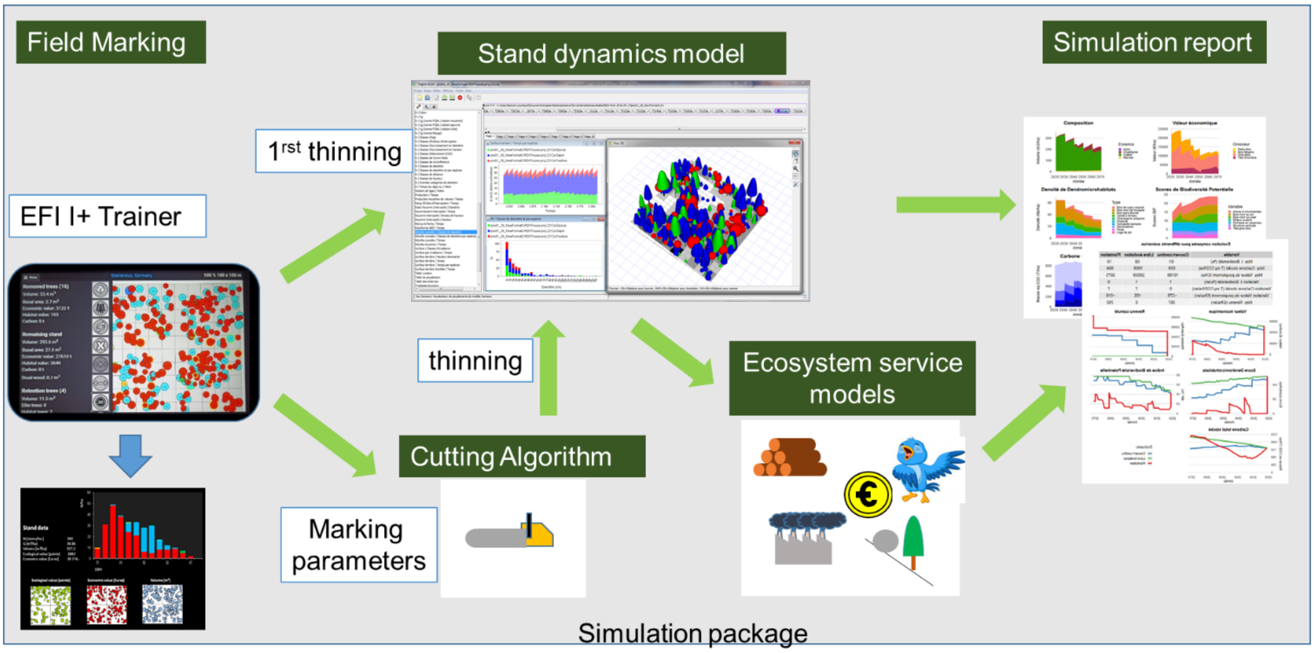


Figure 9: Principle of the R package connecting the I+Trainer field marking tool to the forest stand dynamics simulator Samsara

6. LITERATURE

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Attachment 1: Presentation of forest living lab Soteska, Slovenia

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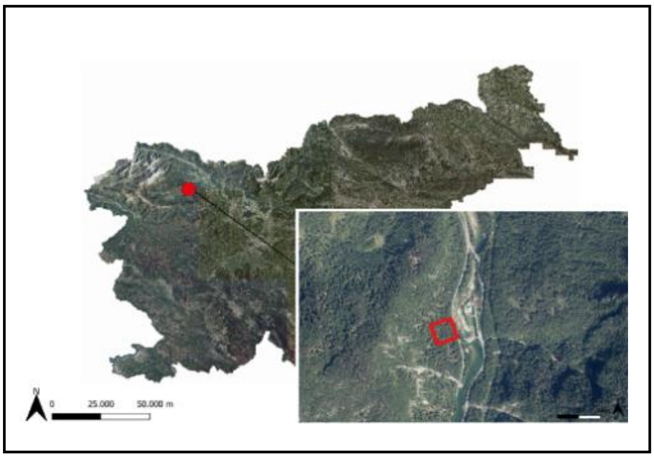

Name of FLL:	Soteska
Country, Region:	Slovenia, Bohinj municipality (Soteska valley), Gorenjska region
Coordinates:	46.315977, 14.062031
Main risks:	wind, bark beetle, rockfall
Characteristics of this area:	Significant proportion of forests with designated protective function provide protection against rockfall for the road, railway and bicycle path.
Needs and problems to be addressed:	Insufficient management of forests with a designated protective function has resulted in reduced stand stability and over-aged structure without sufficient regeneration.
Goal of FLL:	Optimize management (thinning) in protective forests to improve the protective function (prevention and mitigation of landslides, rockfalls, erosion etc.)
Case studies, research,	Podjelje, Soteska, Potoška gora
Test sites:	Karst, Jelovica
Name of the Marteloscope(s):	Soteska, Šmarna gora

Slovenia has a long-standing tradition of sustainable, close-to-nature, forest management. It functions on the principle of sustaining or creating suitable (i.e., diverse and mixed) forest stands, rejecting monocultures and clear-cutting. It aims to preserve healthy forests, with strong ecosystems, while retaining its economic value (ARSO, 2023; Ministrstvo za kulturo, 2024; Sonaravno gospodarjenje z gozdovi…,2024) With this type of management we try to mimic natural processes in non-managed forests (e.g. old-growth forest reserves).

We believe that with this type of management forests are able to develop naturally, providing healthy and resistant forest ecosystems and all forest functions including protective function. These forests are more resistant to damages, are less susceptible to pests and can recover more quickly from natural disturbances (Sonaravno gospodarjenje z gozdovi…,2024).

Figure 10: Natural regeneration after natural disturbance (photo: Slovenia Forest Service).

Slovenia is an Alpine and highly mountainous country. A large share of forests therefore grows on extreme sites with steep slopes, which limits their site potential while also determining their important role in protecting the soil from various forms of erosion. Such forests are referred to as protective forests.

Protective forests are defined as forests that protect land from landslides, erosion, and rockfall; forests on steep slopes or riverbanks; forests exposed to strong winds; forests in torrential areas that reduce rapid water runoff and thus protect land from erosion and landslides; forest belts that protect forests and land from wind, water, snowdrifts, and avalanches; forests in agricultural and peri-urban landscapes with an especially important role in biodiversity conservation; and forests at the upper tree line.

Due to their exceptional importance, protective forests are designated by a government regulation – the Decree on Protective Forests and Forests with Special Purpose. The decree was first adopted in 2005 and has since been amended every few years. It defines a specific management regime for protective forests and limitations regarding interventions in these forests.

In Slovenia, 98,828 hectares of protective forests have been designated, which represents just over 8% of the country’s total forest area (figure 2, Varovalni gozdovi, n.d.).

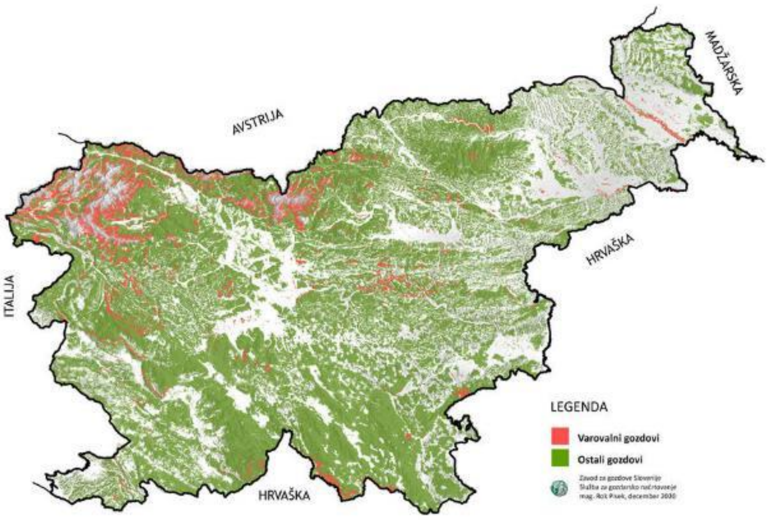

Figure 11: Protective forests of Slovenia (red colour)

In Slovenia, 17 forest functions are specified within 3 main groups: social, economic and ecological functions. Additionaly to protective forests, there are also two types of protective function specified:

- Protective function – forests provide protection of the forest stand from soil erosion,
- Protective function - forests provide protection of infrastructure (e.g., step areas above settlements, roads and railroads (Guček et al. 2012; Varovalni gozdovi, n.d.).

Protective forests in Slovenia are managed with very low intensity, primarily due to challenging terrain, safety risks, and limited economic viability. Despite this, enhancing their protective role requires an active and adaptive approach. Forest management must be tailored to harsh site conditions and specific local characteristics to maintain long-term forest stability and ensure their protective functions are not compromised.

Management efforts aim to sustain optimal forest structure and function with minimal input, through carefully planned interventions such as selective harvesting and, where needed, technical measures. However, implementation is often limited by practical obstacles — including uniform stand structure, aging trees, low regeneration, poor accessibility, outdated equipment, lack of knowledge and fragmented ownership.

Silvicultural measures are seldom applied, partly because of a preference for non-intervention in protective forests among forestry professionals, lack of knowledge and resistance from the public toward visible forestry activities in sensitive areas. Yet, allowing forests to develop without management can reduce their resilience and effectiveness in protecting against natural hazards. For this reason, protective forests should be actively managed in line with forest management plans to uphold their essential ecosystem services (Guček et al. 2012, Varovalni gozdovi, n.d.).

Introduction of the area

Due to the specificity of the MOSAIC project, protective forest locations in the Alps were considered for the placement of the FLL. Finally, the area of the Bohinj municipality and the Soteska protective forests were recognized as suitable sites.

The Bohinj municipality administrative unit is situated in the Southeast part of the Julian Alps, with 66 % of the area belonging to the Triglav National Park and 84 % in the Natura 2000. It covers an area of 333.7 km^2. The population is relatively low with the density of 16 inhabitants per km^2, resulting in a prevalent natural landscape (Municipality Bohinj). Due to the pristine nature and easy accessibility the area is under a big preassure in terms of visitors, especially during the summer.

Soteska is a valley connecting Bled and Bohinj, with a river Sava Bohinjka, reginal road, railway and cycling path running at a bottom. On the both sides there are forests on steep slopes designated as protective forests, protecting mainly from rockfall. In the area of Soteska alpine and sub-alpine beech forests on steep slopes prevail, big part of the area is Natura 2000 (Pregledovalnik ZGS).

The site was also chosen as suitable for a marteloscope due to its multifunctional value and its forest type, which is representative of the wider area. The forest serves various important roles, including protective functions, biodiversity conservation, aesthetic value, cultural heritage preservation, protection of natural features and forest stands, as well as hydrological regulation.

A common problem in the area are spruce forest stands attacked by bark beetles (see the test site and Case study Soteska). Other main potential threats in the area are windbreak, erosion, torrent waters and rockfall. The natural hazards have a great impact towards the stability of the forest stand, whose primary function is protection. Falling trees and rocks tend to reach the bottom of the stand, where a railroad and a newly constructed cycling path are located. Both are quite frequented by trains, cyclists or hikers.

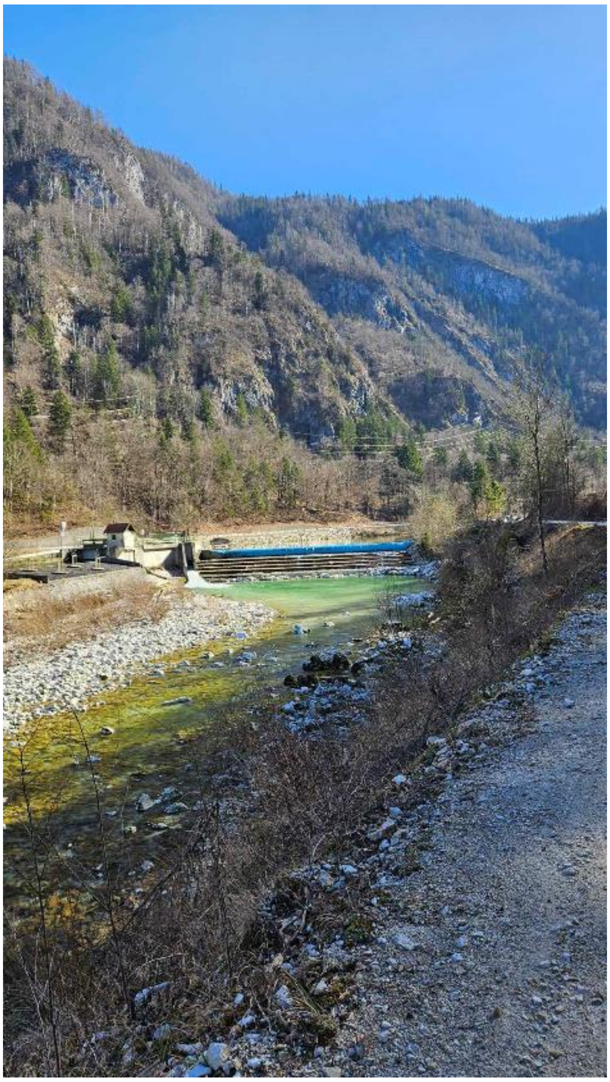

Figure 12: Protective forests in Soteska valley, photo: Kristina Sever

Figure 4: Protective forest above the railway (Marteloscope location), photo: Kristina Sever

Current management with protective forests

Protective forests management in Slovenia

Measures to reduce the negative impacts of natural hazards in protective forests can be divided into three groups: 1) silvicultural measures (interventions in the management of these forests, such as, thinning, aimed at risk reduction), 2) biotechnical measures (natural base solutions: planting tree species for slope stabilization, hydromulching, hydroseeding, "fašine", etc.), and 3) technical measures (construction of protection barriers). From both an ecological and financial perspective, forest management should aim to ensure the most effective protective function of the forest, so that technical measures are only necessary in areas where the forest's protective effect is insufficient (Usmeritve za gospodarjenje in načrtovanje ukrepov …, 2021).

The goal of managing protective forests is to ensure the sustainable and optimal functioning of the forest for protective purposes at minimal costs.

According to the "Regulation of protective forests and forests with special purposes" (Uredba o varovalnih gozdovih..., 2005), the Slovenian Forest Service (SFS) is required to ensure the following: timely regeneration or removal of overmature trees; implementation of small-scale selective logging; retention of sufficiently high stumps during tree felling in landslide-prone areas and avalanche risk zones; restoration of damaged soils to prevent erosion; removal of trees from torrent channels; methods of timber harvesting and extraction should be as specified in the forest management plan and finally, prompt execution of all silvicultural activities is necessary, to maintain and stabilize the protective functions of the forest.

In Slovenia, managing protective forests faces challenges such as the common view of protection as "non-intervention" and difficulties promoting non-profitable management since economic benefit is not the main goal. Complex site conditions and associated hazards frequently prompt forest owners to refrain from implementing silvicultural interventions, resulting in aging forest stands, that progressively weaken their protective functions. Active management, supported by new research tools, is essential for maintaining protective functions. Economics, technology and communication between forest owners and experts play crucial roles. Lack of knowledge and resources prevents execution of necessary biotechnical measures, making long-term goals often only theoretical. Climate change adds further complexity to forest management of protective forests.

Policy measures for management of protective forests in Slovenia

The main sources of funding measures in protective forests in Slovenia are:

1) **Common Agricultural Policy - CAP** (*Skupna kmetijska politika - SKP*) - provides financial support for prevention of forest damage caused by fires, natural disasters or catastrophic events, and restoring damaged forests, as part of Slovenia's forestry interventions under its CAP Strategic Plan (Forestry explained, n.d.);
2) **Forest fund** (*Gozdni sklad*) - supports conservation activities in Natura 2000 areas (also within protective) in private owned forests, including maintaining habitats, preserving deadwood and other ecological measures (Natura 2000 Slovenija, n.d.);
3) **State budget of Republic of Slovenia** (*Proračun Republike Slovenije*) - finances or co-finances the cost of silvicultural, protective and wildlife habitat maintenance work, as well as forest road maintenance (Zavod za gozdove Slovenie, n.d.);
4) **European projects and cross-border programs** – include funding from initiatives like ForestValue2 and Interreg, supporting research, innovation and cross-border cooperation in sustainable forest management.

All the measures mentioned below are 100% financed and implemented, as part of the planned works for protective forests and forests in torrential areas, both privately and municipally owned. Measures are co-financed from the funds of the Republic of Slovenia state budget and labor is charged based on time spent (Navodila za izvajanje del po Pravilniku o financiranju…, 2009):

1) **Construction of check dams** –carried out within forest areas located in erosion-prone zones;
2) **Anti-erosion protection** – suitable methods include grass seeding, cover crops, scion grafting of narrow-leaved willow, covering surfaces with straw and bitumen and

covering surfaces with biodegradable fabric materials (regeneration with added grass seed);

3) **Felling of heavy trees in protective forests** –must be written in the forest management plan. Trees must be properly marked before felling;
4) **Cutting and anchoring of trees in protective forests –** to ensure safety, in cases where the removal of fallen or felled trees in protective forests is not possible.

Living lab method

The forest living lab (FLL) was established in the Soteska valley, since it is a good example of protective forest on steeps slopes protecting road, railway and bicycle path from rockfall. The main phases of FLL establishment included:

(1) **Identification of main problems with stakeholders**: the first phase involved determining the problem through workshops and meetings, where the main challenges facing protective forests in the Soteska area were discussed with various stakeholders, including: district foresters, silviculturists and planners employed by the Slovenian Forest Service (SFS), forest owners, contracting companies, nature conservation organizations etc. This collaborative effort served as the foundation for the subsequent establishment of the FLL. As one of the main problem, lack of knowledge on protective forest management was addressed for various stakeholders.

(2) **Data collection and analysis**: the second phase focused on gathering and analyzing data and knowledge to identify potential solutions to the problem. This was achieved through multiple case studies, test and research sites, good and bad practice examples, workshops and meetings. The knowledge and information gained from these case studies and test sites confirmed the central issue: there is an increasing need for knowledge transfer on management of protective forests. These forests in Slovenia are presently managed insufficiently, mainly because of the lack of knowledge and because of that their protective function is being at risk. Furthermore, the educational plot for knowledge transfer named Martelsocope was established and used in the area of Soteska and Šmarna Gora.

(3) **Implementation of solutions**: in the final phase, we synthesized all collected information to implement appropriate solutions. Through the activities of the MOSAIC project, we aimed to:

- Facilitate knowledge transfer among stakeholders, particularly SFS district foresters, forest planners, silviculturists and forest owners; (trainings on Marteloscope plots, workshops, educational material).
- Enhance forest management in protective forests across Slovenia, integrating nature-based solutions where necessary; providing knowledge on funding measures in protective forests (workshops, meetings, educational material).
- Raise awareness about the importance of protective forests and their management (educational materials and videos, workshops, events, field visits).

Table 2: Key elements of living labs

Multi stakeholder participation	***Co-creation***	***Active user involvement***	***Real life setting***	***Multimethod approach***	***Orchestration***
involving stakeholders from the quadruple helix model (government, academia, private sector, and citizens) *PPPP: science, policy, practice, citizens* • **SFS** (district foresters, forest planners, forest managers) • **Forest owners** (Metropolitana - Church, SidG, private owners…) • **TNP** (Triglav National Park) • **GG BLED** (contracting company) • **Local residents** • **Municipality Bohinj** • **MGKP** (Ministry of Agriculture, Forestry and Food)	*co-created not only for but also by all relevant stakeholders* *How to include them in the process?* • **SFS foresters - main** stakeholder • **Integration forums** (innovation): workshops, meetings, field trips, Marteloscope trainings…	*a living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation* • **SFS** (district foresters, forest planners, forest managers) • ***Forest owners*** • ***General public***	*a living lab operates in the real-life setting of the end users, infusing innovations into their real life instead of moving the users to test sites to explore the innovations* **Real life setting – FLL Soteska:** The current development in Soteska is the construction of a cycling path, which is also protected by protective forests. These forests must be managed appropriately to ensure they can fulfill their protective function.	*Problem driven activities – finding solutions for problems* **PROBLEM:** reduction of protective function due to insufficient management of protective forests **SOLUTIONS:** improve the knowledge of SFS foresters to improve the protective function of forests through appropriate management **METHODS:** • ***Marteloscope*** *(knowledge transfer)* • ***Case studies:*** *Soteska, Podjelje* • ***Test sites:*** *Karst* • ***Research sites:*** *Jelovica, Karst*	*The living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders* *Orchestration refers to the process of coordinating, managing and facilitating the activities, interactions, and collaborations among all the different stakeholders involved in the Living Lab.* Systems for facilitation of protective forest management (co-financing) We achieved successful orchestration throughout the entire process of establishing the FLL by actively involving stakeholders at each stage. Initially, we engaged them in defining the core problem through a series of workshops. We involved stakeholders during the Marteloscope establishment, when gathering information on test sites and case studies. They will be further involved in Marteloscopes trainings and in co-creation of Mosaic's final outputs – Catalogue of illustrated fact sheets.

The goal of MOSAIC's forest living lab is to adress recognised challenges and involve different stakeholders to start working on sollutions to:

- Ensure regular and integrated management of protective forests for the importance of directing the sustainable development of the forest.
- Define forestry measures in protective forests (defining appropriate measures - curative measures (e.g. removal of dangerous trees, dead trees along watercourses) and preventive measures (implementation of forest tending for stand stability and strengthening of protective function).
- Ensure implementation of forestry measures and control (forest opening with forest roads, training of professional forestry workers for the safe and correct implementation of measures.
- Promote and update the co-financing system.
- Educate and inform forestry and other professionals as well as inform the general public.
- Update categorization of protective forests (e.g. protective forests with no management, forests where management is necessary).
- Refine the criteria for determining protective forests (e.g. collaboration with other professions, use of risk maps).
- Improve inventory methods (introduce minimum standards of forest inventory and verification of the effects of implemented measures).
- Include the comprehensive risk management into management of protective forests (management of natural hazards).

Stakeholders and knowledge transfer

On the first stakeholder meeting in February 2024, we identified main stakeholders that will be included in Soteska FLL, using the method Wenn diagram (Figure 5). In Table 2 the main stakeholders are listed and ranked according to their importance or influence (size of the circle) and connection to the topic (distance) of management protective forests in Soteska area.

Figure 5: Stakeholder identification in relation to maganement of protective forest in Soteska valley

Table 3: Stakeholders identified and ranked for the involvement in FLL Soteska

Name	Group (according to Jems)	Role	Stakeholder importance (influence)	Connection to the topic (distance)	Ranking (combination)
Zavod za gozdove Slovenije	Infrastructure and (public) service provider	Public forest service, forest management plans	high	high	high
Biotehniška fakulteta, Oddelek za gozdarstvo	Higher education and research organisations	Research and education	high	high	high
Občina Bohinj in Bled	Local public authority	"users" of protective function in this area	high	high	high
Inšpektorat za gozdarstvo	National public authority	Forestry control	high	medium	high
Inšpektorat za infrastrukturo	National public authority	Infrastructure control	high	medium	high
Nadškofija (lastnik gozda)	Enterprise, except SME	Forest management	high	high	high
SŽ - Slovenske železnice (infrastruktura d.o.o.)	Infrastructure and (public) service provider	Railway traffic provider	high	high	high
JZT - Javni zavod za turizem Bohinj	Local public authority		high	low	medium
ZRSVN - Zavod republike Slovenije za varstvo narave	Sectoral agency	Nature conservation	medium	medium	medium
MKGP - Ministrstvo za kmetijstvo gozdarstvo in prehrano	National public authority	Political decision makers	medium	medium	medium
MOP - Ministrstvo za okolje in prostor	National public authority	Political decision makers	medium	medium	medium
Lastniki gozdov (celotna skupina)	Interest groups including NGOs	Forest management	high	low	medium
DRSV - Direkcija Republike Slovenije za vode	National public authority	Political decision makers	high	medium	medium
VGP - vodnogospodarska podjetja	Infrastructure and (public) service provider		medium	medium	medium
Lovska družina	Interest groups including NGOs	game management	low	high	medium
Ribiške družine	Interest groups including NGOs		low	high	medium
TNP - Triglavski narodni park	Regional public authority	Nature conservation	medium	medium	medium
Izvajalci gozdarskih del (GG Bled)	Enterprise, except SME	Contractors of forestry works	medium	low	medium
ZRSVKD - Zavod republike Slovenije za varstvo kulturne dediščine	Sectoral agency	Cultural heritage conservation	medium	low	low
KGZS - Kmetijsko gozdarska zbornica Slovenije	National public authority		low	low	low
Sidg - Slovenski državni gozdovi (lastnik gozda)	Enterprise, except SME	Forest management	low	medium	low
DOPPS - Društvo za opazovanje in proučevanje ptic Slovenije	Interest groups including NGOs	nature and bird conservation	medium	low	low
DRSI - Direkcija Republike Slovenije za infrastrukturo	National public authority	Political decision makers	medium	low	low
ELES - Elektro podjetje	Infrastructure and (public) service provider		low	medium	low

Furthermore, different events (workshops, meetings, presentations, field trips, educational material…etc.) were organized within the project to include the stakeholders into creation of our FLL. All important events are listed in Table 3.

Table 4 : Mosaic workshops overview

YEAR 2023 - events	STAKEHOLDERS
Workshop on protective forests	*district foresters, silviculturists, SFS forest planners, large forest owners, contracting companies, nature conservation organizations etc*
Workshop: How to manage forests for improvement of protective function against the risk of torrent flows and landslides	*professionals from the field of forestry and torrent management.*
Presentation on Marteloscopes and Mosaic project	*students of Pedagogic faculty.*
YEAR 2024 - events	
Workshop on Biotechnical measures in forested torrential areas	*professionals from the field of forestry and torrent management.*
Identification of stakeholders in forest living lab Soteska	*SFS – regional unit Bled, GG Bled, UL, Rejda d.o.o.*
Excursion to Soteska	*Danish foresters of Pro Silva and forestry students.*
Opening of the Marteloscope Šmarna gora	*partners of Multipliers project (EFI, educational centers and schools from project countries).*
Workshop on forest protection – attendance and participation	*SFI, SFS foresters and other.*
Presentation of the test site and Mosaic project to the Ministry of forestry and agriculture	*state secretary.*
Forest movement Europe meeting at Pokljuka	*nature conservationists.*
Presentation of posters – Close to nature forestry at the event Green pulse	*general public.*
Pro Silva Slovenia – the visit of protective forests in mountain Požar	*Pro Silva Slovenia members.*
Lecture on Slovenian forests, forestry and protective forests and management of torrential areas	*general public and forestry professionals.*
Workshop with Mosaic stakeholders on forestry measures for protective forests	*forestry professionals.*
Workshop on silvicultural and forest protection measures to enhance the protective role of forests in areas susceptible to erosion	*field workers in Regional Units.*
YEAR 2025 - events	
Training course about torrent supervision in Austria	*SFS, SFI.*
Yuno lectures on topics: social functions of the forest, close-to-nature forestry and protective forests.	*school children and general public.*
Marteloscope training – management in protective forest	*project partners.*
Workshop on measures in protective forest for Mosaic stakeholders – training in Marteloscope Soteska	*SFS employees.*

Case studies, research, test and demonstration sites for FLL Soteska, Slovenia

MARTELOSCOPES – DEMONSTRATION SITES

Marteloscope Šmarna gora

The marteloscope site at Šmarna gora, Slovenia, was established in 2023 in a privately owned forest. It is a beech forest mixed with sessile oak, chestnut and Norway spruce, with a small percentage of Scots pine. On an area of 0.2 ha there are 77 trees with the basal area calculated 32.0 m^2/ha, the volume 392,5 m^3/ha and the habitat value having 5295 points per hectare. More information atout marteloscope Šmarna gora is available in info sheet: http://iplus.efi.int/uploads/SI_InfoSheet_Smarna_gora_en.pdf

It was primarily established as a learning tool for school children to learn about forests, economic value of trees and importance of biodiversity. It is thus located in the proximity of the urban centre of Ljubljana in an easily accessible area. Because it is meant to be use by children and school teachers is smaller than standard marteloscopes.

Marteloscopes are used together with the application I+ Trainer where map is displayed (Figure 6). Every circle represents a tree, the size indicates the size of the tree and colour represents different tree species. At Šmarna gora, the most frequent is the common beech (53.8 %) in purple, followed by the sessile oak (light green) and Scots pine (light blue), both at 15.9 %. Next is Norway spruce in dark green (13.5 %), while sweet chestnut (black), alpine labumum (red), silver fir (dark blue) and rowan (yellow) are all below 1 %.

The marteloscope has a total of 98 microhabitats. Most frequent are bryophytes, foliose lichens, lianas, ferns and mistletoes.

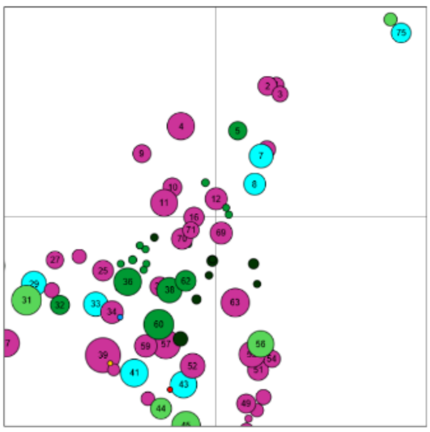

Figure 6: Map of Marteloscope Šmarna gora in the I+ Trainer app

Figure 7: Presentation of tree microhabitats in I+ Trainer

Marteloscope Soteska

The marteloscope Soteska was established in 2024. It is a privately owned forest in an area with a recognized protective function. It is a Beech-Norway spruce mixed forest, with a small percentage of black pine, larch, sycamore maple, Scots pine and European hop-hornbeam. On an area of 1.0 ha there are 383 trees with the basal area of 31.9 m^2/ha, the volume 338.5 m^3/ha and the habitat value 11828 points per hectare.

The most frequent tree species in the marteloscope plot (Figure 8) is the common beech at 56.4 % (in yellow), next is the Norway spruce (light green) at 34.4 %. Black pine (dark green), larch (orange) and sycamore maple (red) are present with 5.6 %, 1.8 % and 1.1 %, respectively. Scots pine in dark green and European hop-hornbeam in light blue are present in less than 1% each.

There are 777 measured microhabitats in the plot. Proportionally to the area, most frequent are trunk and mould cavities and exposed sapwood. The reason could be injuries from falling rocks, that are frequent in this area.

The Soteska marteloscope was established in a protective forest with the aim to provide a learning tool on the importance and management of protective forests. Due to the proximity of transit ways and high amount of recreational tourist various stakeholders are included, but the most important are forestry professionals, to learn how to effectively manage the protective forests in term to ensure their protection role.

More information atout marteloscope Soteska is available in info sheet: http://iplus.efi.int/uploads/SI_Soteska_MOSAIC_Project_en.pdf

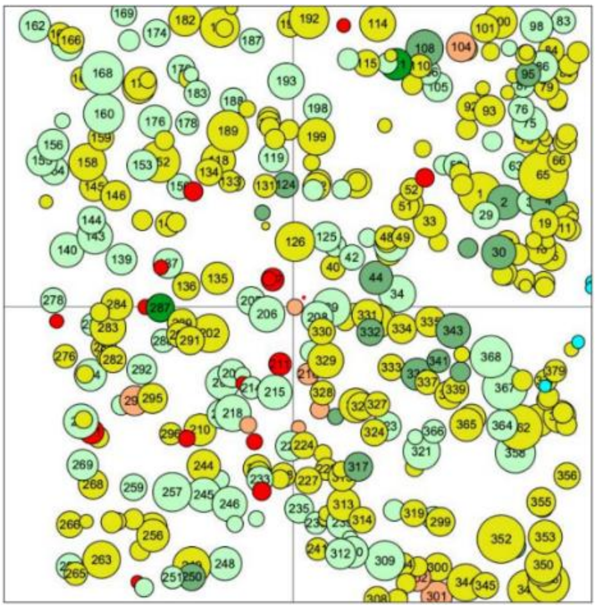

Figure 8: Map of Marteloscope Soteska in the I+ Trainer app

Figure 9: Training of trainers in Marteloscope Soteska

CASE STUDY AND TEST SITE SOTESKA

Demonstration site Soteska: Sanitary cut in a protective forest (1st location)

In a protective forest above the state-owned road Bled-Bohinj and the railroad, there were small areas of spruce stands that have been attacked by bark beetles. Sanitary felling had not been carried out in time, so the attacked trees started to decay. Since these trees were growing on a steep slope they started to, forced by strong winds, fall down on the busy road below. The natural regeneration was aggravated, because of the shallow ground and lack of sunlight. Due to the steepness of the slope, it was decided that the attacked trees were going to be cut down and be anchored horizontally on the slope. Additionaly, high stumps were left to protect from erosion and falling rocks. At the same time, the decaying biomass is going to be left in the stand, which is important for the natural regeneration. By the time those trunks completely decay, it is expected that the natural regeneration will be strong enough to take over protection against erosion. To ensure soil stabilization the planting of natural tree species was carried out.

Figure 10: High stumps left in the Soteska protective forest following sanitary felling, photo: Kristina Sever

Demonstration site Soteska: Regeneration after sanitary cut in a protective forest (2nd location)

Figure 11: Protective forest after the bark beetle attack and before sanitary cut (year 2023), photo: Stane Kunej

In 2020 the bark beetle outbreak occurred in the spruce stand above the main road connecting Bled and Bohinjska Bistrica. Although the forest had already been designated as protective, no active management had been carried out. During the bark beetle outbreak, dead and uprooted trees were falling on the road, bringing down stones and debris from the forest stand (Figure 11). At that time, there were no protective measures in place to prevent such occurrences. As a result, the road maintenance service had to make frequent visits to remove fallen trees and rocks from the road.

Due to the high risk of falling logs and rocks, a sanitary cut was performed with additional protective measures. High stumps were left standing at a height of 1.3 meters and the felled trees were anchored horizontally on the slope (70° angle on fall line).

We learned that in directional felling, it is crucial that the trees are healthy when you cut them. If they are already in a state of decay, directional felling becomes impossible, as they may fall unpredictably elsewhere, with the possibility to fall onto the road.

Currently, the forest stand is regenerating naturally very well, as visible in figure 13. The stumps are still present, although they are barely visible due to the growth of vegetation. It typically takes around 15 years for such tall stumps to decompose, by which time the stand will have fully regenerated. It is important to note that after the sanitary felling, the condition of the forest stand improved significantly and rocks stopped falling onto the road. This natural-based solution measure is much cheaper in comparison to technical measures (e.g. rockfall protection barriers).

The costs associated with such an operation were also discussed. The district forester marked each tree and the direction of felling. Based on this, the additional time required for directional felling was calculated, allowing for an estimation of the cost of the intervention. The costs also included the temporary closure of the road. During the work, only one lane was closed, which cost €1,500 per week. This cost was borne by the executor. All the costs were subsidized 100% according to the Slovenian subsidy system.

Figure 12: The risk of rockfall before the sanitary cut was high (year 2023), photo: Stane Kunej

Figure 13: Successful natural regeneration of the protective forest two years after completed sanitary cut (year 2025), photo: Magdalena Cholkova

Demonstration site Soteska: rockfall protection barriers above the cycling path

Rockfall protection barriers were constructed on critical parts of cycling path, connecting Bled and Bohinj, to prevent rockfall. In a viewed location a 20-meter strip of forest was cleared for rockfall protection barriers to be installed. The district forester marked trees to be cut and made an effort to mark as few trees as possible, in order to preserve the natural protective function of forest. Although the forest owner was present on-site with the district forester and they jointly marked trees for felling, the owner later claimed that they didn't agree with the decision. They even demanded the removal of the protection barrier that was already established. The marked trees have already been felled and removing the barrier at this point would cause a significant risk, as falling rocks could land directly on the cycling path below. This is yet another example of poor practice resulting from miscommunication.

Figure 14: Rockfall protection barriers above the cycling path in Soteska, photo: Magdalena Cholkova

CASE STUDY PODJELJE

Above the village Podjelje, in the year 2020, a sanitary felling of spruce trees attacked by bark beetle had been carried out. In autumn 2022, areas of attack had been discovered again, around those same felled areas. The slope is partly opened by forest roads and in some parts the harvest needs to be assisted by cable. Sanitary felling was urgent, as the attacked trees were growing on a very steep slope, just above the village. There is a big risk of rockfall in this area especially during the felling when rocks have potential to roll down the slope and cause damage to the houses situated below. As a solution, the municipality Bohinj and the public institution Triglav National Park decided to install a temporary barrier consisting of 3 meters-high larch tree piles firmly anchored into the ground (Figure 17). Rounded wood assortments were positioned horizontally along the slope and fixed with a metal wire throughout the whole barrier. The purpose of this barrier was to ensure safety, while carrying out the sanitary felling and representing protection against the falling rocks in the future, as well as for the vast opened area left behind by sanitary felling.

The forest management in this area is adapted to the role of protective forests. The stands need to maintain their structure and stability to provide protection role. The forest roads should be constructed where possible; the harvest should be performed in dry weather in order to mitigate the risk of erosion. Natural regeneration occurs gradually, and likewise, forest management should follow a gradual approach, while the sanitary felling of trees attacked by bark beetles (or otherwise damaged) should be carried out in time.

Figure 15: Protective Forest above the village Podjelje, photo: Slovenia Forest Service

Figure 16: High stumps left to protect from falling rocks, photo: Slovenia Forest Service

Figure 17: Temporary barrier consisting of 3 meters-high larch tree piles anchored into the ground, photo: Slovenia Forest Service

Figure 18: Placing felled trees horizontally on the slope, photo: Slovenia Forest Service

TEST SITE POTOŠKA GORA

On March 28, 2022, a rapidly spreading forest fire ignited on the southern slope of Potoška gora near Potoče, Preddvor, affecting 70.35 hectares of forest. Over 1.400 firefighters and aerial support containing 455.000 liters of water battled the fire, which destroyed several weekend houses and threatened popular hiking areas. The fire caused significant damage, particularly to spruce and beech stands, with 8.354 m³ of spruce estimated lost and a high risk of bark beetle infestation of damaged trees. Post-fire restoration included sanitary cutting of damaged trees in more than 20 hectares. Reforestation plans were made in area covering 44 hectares with multiple native tree species. The seeds from local trees were collected and are now in the process of growing. When the seedlings will be big enough, they will be planted in the damaged area.

The event highlighted the importance of forest roads for fire access and the protective role of forests against hazards like rockfall, as confirmed by rockfall modeling in Rockfyor3d showing greater risk without forest cover. Urgent wildlife management measures are also needed to ensure successful forest regeneration, as browsing by deer and other game affects seedling survival (Načrt sanacije gozdov poškodovanih v požaru…, 2022; Rozman et al., 2024; Ponikvar, 2024).

Figure 19: Post-fire landscape of Potoška Gora, year 2022, photo: Primož Šenk

TEST and RESEARCH SITE KARST

Test and research site: Planting seedlings using hydrogel and mycorrhiza

In March 2024, planting of sessile oaks *(Quercus petraea*) seedlings was performed in the Karst region after a forest fire in 2022. The planting was conducted using different treatments: hydrogel with mycorrhiza; only hydrogel; only mycorrhiza and no treatment. Hydrogel, a cellulose-based polymer, enhances soil moisture retention by absorbing and holding water, thereby promoting seedling growth and reducing the need for frequent watering.

The main goal of this experiment was to see if there is better surviving rate and faster growth of seedlings treated with hydrogel and mycorrhiza.

Seedling survival and growth were monitored in autumn 2024 and spring 2025, with further monitoring planned for autumn 2025. The best results were observed in the plots treated with both hydrogel and mycorrhiza, demonstrating that this combination significantly improves seedling establishment and growth in post-fire forest restoration (Rantaša, 2024).

Figure 20: Planting seedlings using hydrogel and mycorrhiza, photo: Gregor Skoberne

Test site: Drone seeding using seed bombs

Climate change is increasing the frequency of natural disturbances, making forest restoration essential, especially in damaged or hard-to-reach areas. In Slovenia, innovative drone technology using seed bombs is being tested and applied to restore forests efficiently, particularly in challenging terrains, like some areas of the Karst region. This method involves precise aerial seeding guided by advanced mapping and AI, enabling rapid planting of native species with higher cost efficiency and access to inaccessible sites. Organizations like Project O2 have developed specialized seed bombs combining seeds, clay and natural enhancers to improve germination and resilience. While drone seeding offers significant benefits in speed, scale and precision, challenges remain with seed survival, biodiversity sourcing, technical constraints, regulatory issues and uncertain long-term ecosystem outcomes. Ongoing monitoring and adaptive management are crucial to ensure the success and sustainability of these innovative reforestation efforts (Radenska je z droni… 2024; Obnova gozdov…,2024; Reforestation by air…,2025; Projekt O2, 2025).

Figure 21: Drone seeding with seed bombs, photo: Slovenia Forest Service

Figure 22: Drones used for seeding, photo: Slovenia Forest Service

Figure 23: Seed bombs used for seeding, photo: Slovenia Forest Service

Research site Karst: regeneration after forest fire in Karst

The regeneration inventory following the Karst fire involves systematically measuring permanent sample plots to monitor forest regeneration and growth of seedlings, alongside assessing the presence and coverage of invasive alien plant species. This approach follows established guidelines to ensure consistent data collection, enabling effective evaluation of forest health and regeneration dynamics. The collected information supports forest management decisions aimed at maintaining sustainable and resilient forest ecosystems. In 2021, permanent sample plots were measured in the area for the purpose of "Forest management restoration plan" of the Forest Management Unit. One year later (2022) a forest fire caused damage on 2.900 ha of forest. This was an opportunity to remeasure the regeneration and see how it is developing after such a big disturbance. In 2023, the first regeneration inventory was conducted, and the second measurements are going underway in 2025 (Guček et al., 2023).

Figure 24: Post-fire landscape of Karst area, year 2025, photo: Magdalena Cholkova

Figure 25: Natural regeneration three years after the Karst fire (year 2025), photo: Magdalena Cholkova

Figure 26: Natural regeneration inventory on one of the research plots of the Karst area (year 2025), photo: Magdalena Cholkova

RESEARCH SITE JELOVICA – regeneration after natural disturbances (windbreak)

Natural disturbances play a major role in dynamics of forest structure and composition. In close-to-nature silviculture understanding natural succession and regeneration following a devastating disturbance is crucial and successful regeneration represents a challenge for forest management. In 2006 windstorm damaged 160 ha of pure mature secondary Norway spruce (*Picea abies)* forest stands in the Slovenian Alps, growing on sites with natural presence of mixed *Fagus sylvatica-Picea abies-Abies alba* forests. The dynamics and patterns of natural tree species regeneration were examined on 125 ha of totally damaged forest area. A systematic grid of 81 permanent sampling plots (100 × 200 m; 4 × 4 m each) was established and tree species composition, height structure and browsing damages were surveyed; consecutive regeneration inventories were realized in 2008, 2017 and 2025 (Bončina et al., 2018).

Figure 27: Research site Jelovica 19 years after the windthrow (year 2025), photo: Eva Dušak

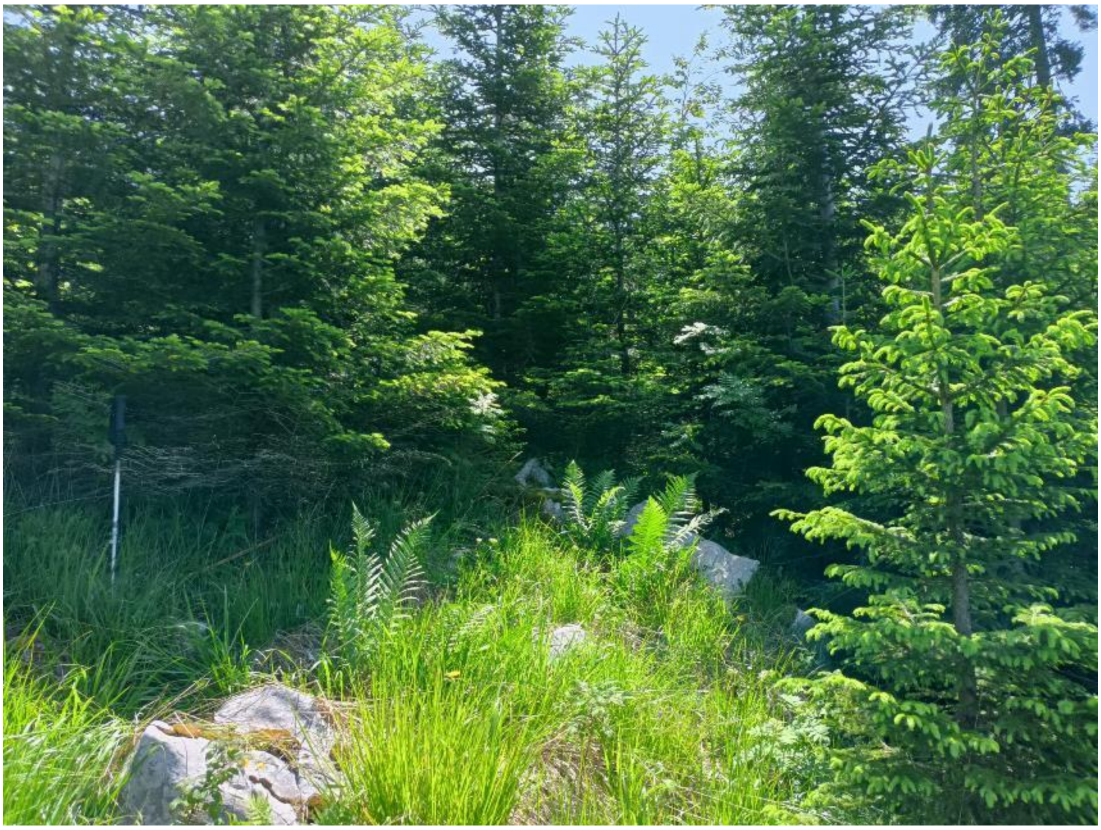

Figure 28: Regeneration inventory on one of the research plots on Jelovica site (year 2025), photo: Eva Dušak

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Attachment 2: Presentation of forest living lab Rindbach experimental catchment, Austria

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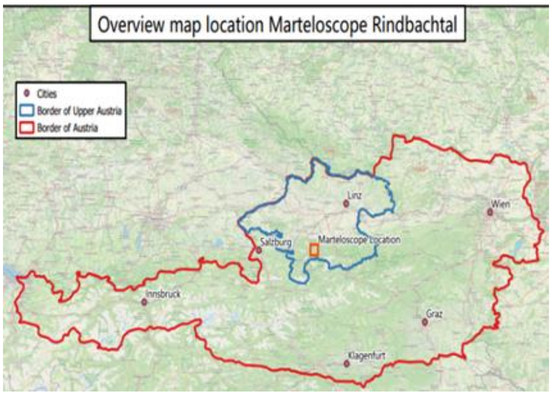

Name of FLL and of the Marteloscope:	Rindbach experimental catchment, Rindbach
Country, Region:	Austria, Upper Austria, Municipality of Ebensee am Traunsee, Rindbach district
Coordinates:	47.805073, 13.8450195
Main risks:	Torrential floods, shallow landslides, rockfall, snow avalanches, windthrow, bark beetle outbreaks
Characteristics of this area:	Designated protective forest safeguarding popular hiking routes and the main forest road in the Rindbach Valley. It is primarily a flood (indirect) protective forest, actively managed by its owner, the Austrian Federal Forests (ÖBf AG).
Needs and problems to be Addressed:	Assess how compound disturbances, such as windthrow and bark beetle outbreaks, affect forest stand structure and alter its protective effects. Investigate silvicultural techniques to enhance stand regeneration and promote species diversity.
Goal of FLL:	To improve stand resiliency against climate change impacts and compound disturbances and investigate various silvicultural techniques to enhance regeneration and optimize stand structure, thereby enhancing protective effects into the future.

Background and description of the problem

In Austria, 42% of the forest area or 1.6 million hectares are designated as forest with a protective function. Over half of this forest area is comprised of Norway spruce (*Picea abies*), which is increasingly being affected by climate change including drought and increased bark beetle infestations. Foresters and forest managers are working to make protective forests more resilient, but they are limited in the resources and tools available to assess how their prescriptions or silvicultural plans may affect future forest development and protective effects. The Rindbach Valley forms a watershed catchment area that is narrow with steep, forested slopes, where the Rindbach stream carves deep channels and eventually empties into the large Traun Lake. The main forest road within the valley is exposed to several natural hazards, including rockfall, erosion, shallow landslides, and snow avalanches originating from the surrounding forested terrain, as well as torrential flooding, which is the primary natural hazard in the area. Although uninhabited, the valley is heavily used by hikers, cyclists, and hunters who depend on the forest road and nearby trails for recreation. Local foresters also rely on the forest road for access and management purposes.

Some current issues affecting the protective forest in this catchment include:

- Stand structure composed primarily of even-aged beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) with limited vertical layering
- Steep, difficult-to-access forest areas that hinder proactive management
- Regeneration challenges due to browsing pressure
- Bark beetle outbreaks and past windthrow events creating potential new snow avalanche release zones
- Accumulation of coarse woody debris in side stream channels, increasing the risk of future flood events
- Rockfall, erosion, and shallow landslides impacting the main forest road and hiking trails

The purpose of this living lab is to provide foresters and forest practitioners with a site to investigate the impacts of compound disturbances (e.g., bark beetle infestation and windthrow), limited regeneration, and how these factors influence forest stand stability and protective effects. Furthermore, this experimental catchment serves as a natural laboratory for scientists and as an education and training site for forestry professionals from both private and public agencies, as well as students from various forestry schools and universities. With a long-term perspective (>30 years), it also supports knowledge transfer, stakeholder capacity building, and the development of sustainable forest and water management practices in the face of climate change.

Figure 13: Shallow landslide triggered by a heavy precipitation event in 2013, with surrounding forest cover changes visible. Photo A. Giunta

Introduction of the area

The Rindbach Valley is a steep, forested headwater catchment ranging from 400 to 1,500 meters in elevation and covering approximately 23 km². The forest cover is composed primarily of European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), particularly at higher elevations, with minor components of sycamore maple (*Acer pseudotplataneous*) and alder (*Alnus* sp.) along the streambanks. Due to the rugged topography and high precipitation (> 1100 mm) per year, gravitational hazards such as rockfall, debris flows, shallow landslides, and snow avalanches are common.

Recent bark beetle outbreaks and past windthrow events have greatly altered the stand structure in the upper catchment area. In July 2013, a heavy precipitation event triggered shallow landslides, mass sediment transport, and debris flows, leading to the flooding of the municipality of Ebensee am Traunsee. This event caused extensive damage to infrastructure, including bridges, roads, and residential buildings.

In response, the long-term “Rindbach experimental catchment” project was initiated as a collaborative effort between the Austrian Service for Torrent and Avalanche Control (WSL), the Austrian Research Centre for Forests (BFW), BOKU University, and the Austrian Federal Forests (ÖBf AG). The project's goal is to monitor and investigate geological, hydrological, forestry, and structural engineering dynamics within this natural, steep forested catchment.

A key component of the project involves evaluating methods for assessing protective forest indicators using LiDAR, orthoimagery, and ground-based survey plots.

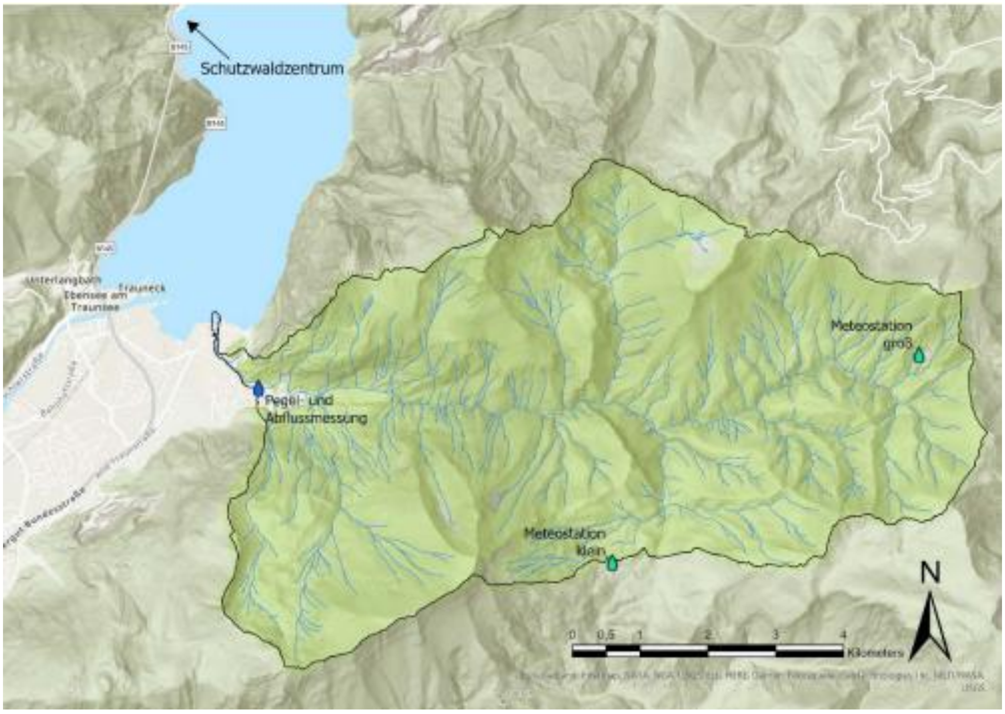

Figure 14: Overview of the Rindbach watershed catchment with level and discharge measuring station ("Pegel- und Abflussmessung"), and small and large meteorological measurement stations ("Meteostation klein" and "groß").

To better assess and discuss the management of protective forests in steep, forested catchments, a Marteloscope training plot was established. The Marteloscope is located on a south-southwest-facing slope, with steepness ranging from 25% to 80% at elevations between 780 and 820 meters. The forest cover is dominated by European beech (>75%) and Norway spruce (10%), with minor components of fir (*Abies alba*), sycamore maple (*Acer pseudoplatanus*), and mountain elm (*Ulmus glabra*). Evidence of a prior bark beetle infestation is present, with standing dead trees and coarse woody debris scattered throughout the site, providing important habitat structure within the forest stand.

Above the site, the forest continues across steep slopes, including an avalanche path in the uppermost section of the catchment. This location was chosen primarily because of the presence of current or potential disturbance factors such as bark beetle infestations, windthrow, and avalanche risk. The site is managed by the local Austrian Federal Forests (ÖBf AG) office, which has committed to a ten-year period without harvesting or other management activities, ensuring the longevity and usefulness of the Marteloscope as a training tool for foresters and researchers over the next decade.

Additionally, the site's proximity to a popular hiking trail offers valuable outreach opportunities, allowing visitors to learn more about protective forests and their management.

Figure 15: Marteloscope area in red with potential avalanche release areas up-slope.

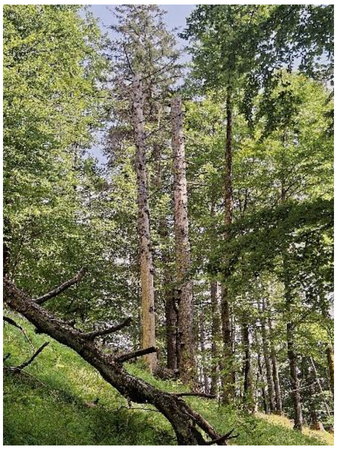

Figure 16. Past bark beetle infestation.

Figure 17. Example of habitat tree following infestation.

Figure 18. CWD laid horizontally to help slope stabilization

Figure 19. Limited regeneration in the plot

Current management of protective forests

In Austria, the Forest Act from 1975 defines the criteria by which a forest is considered a protective forest. It also includes legal provisions for their management and use. If the criteria for a protective forest are met, a forest owner is required to manage it according to local conditions. They are responsible to ensure a stable vegetation that is appropriate to the site with a robust structure and timely rejuvenation.

Protective forests are subdivided into three categories: *site-protective* forests protect their own location when it is threatened by eroding forces such as wind, water, or gravity. *Object-protective forests* safeguard people, their settlements, infrastructure, or cultivated land from natural hazards like snow avalanches, rockfall, landslides, floods, wind erosion, or harmful environmental influences. "*Bannwald*" as a further specification of object-protective forests, are officially restricted to directly counter natural hazards. This means that public or economic interests are subordinate to the protection objective and any potential restrictions resulting from the designation of a "Bannwald". Actions or tasks in "Bannwälder" are exclusively carried out under official directives (Pichler et al. 2025).

Living lab method-Marteloscope

The Rindbach Marteloscope was established in a forest district managed by the ÖBf AG in cooperation with a local district forester, whose support was crucial in identifying potential suitable sites within the Rindbach experimental catchment. The district forester provided maps and conducted an on-site tour, explaining local silvicultural practices and offering valuable support for the project. The site location was selected due to its potential for compound disturbances having had a recent bark beetle outbreak and exposure to wind events while being susceptible to rockfall and avlanches. Furthermore, the site is easily accesible from a short distance along a well established hiking trail.

Following the European Forest Institute (EFI) protocol, the Marteloscope was set up by staff from the BFW in July 2024. Over the course of a week, all trees within the 1-hectare plot were measured, mapped, and recorded. Additional data on tree microhabitats for biodiversity and wood quality assesments were also collected. In July of 2025 an extenstive coarse woody debris (CWD) mapping and measurement campaign was completed to assess the amount and location of CWD in the plot which can have an influence on protective effects.

The Marteloscope covers an elevation ranging from 780-820 m along a southwest aspect with an average slope of 32 degrees. Under the Austrian forest growth regional guidelines the site is classified as a low montane beech forest (Kilian et al. 1994). Tree species composition is dominated by beech-*Fagus sylvatica* (74%), followed by norway spruce-*Picea abies* (18%), with minor components of sycamore maple- *Acer pseudoplataneous* (7%), silver fir- *Abies alba* (< 1%) and Scots elm- *Ulmus glabra* (< 1%). Tree density is 322 trees per hectare with a calculated basal area of 27.8 m^2 ha^{-1}, a quadratic mean diameter of 33.1 cm, and an estimated volume of 264 m^3 ha^{-1}. The amount of standing dead trees is aproximately 8%. Estimated coarse woody debris biomass is 1.93 tons per hecare. A total of 319 indivial tree microhabitats were observed with the most frequent being branch holes, insect galleries, root cavities,and epiphytic moss.

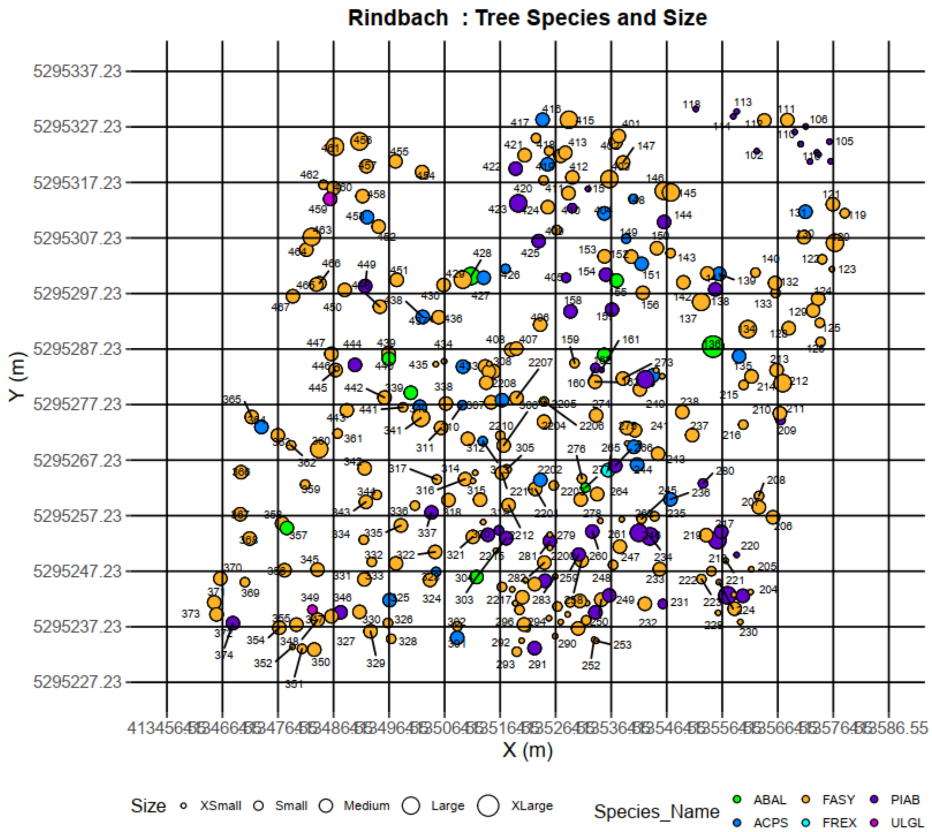

Figure 20. Map of tree loctions including tree species and size for the Rindbach Marteloscope derrived from Samsara tree growth simulation model software.

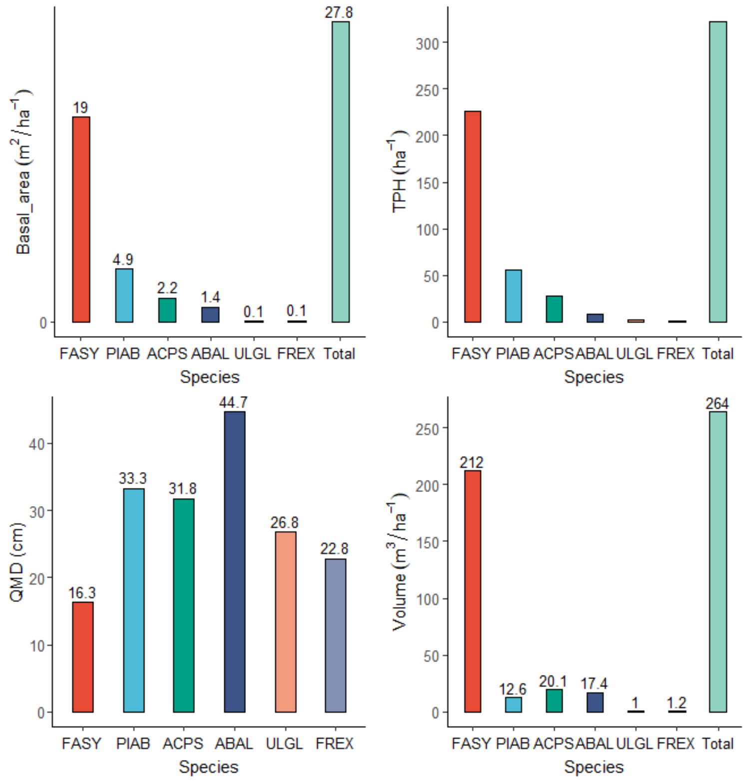

Figure 21. Stand characteristics including basal area, trees per hecatre (TPH), quadratic mean diameter (QMD), and volume per species for the Rindbach Marteloscope site.

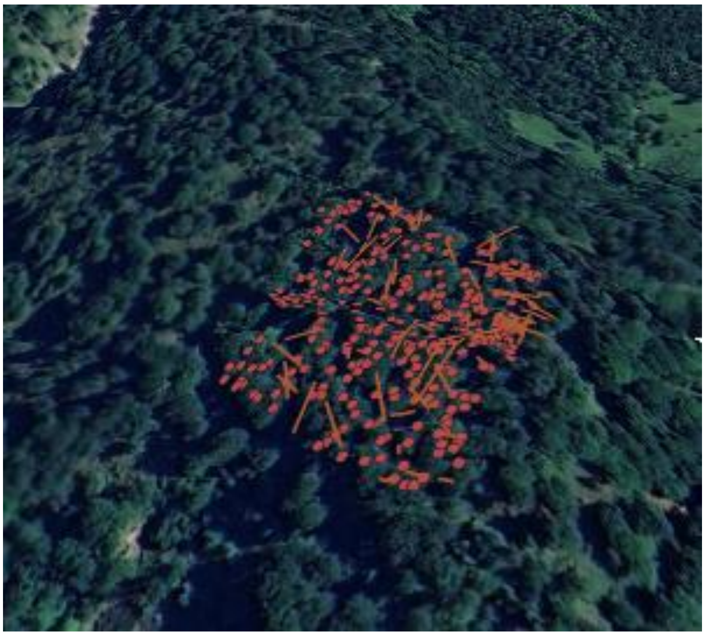

Figure 22. Map of tree locations and coarse woody debris (CWD) within the Marteloscope site. Trees are denoted by red circles and cwd by brown lines.

The management of the Marteloscope will be transferred to the nearby Forestry Training Centre Traunkirchen (FAST Traunkirchen). This center operates a forestry school serving students across Austria and offers numerous forestry-related courses, training programs, and certifications for active forestry practitioners, forest landowners, and the public.

Figure 23: Tree measurements taken during plot installation.

Figure 24. Mapping and measuring coarse woody debris (CWD) in the Marteloscope plot.

Stakeholder involvement and knowledge transfer

One of the largest and most critical stakeholders in our FLL is the FAST Traunkirchen (https://fasttraunkirchen.at/). Operating under the BFW, the FAST Traunkirchen is responsible for teaching forestry courses, hosting forest seminars, and providing certification programs. The center also houses the Austrian Protective Forest Hub (www.protective-forest.at/protectiveforesthub/about.html). Once the data from our FLL was uploaded into the I+ software, the program was tested, model outputs were reviewed, and reports were generated. After completing data quality control, a training workshop will be conducted to teach future trainers at FAST how to operate the I+ software, run exercises with participants, produce reports, and identify key discussion topics for Marteloscope users focused on protective forest management.

Other key stakeholders include the ÖBf AG, who are the forest owners; the Austrian Service for Torrent and Avalanche Control (WLV), which manages protective measures within the Rindbach catchment area; professors, researchers, and students from BOKU University; and the State of Upper Austria's Department of Agriculture and Forestry. These stakeholders will collaborate to utilize the Marteloscope for training purposes, facilitated by FAST.

Completed Activities

- Installation of the Marteloscope (July 2024)

- Site visit with the HILUC (Hydrological Impact of Historical Land Use and Climate) research group from the University of Innsbruck to discuss Marteloscope use in protective forest management (May 9, 2025)
- Completion of tree marking and coarse woody debris site survey (July 2025)

Planned Activities

- Conduct a Marteloscope workshop for FAST staff (Spring 2026) to introduce the concept of Marteloscopes, organize and lead field exercises, train I+ software operation, report generation, and facilitate discussion on protective forest management topics
- Develop a Marteloscope presentation for WLV and ÖBf to assess their interest in adopting the tool for their forest managers and staff
- Design and distribute a survey to FAST trainers and future workshop participants to evaluate the effectiveness of Marteloscope use in protective forest management training
- Installation of an information board next to the Marteloscope site along the hiking path to inform public about protective forests and protective forest management in the face of compound induced disturbances

Figure 25. Marteloscope site visit and discussions of regeneration challenges with the Hydrological Impact of Historical Land Use and Climate (HILUC) research group from the University of Innsbruck, BOKU; BFW, Office of the Tyrolean Government May 9, 2025.

Table 5: Key elements of Rindbach experimental catchment living lab.

Multi stakeholder participation	***Co-creation***	***Active user involvement***	***Real life setting***	***Multimethod approach***	***Orchestration***
Involving stakeholders from the quadruple helix model (government, academia, private sector, and citizens) PPPP: science, policy, practice, citizens	Co-created not only for but also by all relevant stakeholders How to include them in the process?	A living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation	A living lab operates in the real-life setting of the end users, infusing innovations into their real life instead of moving the users to test sites to explore the innovations	Problem driven activities – searching for solutions with various methods	The living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders
• *Austrian Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management (BMLUK)* • *Austrian Service for Torrent and Avalanche Control (WLV)* • *Austrian Federal Forests (ÖBf AG)* • *BOKU University* • *Austrian Research Centre for Forests (BFW)* • *Forestry Training Centre Traunkirchen (FAST Traunkirchen; https://fasttraunkirchen.at/)* • *Austrian Protective Forest Hub (www.protective-forest.at/protectiveforesthub/about.html)*	*The Rindbach experimental catchment project is a collaboration between the listed stakeholders, and is supported by the municipality of Ebensee am Traunsee*	• *FAST Traunkirchen* • *ÖBf AG* • *WLV* • *Scientists* • *Forestry professionals from private and public agencies* • *Students from different forestry schools and universities, but mainly BOKU (Master program Alpine Natural Hazards / Watershed Regulation)* • *The public*	*Yes, see description.*	• *Test sites and instrumentation for hydrological runoff monitoring* • *Modeling case studies* • *Research sites and forest plots with different foci* • *Meteorological stations (2)* • *Marteloscope*	*Yes, since this is a collaborative effort, all the stakeholders listed previously are involved and connected.*

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Attachment 3: Presentation of forest living lab Mompantero, Italy

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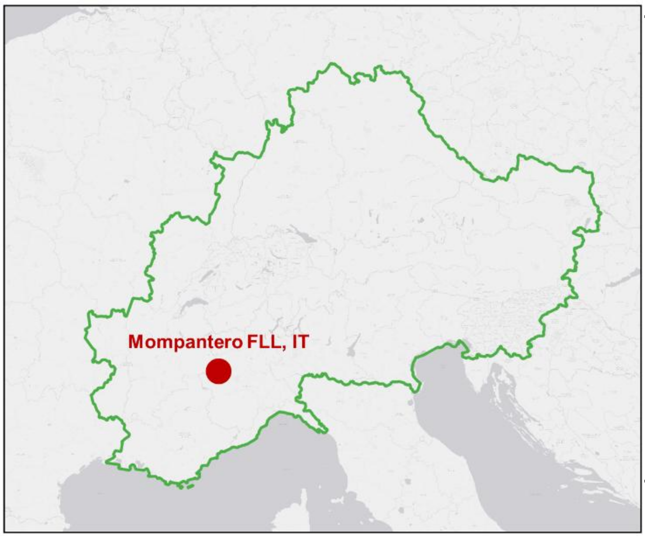

Name of FLL:	Mompantero
Country, Region:	Italy, Piemonte Region
Coordinates:	45.15642, 7.04291
Main risks:	Wildfire, rockfall, debris flow
Characteristics of this area:	Most forest stands have a protective function. Forests of the FLL have been affected by a large mixed-severity wildfire in 2017 (almost 4000 ha), and the Mompantero area is mostly in the high severity class.
Needs and problems to be addressed:	Restoring the stands that burned with high severity or with a stand-replacing behavior, while recovering the protective function of the forest.
Goal of FLL:	Raise awareness about post-fire management in protective forests; Disseminate knowledge on the importance of assessing disturbance severity and defining intervention priorities; recover the protective function of the burned forests by promoting natural regeneration and properly managing deadwood; target areas where to perform active restoration to improve effectiveness and efficiency of interventions.
Case studies, research, test sites:	Mompantero wildfire case study,

Background and description of the problem

Describe the problem(s) that you are facing and you would like to solve or research with the living lab approach.

Mediterranean mountain forests are sensitive to global change because of historical land use and abandonment, as well as due to their low resilience when affected by high-severity disturbances. Pine stands dominated by species like *Pinus sylvestris* and *Pinus nigra*, which lack specific fire-related traits, have been increasingly affected by larger and more severe disturbance events in the last few years. During autumn 2017 a particularly severe early fire season affected mountain forests in Piedmont, with the Mompantero wildfire representing the larger event of that season. In the context of this increasing hazard to forest ecosystems, post-disturbance management has a crucial role in post-fire regeneration dynamics, as salvage logging – the harvesting of dead or damaged trees from sites after disturbance events – is still the main practice in many forest ecosystems, whereas its negative ecological implications have been increasingly demonstrated. Scots pine stands are also suffering from large diebacks and mortality in South expositions all over the Alpine area (e.g., Aosta Valley, Valais, Susa Valley). The Mompantero site is therefore a perfect pilot site to test for increasing wildfires in protective pine forests under global change and the effects of post-disturbance management.

Introduction of the area

Introduction of the area that is included in FLL approach and why this area was chosen (include photos/illustrations/maps)

Autumn 2017 was characterized by an uncommon fire season in Piedmont (North-Western Italy), triggered by extreme winds, temperatures 2.9°C above the average of 1970-2000, and very scarce precipitation (98% lower than the average) (Figure 1A). The Southern slopes of the lower part of Susa Valley experienced the largest of these wildfires (~ 4000 ha, of which 2500 ha occurred in forests) in November 2017. Mompantero municipality was particularly affected as the protective forests of this municipality are mainly composed of Scots pine and European larch (*Larix decidua* Mill.) stands, that are prone to intense and severe crown fires (Figure 1B). The area ranges between 500 and 2500 m a.s.l. and the soils are Cambisols according to the Working Group World Reference Base for Soil Resources. The mean annual precipitation is approximately 800 mm and the mean annual temperature is 12 °C.

The main ecosystem service provided by those forests is protection and cultural, being the pre-existing forest a large and pure pine stand that protects roads and villages from avalanches, rockfalls, and landslides. In Bussoleno (a municipality close to Mompantero), a large debris flow affected several buildings in the alluvial fan in June 2018, triggered by the scarcity of forest covered after the wildfire. Forest species composition, topography, and post-fire management (i.e., practices related to deadwood management and plantations) have the potential to create predisposition for cascading and compound effects in Mompantero as well, determining the need for a proper evaluation of the best post-disturbance strategies in the area of the forest living lab.

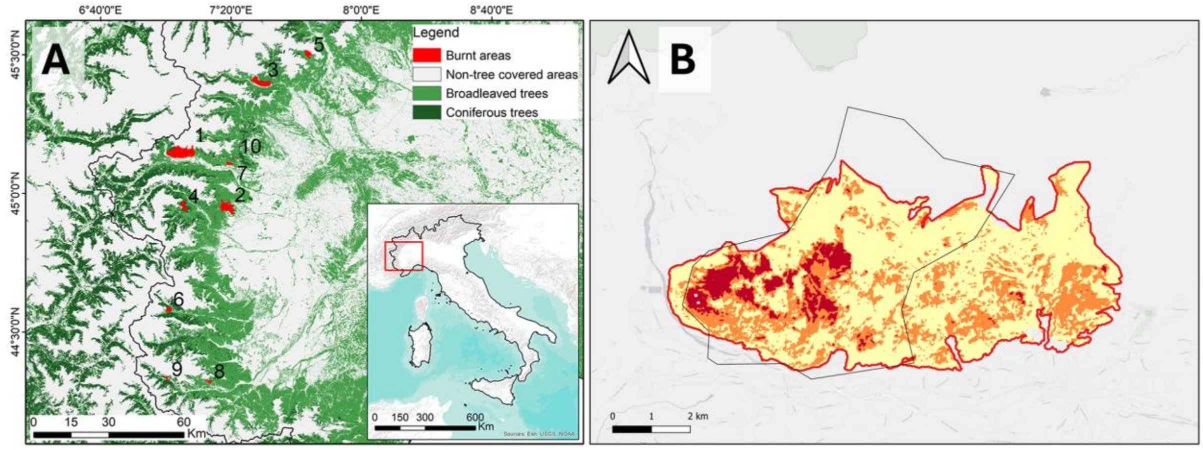

Figure 1. (Panel A) Localization of the ten large wildfires affecting Piemonte Region in Autumn 2017 [Mompantero wildfire is the number 1] and (B) detail of the Mompantero wildfire with severity (yellow = low severity, red = high severity) and the borders of Mompantero municipality in black (modified from Morresi et al. 2022).

Current management with protective forests

Describe what are main activities and management in protective forests, systems for facilitation of protective forest management (cofinancing, financing of measures)…

The current strategies are related to the post-fire management of deadwood and regeneration dynamics. A mixture of different techniques and strategies have been adopted by managers and policymakers (i.e., local administrations, metropolitan city of Turin, forest practitioners), assisted by prior knowledge and models developed by the research group of the University of Turin.

In general, the main goal was to reduce traditional active interventions (i.e., salvage logging followed by regular plantations) while preferring nature-based solutions (NbS) like targeting microsites conditions close to deadwood and shrubs and favoring natural regeneration over artificial one. Active removal of deadwood and damaged trees was carried out mostly in groups and in areas with greater risk (i.e., close to infrastructures, where the falling trees could have threatened human lives). A limited number of natural engineering artifacts were predisposed only in proximity to roads, villages, and water streams, while the role of deadwood for protection was favored. These operations were funded by a dedicated post-fire regional management plan developed after the ten 2017 wildfires.

Trees were planted or seeded in 64 ha based on targeted intervention priority maps developed through statistical models developed by University of Turin and funded by a PNRR Grant managed by the Metropolitan City of Piemonte. A mixture of conifer and broadleaf species was favored to increase the resilience of the novel forest ecosystem. Forest practitioners were trained to identify favorable microsite conditions (e.g., close to logs, rocks, or shrubs). The effectiveness of seeding was tested to derive insights into the applicability of this technique compared to planting and predation has been monitored together with entomologists to identify threats and issues in the germination and establishment of seeds.

The area was therefore designated to translate scientific and ecological knowledge into practical action and to test new hypotheses helping to guide future management of protection forests after a severe disturbance.

Living lab method

Describe the process of your FLL establishment and what is the goal and main activities of your FLL, (3 steps, key elements), organization and management of FLL, evaluation of solutions – 3rd step)

The goals of the FLL are many: (i) raise awareness about post-fire management in protective forests; (ii) disseminating knowledge on the importance of assessing disturbance severity and defining intervention priorities; (iii) recover the protective function of the surviving forests by promoting natural regeneration and properly managing deadwood; (iv) target areas where to perform active restoration to improve effectiveness and efficiency of interventions. The final goal is to produce tools and guidelines for practitioners, policymakers, and forest managers for better managing protection forests affected by fire disturbances.

FLL is managed and organized in order to respond to the above-mentioned four specific goals and to involve and inform several target stakeholders (students and academia, citizens, policymakers, and practitioners) on the scientific and ecological implications of post-disturbance management techniques. Solutions have been tested through sound and reliable scientific analysis and on-going monitoring.

Stakeholder involvement and knowledge transfer

Which stakeholders will be included in FLL and how (eg. Workshops, round tables, trainings…). Who are the end users of FLL and how will you provide knowledge transfer? List and shortly describe activities that are planned/were performed with a goal to involve stakeholders and transfer knowledge.

Several stakeholders have been involved in various study sites within the Mompantero FLL.

Students from the University of Turin participated in several field visits to research sites as part of academic courses on landscape ecology, disturbance ecology, and ecological restoration, with the goal to enhance knowledge transfer within an academic context. Moreover, a group of 32 students and professors from the University of Yamagata (JP) were brought to the FLL to present and discuss the effects of wildfire and the drivers of post-fire regeneration for post-fire management and planning. The students had the opportunity to see a natural dynamic which is very rare in their country and to discuss the implications of disturbances and compound events under a global-change scenario. Colleagues working on post-disturbance dynamics and management from institutions across the world visited the FLL to foster collaboration and discussion. Scientific publications were produced on the mapping of fire severity through satellite-based remote sensing (https://doi.org/10.1080/15481603.2024.2365001) and on the post-fire regeneration dynamics and drivers (https://doi.org/10.1186/s42408-023-00182-7) and several presentations about the scientific results gathered from this FLL have been delivered in national and international scientific conferences.

Citizens have been informed on the activities carried out in the Mompantero FLL through press release articles (e.g., "L'Università: "Rimboschire? Sì, sapendo dove e come" published in the local newspaper "La Valsusa" on 06/07/2023) and involved through two participatory focus groups on 05/12/2024 and 27/01/2025 to collect social perception and thoughts on wildfires and consequent post-disturbance management, especially regarding the application of NbS and the release of deadwood in forest.

Administrators have been actively involved across several levels: from local municipalities administrations to provincial and regional policymakers. Their need, perception, and knowledge were actively included in the creation and implementation of the FLL and they have been participating in a dedicated focus group on 10/04/2025. The participative method was ensured so to respond to political and social needs at different scales.

Local forestry technicians where involved in a dedicated focus group on 21/10/2024 aiming at understanding their knowledge regarding the effects of wildfires on the provision of ecosystem services, post-fire management techniques and the importance of leaving deadwood on the ground after a wildfire.

The Mompantero FLL aimed for integration and synergies between different stakeholders and granted strong transfer of knowledge across several methods, preferring focus groups to directly collect stakeholders opinions and knowledge.

Key elements of living labs:

To check if all key elements are met.

Multi stakeholder participation	***Co-creation***	***Active user involvement***	***Real life setting***	***Multimethod approach***	***Orchestration***
involving stakeholders from the quadruple helix model (government, academia, private sector, and citizens) PPPP: science, policy, practice, citizens	co-created not only for but also by all relevant stakeholders How to include them in the process?	a living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation	a living lab operates in the real-life setting of the end users, infusing innovations into their real life instead of moving the users to test sites to explore the innovations	Problem driven activities – searching for solutions with various methods	the living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders
List/description of stakeholders in your FLL	*Does your stakeholders cocreate your FLL? Which?*	*Who is your end user? Are they involved?*	*Is your FLL set in real life? e.g. protective forest*	*Which methods are used within your FLL? e.g. FLL approach, test sites, case studies, research sites, Marteloskopes*	*Does your FLL connect different stakeholders? Which ones?*

Attachment 4: Presentation of forest living lab Verrayes, Italy

Department of Agricultural, Forest and Food Sciences, University of Turin, IT:
Raffaella Marzano
Matteo Garbarino
Nicolò Anselmetto
Giulia Mantero
Matteo Domanico
Alessia Zampiceni

Contact:
Raffaella Marzano raffaella.marzano@unito.it

Name of FLL:	Verrayes
Country, Region:	Italy, Aosta Valley Region
Coordinates:	45.77030, 7.49772
Main risks:	Wildfires, rockfall, avalanche
Characteristics of this area:	The majority of the forest stands have a protective function. Forests of the FLL have been affected by a large high-severity wildfire in 2005 followed by salvage logging. The Marteloscope area was placed in a nearby forest stand with similar characteristics to the burned pine forest.
Needs and problems to be addressed:	Ecologically inappropriate post-fire intervention (salvage logging) hindered post-fire recovery
Goal of FLL:	Raise awareness about post-fire management in protective forests; Disseminating knowledge on the importance of assessing disturbance severity and defining intervention priorities; recover the protective function of the surviving forests by promoting natural regeneration and properly managing deadwood; target areas where to perform active restoration to improve effectiveness and efficiency of interventions.

Case studies, research, test sites:	Bourra wildfire, Verrayes marteloscope

Background and description of the problem

Shifting paradigms of post-disturbance management and planning has become a urgent task in ecosystems affected by new disturbances regimes and severe consequences of global change, especially when the forest species lack resilience traits and struggle in self-regulating after large events. Larger, more frequent, and more severe wildfire events are shaping the forest ecosystems of the Alpine Space as a result of drier climate conditions and increasing canopy cover and forest connectivity because of ongoing land abandonment in the region. When high-severity wildfires occur in dry pine stands, for example, the probability of having large stand-replacing patches is increasing. In those cases, natural regeneration of the pre-existing stand can be hindered by the distance from seed-bearing trees (i.e., seedtrees), that was proved to be one of the main factors driving regeneration for species lacking adaptive traits that would create a seed bank in the soil. When dealing with those disturbance events, the removal of dead or damaged trees and coarse woody debris in such patches (i.e., salvage logging) could be an additional problem for the ecosystem recover for two main reasons: (i) the possibility of damaging existing young trees through mechanical operations, (ii) the dampening of favorable microclimatic conditions and protection through the removal of sheltering objects like deadwood.

Introduction of the area

A large fire occurred in Bourra (Verrayes municipality, Aosta Valley, Italy) in March 2005, burning 257 ha. The burnt area ranges between 1650 and 1800 m a.s.l. in a predominantly south-exposed slope with an average slope inclination of 25°. The site represents dry mountain/subalpine conditions of many internal dry valleys of the Alps, with mean annual temperature of 5.6°C and mean annual precipitation of 750 mm. February is the driest month of the year, coinciding with the peak of the fire season. The central part of the disturbed area (160 ha, 62% of the total area) was a large patch of high severity, where the main species of the pre-existing secondary forest – Scots pine (*Pinus sylvestris* L.) – naturally suffer to regenerate, lacking specific fire-related traits (Figure 1).

In addition to the natural disturbance, salvage operation started in 2007 including most of the area affected by the stand-replacing fire. In those areas dead trees were removed from the sites, while branches were left piled up. The operations resulted in a dramatic forest degradation, and the area still shows very low density of regeneration – especially Scots pine – after 20 years. Within this framework of high-severity and large wildfires in dry Scots pine stands followed by salvage logging operations, the area represents an important and unique case, research, and test study to monitor the effects of ecologically inappropriate post-fire intervention (i.e., salvage logging) after severe fires in fragile and not resilient forest ecosystems of the Alps.

The main ecosystem services provided by the pre-existing forests was the protection of roads, buildings, and villages from rockfalls, avalanches and landslides. The absence of tree cover, stems, and also the removal of deadwood – that could act as an effective barrier to falling rocks and that increases the roughness of release areas to prevent avalanches – has severely dampened this important ecosystem service for the last 20 years.

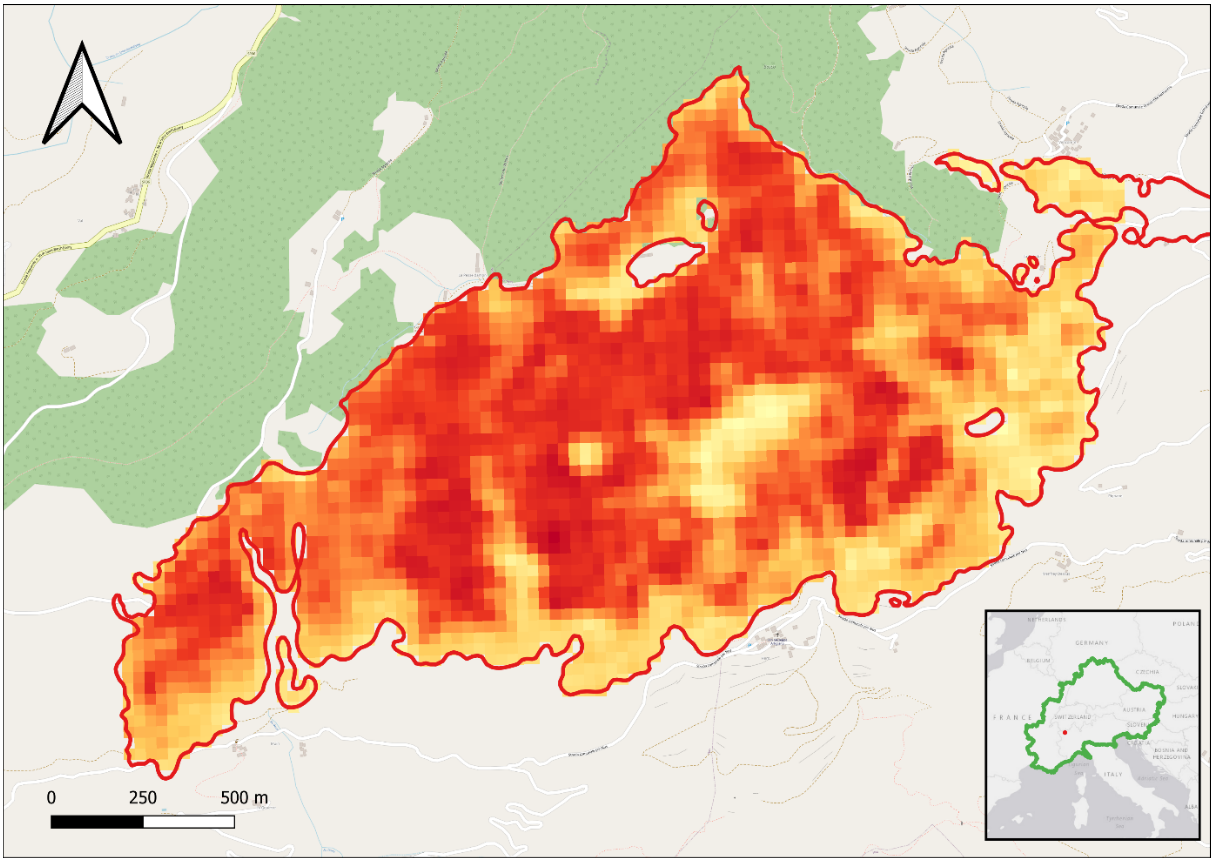

Figure 1. Bourra 2005 wildfire severity (yellow = lower, red = higher), border, and localization within the Alpine Space (small panel on the right).

Living lab method

The main goals of the Verrayes FLL are: (i) to raise awareness about incorrect and ecologically wrong post-fire management in mountain pine forests; (ii) disseminating knowledge on the importance of assessing disturbance severity and defining intervention priorities in the aftermath of a disturbance; (iii) recover the protective function of the surviving forests by properly managing deadwood; (iv) target areas where to perform active restoration to improve effectiveness and efficiency of interventions through statistical analysis and targeted objectives. The final goal of the FLL is to produce guidelines for practitioners, policymakers, and forest managers for better managing post-fire stands in protective forests.

FLL was created and is organized in order to respond to the above-mentioned specific and general goals and to involve and inform several target stakeholders (students and academia, local and regional policymakers, forest owners, technicians) on the scientific and ecological implications of post-disturbance management techniques and the consequences of bad practices. Solutions have been investigated and tested through sound and reliable scientific analysis and on-going monitoring.

Stakeholder involvement and knowledge transfer

Several stakeholders have been involved in various study sites within the Verrayes FLL over the years.

Students from the University of Turin and Padova participated in several field visits to research sites as part of academic courses on landscape ecology, disturbance ecology, and ecological restoration, with the goal to enhance knowledge transfer within an academic context. The Forest Landscape Laboratory (FLL) also welcomed researchers working on post-disturbance dynamics and management from institutions worldwide, fostering collaboration and scientific exchange. In 2024, a group of 37 students from the Swedish University of Agricultural Sciences visited the FLL and nearby protective forests to study disturbance-driven dynamics in Alpine ecosystems. Interest in the site continues to grow: the University of Sassari, recognizing the FLL's pivotal role in illustrating the consequences of ecologically inappropriate deadwood manipulation, has arranged a forthcoming student visit. As a result, the Verrayes FLL has emerged as a key center for research, training, and knowledge transfer in the Western Alps—an area increasingly affected by large and severe wildfires under a changing climate. Using data and experiments carried out in Verrayes FLL, many scientific publications were produced over time on the role of deadwood on favoring forest regeneration (http://dx.doi.org/10.1016/j.ecoleng.2012.12.030), the best practices on deadwood management (https://doi.org/10.3390/f10111014, https://doi.org/10.3390/f14091820), defining priority interventions through correlative statistical modeling (https://doi.org/10.1016/j.foreco.2023.121520). Several presentations about the scientific results gathered from this FLL have been delivered in national and international scientific conferences.

Administrators have played an active role in the development of the Forest Landscape Laboratory (FLL), both at the local level—particularly the Municipality of Verrayes—and at the regional level through the Aosta Valley Region. Their needs, perceptions, and local knowledge were directly integrated into the design and implementation of the FLL. The Municipality of Verrayes stood out for its strong engagement throughout the research, experimentation, and knowledge transfer phases. Notably, the local administration demonstrated a keen interest in post-fire management, especially regarding deadwood, and showed a clear commitment to adopting scientifically informed practices for sustainable landscape management.

Local firefighters (AIB – Anti Incendi Boschivi) were actively involved in the dissemination of results, driven by their interest in practical knowledge and the consequences of inappropriate post-fire management practices. Forest owners also played a key role in the co-creation of the Forest Landscape Laboratories (FLLs), contributing their on-the-ground experience and perspectives.

The Verrayes FLL was designed to foster integration and synergy among diverse stakeholders, ensuring a robust transfer of knowledge through a variety of participatory and science-based approaches.

Key elements of living labs:

To check if all key elements are met.

Multi stakeholder participation	***Co-creation***	***Active user involvement***	***Real life setting***	***Multimethod approach***	***Orchestration***
involving stakeholders from the quadruple helix model (government, academia, private sector, and citizens) PPPP: science, policy, practice, citizens	co-created not only for but also by all relevant stakeholders How to include them in the process?	a living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation	a living lab operates in the real-life setting of the end users, infusing innovations into their real life instead of moving the users to test sites to explore the innovations	Problem driven activities – searching for solutions with various methods	the living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders
List/description of stakeholders in your FLL	*Does your stakeholders cocreate your FLL? Which?*	*Who is your end user? Are they involved?*	*Is your FLL set in real life? e.g. protective forest*	*Which methods are used within your FLL? e.g. FLL approach, test sites, case studies, research sites, Marteloskopes*	*Does your FLL connect different stakeholders? Which ones?*

Case studies, best practice examples, research, test and demonstration sites for FLL name, Country

MARTELOSCOPES VERRAYES – DEMONSTRATION SITES

The Verrayes marteloscope (45.7821°N, 7.5293°E) covers approximately 7,500 m² at an elevation of 1,470 meters above sea level, situated on a south-facing slope with an average incline of 11°. Located just 2 km from the Bourra wildfire site, the marteloscope shares similar climatic conditions, topography, species composition, and stand structure with the affected area—making it particularly relevant for comparative studies with the Bourra case study. The site is a dry Scots pine (*Pinus sylvestris*) forest that functions as a protective forest against avalanche and rockfall hazards, safeguarding local infrastructure and the village of Grand Villa. It is primarily composed of abandoned terraced land on private properties.

Scots pine dominates the stand (approximately 75%), with an average diameter at breast height (dbh) of 17.7 cm and an average height of 8 meters. European larch (Larix decidua) and Norway spruce (Picea abies) are also present. Although the forest exhibits generally poor health and timber quality, it hosts a variety of microhabitats – particularly types EP31, DE11, and DE13 – indicating ecological value.

The primary objective of the marteloscope is to enhance thinning and silvicultural practices in protective forests, with a focus on resilience to compound and cascading disturbance events—especially wildfires—under changing climate conditions.

Interreg Alpine Space
Co-funded by the European Union

MOSAIC

Attachment 5: Presentation of forest living lab Agordino, Italy

Department of Land, Environment, Agriculture and Forestry, University of Padova
Emanuele Lingua
Tommaso Baggio
Davide Marangon
Paul Richter

Contact:
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Name of FLL:	Agordino
Country, Region:	Italy, Veneto region
Coordinates:	46.315977, 14.062031
Main risks:	windthrow, bark beetle, rockfall, snow avalanches, shallow landslides, wildfires
Characteristics of this area:	Forests of the FLLs are recently impacted by different natural disturbances consequently reducing their protective capacity
Needs and problems to be Adressed:	Assess the residual protection provided by disturbed forests and analyze possible compounds events. Evaluate the regeneration dynamic of disturbed forests and identify the regeneration drivers
Goal of FLL:	Improve the management of post-disturbed forests to rapidly restore the protective function with alternative and nature based solutions
Case studies, research, test sites:	Franza, Col di Lana, Taibon Agordino, La Muda, Malgonera, Nevegal

Background and description of the problem

In the last years the Agordino area was hit by different natural disturbances that dramatically altered the forest structure and consequently their protection capacity, especially against gravitational hazards. In particular, one windstorm occurred in October 2018 windthrown hectares of forests in the area of the forest living lab, posing challenges for the evaluation of possible new areas for snow avalanches, rockfalls, landslides. In the following five years strong bark beetle outbreaks caused even more timber loss than the storm of October 2018, increasing the forest damages in the protective forests.

Introduction of the area

The Agordino area is a mountain zone located in the province of Belluno (eastern Italian Alps) and it is part of the dolomite mountain group. The area extends for 695 km^2 of which half is covered by coniferous or mixed forests. Forests actively and passively protect infrastructures, inhabitants and houses from natural hazards such as rockfalls, snow avalanches, shallow landslides and floods. However recent natural disturbances had altered the forest structure of the area decreasing the protection efficiency. In particular, an intense windstorm event in October 2018 severely damaged 39 km^2 of forests (Fig. 1). Moreover, in October 2018 a high intensity wildfire spread for hectares of forests, next to the village of Taibon Agordino.

Especially the windstorm event caused the destruction of hectares of protection forests and therefore the protection level decreased. However, the biomass on the ground and especially the lying logs can still provide a protection effect especially against the release of snow avalanches and on the stopping of rolling rocks. Such structures will degrade over the next years and at the same time the natural regeneration will slowly grow.

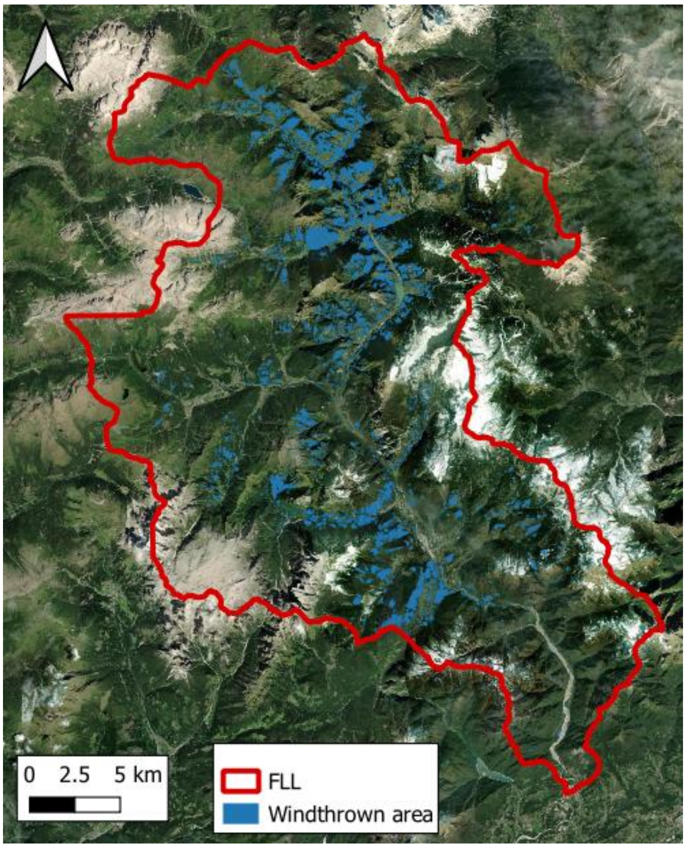

Figure 16: localization of the windthrown areas within the boundaries of the Alto Agordino forest living lab area.

Current management with protective forests

The management of the disturbed areas has the main objective to restore as soon as possible the protection level of the standing forest. For protection against rockfalls and snow avalanches, the procedure consisted in the installation of protection nets immediately upward the sensitive structure and consequently the lying logs have been removed. Afterwards a series of nets have been installed in the cleared area in accordance with the source of hazard and the morphology characteristics of the slope. Windthrown areas that were not considered crucial for protection purposes, the biomass and logs were left on the ground following the no management option.

In some small cases, artificial regeneration was carried out mainly by seedling planting of different tree species. When possible, a good share of broadleaves and larch seedling was preferred respect Norway spruce.

Living lab method

The goal of the forest living lab is to investigate the forest dynamic of disturbed areas in terms of natural hazard protection and regeneration dynamics. Moreover, an analysis of the current forest disturbance susceptibility (i.e. windstorms) is carried out. Data used to perform this analysis based on both remote sensed data (UAVs, LiDAR) and field surveys. The main objective is to understand the protection efficiency offered by disturbed forests and the natural regeneration in different disturbed forests. The final goal is to provide efficient tools and guidelines for practitioners and forest managers for better manage protection forests and accurate evaluate the protection measure provided by disturbed forests.

Stakeholders and knowledge transfer

Forest students have visited different research sites of the forest living labs. Thanks to the summer schools for students and practitioners that will be held in autumn 2025 the difficulties in choosing between the different management options will be discussed directly on the field within the forest living lab area. Moreover, the research sites are shown either through field trips or by presentations.

Case studies, research, test and demonstration sites for FLL Agordino, Italy

MARTELOSCOPES – DEMONSTRATION SITES

Marteloscope Nevegal

The marteloscope located next to the city of Belluno will be established and used for training students, foresters and practitioners. The area extends to the northwest side of the Nevegal Mount at an elevation between 1150 and 1200 m a.s.l. The slope is in the range 20-25°. The plot is a standing forest within a patch of a windthrown area. The main species is Norway spruce followed by beech and larch. The structure of the forest is heterogenous with the presence of large trees and natural regeneration areas.

RESEARCH SITES Col di Lana – Franza

Assessment of the forest protection of windthrown areas against the release of snow avalanches

These two study sites are located next each other within the municipality of Livinallongo del col di Lana. The Col di Lana and the Franza sites have an extent of 5 ha and 9 ha respectively. They are two windthrown areas (completely damaged by the storm Vaia in 2018) with different pre-storm standing structures. The two sites have been recorded by UAV photogrammetric and LiDAR surveys to detect the changes in the biomass height respect the terrain. The final goal is to develop a model for assessing the protection against the release of snow avalanches in windthrown areas.

The combination of LiDAR and photogrammetric Drone surveys allowed a precise analysis of the provided effective barrier height of windthrown areas against rockfall. Consequently, the obtained results will further be used to improve Rockfall-Models and include Deadwood as barriers against Rockfall. Additionally, deadwood samples have been taken to analyse the drymatter density in altitudes of 1600-2000 m.a.s.l) in the same time-span after the windstorm-event.

In every area in 2024 two TDR stations have been installed for a long-term measurement of the water content of windthrown logs. The objective is to study the fluctuation of water contents in windthrown logs and their effect on the degradation of the deadwood-material and water-storage capacities, mainly to improve the regeneration success.

RESEARCH SITE Taibon Agordino

The area affected by a big wildfire event in October 2018 was used to survey the natural regeneration grow after a high magnitude event. Parameters of the regeneration was surveyed in different plots in several field campaigns.

RESEARCH SITE Alto Agordino

The disastrous windstorm event occurred in October 2018 posed the attention on the forest wind vulnerability. Thanks to LiDAR data and high-resolution climate model outputs covering the forest living lab area, we calculated the hazard exposure of the forests through the use of the semi-mechanistic model ForestGALES. Thanks to future wind projection we assessed the future wind hazard that showed an increase of forest exposure in terms of area and growing stock.

Different areas within the alto Agordino area were selected for performing natural regeneration surveys to investigate the role of the biomass in seedling growth. These data where then used to derive the drivers of natural regenerations after forest disturbances.

RESEARCH SITE Malgonera

Assessment of protection efficiency provided by lying logs against Rockfall was studied in the same way as in Franza and Col di Lana. The site provided us moreover a full coverage of different altitude classes (around 1300 – 1600 m.a.s.l.). Deadwood samples have been taken and later analysed in the laboratory.

Attachment 6: Presentation of forest living lab and marteloscope "Prelenfrey, France"

INRAE, LESSEM
Benoit Courbaud, researcher
Frédéric Berger, researcher

National Forest Office
Emmanuel Dupont,
Forestry technicien, Vercors foothills,
Grenoble territorial Unit

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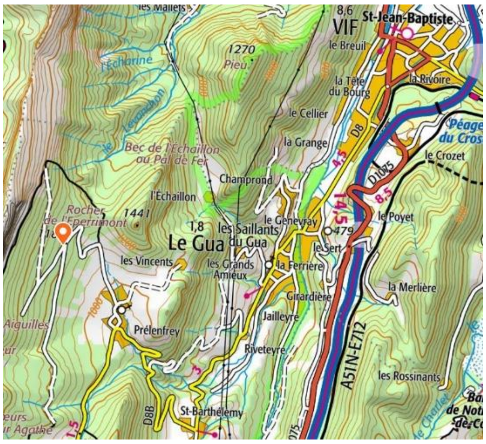


Name of FLL: PRELENFREY

Country, Region: France, Auvergne-Rhône-Alpes

Coordinates:

Longitude : 5.600168 decimal degrees

Latitude : 45.024968 decimal degrees

Main risks: Rock falls, Avalanches

Characteristics of this area:

The village of Prélenfrey lies on the slopes overlooking the Drac valley, 20 kilometers South of Grenoble, at an altitude of 978m, and is dominated by the crests of the Vercors massif (2147 m). Above the village is a forest on an average slope of 40°, followed by a 600m-high vertical cliff. Rocks are frequently falling from the cliff and snowpacks falling from the crests can occasionally create small avalanches, giving the forest and important role of protection against natural hazards.

Needs and problems to be adressed:
The forest is quite mature and composed of a canopy of large dominant European fir trees and an understorey composed of smaller beech and other broadleaved trees. Small regeneration is present but the recruitment flow is only a few trees per year and per ha crossing the size threshold of 17.5 cm of diameter at breast height. The challenge is to stimulate the renewal of the stand without decreasing the protection capacity of the forest. The large fir trees have also a real economic value, and a compromise must be found between the economic objective and the protection objective of the forest.

Goal of FLL:
Demonstrate the use of the EFI I+Trainer and the Samsara marteloscope simulation package.
Train forest managers and forestry students to continuous cover forestry and protection forestry
Illustrate protection forest issues and management with elected representatives of the Grenoble community of municipalities

Case studies, research, test sites:

Name of the Marteloscope(s): Prelenfrey

Background and description of the problem

The management of forests with a protection role against natural hazards requires a specific expertise that is best developed by the analysis of real case studies. The protection role imposes huge constraints and often requires to make compromises between the objectives of protection, production and nature conservation. These two issues will be addressed efficiently with the living lab approach by visits on the field, practical trainings, discussions with forestry instructors and among participants on real case studies.

Introduction of the area

The village of Prélenfrey lies on the slopes overlooking the Drac valley, 20 kilometers South of Grenoble, at an altitude of 978m, and is dominated by the crests of the Vercors massif (2147 m). Above the village is a forest on an average slope of 40°, followed by a 600m-high vertical cliff. Rocks are frequently falling from the cliff and snowpacks falling from the crests can occasionally create small avalanches, giving the forest and important role of protection against natural hazards.

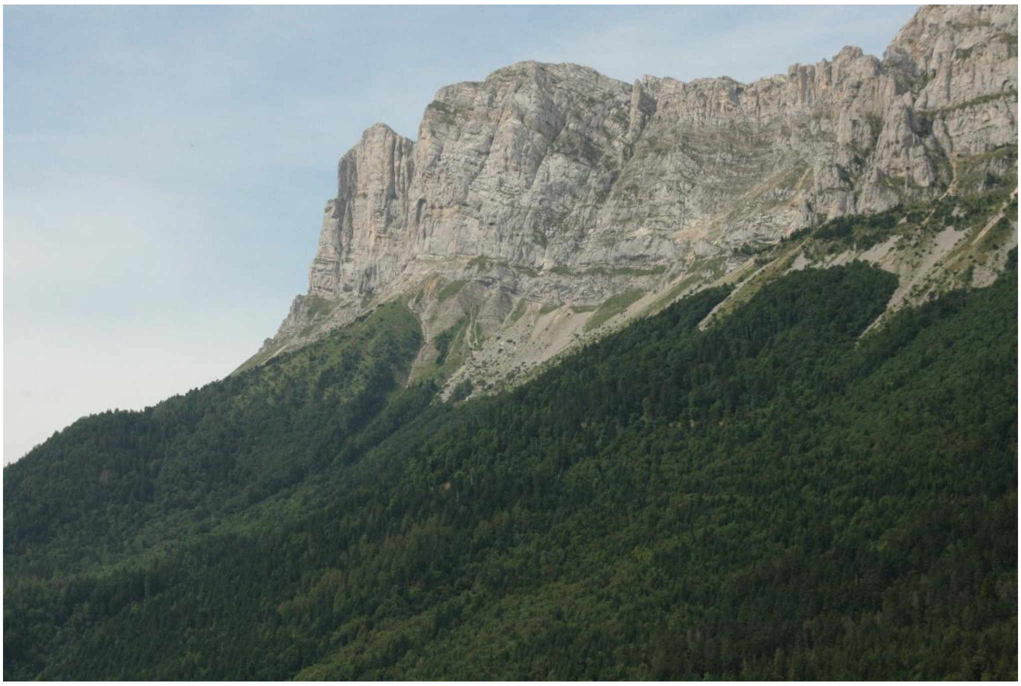
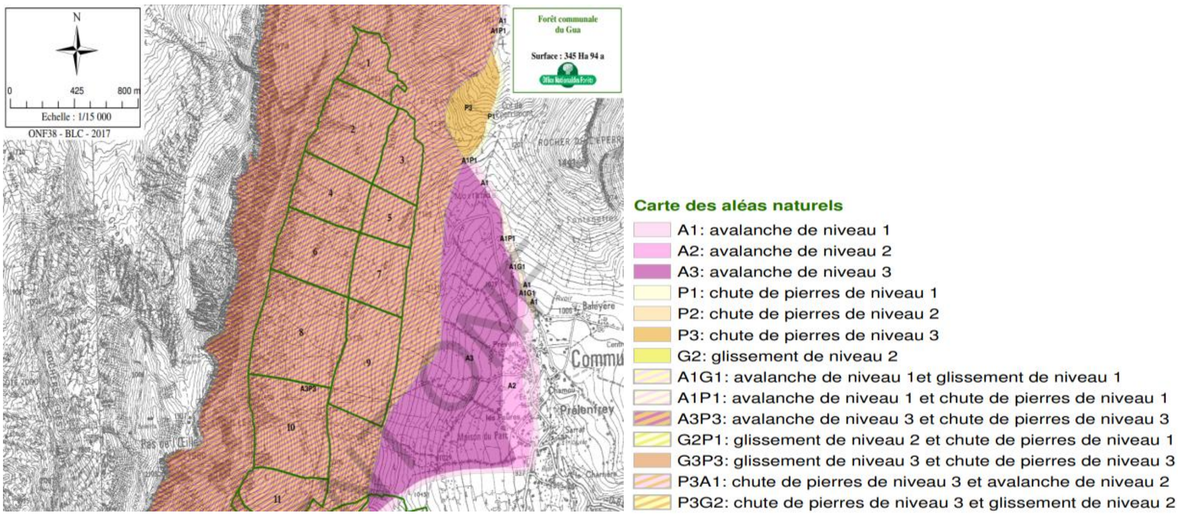


Figure1: The forest, dominated by the cliffs of Vercors just above the pastures and the village

Current management with protective forests

The forest is identified with a high protection role against rock falls and avalanches in the forest management plan. A continuous cover management of low intensity is practiced with the harvest of large trees every 15 years. There are no specific protective measures apart the cautious forest management.



Extract of the forest management plan of the commune forest of Le Gua : the forest is identified as susceptible of rock falls of level 3 and avalanches of level 3. (Aménagement de la forêt communale du Gua, Le Corre. Office National des Forêts, 2018).

The forest is quite mature and composed of a canopy of large dominant European fir trees and an understorey composed of smaller beech and other broadleaved trees. Small regeneration is present but the recruitment flow is only a few trees per year and per ha crossing the size threshold of 17.5 cm of diameter at breast height. The challenge is to stimulate the renewal of the stand without decreasing the protection capacity of the forest. The large fir trees have also a real economic value, and a compromise must be found between the economic objective and the protection objective of the forest.

Method

The goals of the Prelenfrey living lab are

- To demonstrate the use of two marteloscope innovative tools: the EFI I+Trainer and the Samsara marteloscope simulation package.
- To Train forest managers and forestry students to continuous cover forestry and protection forestry
- To Illustrate protection forest issues and management with elected representatives of the Grenoble community of municipalities.

The area and marteloscope location have been chosen in collaboration by INRAE and the Forest Office. Henri Moulin, in charge of silviculture at the Grenoble Terrestrial Unit of the Forest Office initially selected several areas around Grenoble, with forests combining a role of protection against natural hazards, a distance of less than one hour driving from the city of Grenoble, a spruce-fir-beech species composition (species well parameterized in the model Samsara), and cooperative municipalities. Based on the forest management plans of these areas, Lilou Thill, intern at INRAE selected four different forests with a protection role, mature stands where thinning interventions were planned, and easy access by car for groups of trainees. INRAE visited the four forests and selected the forest of Prelenfrey. INRAE and Emmanuel Dupont, the local forest technician validated the site and decided the precise location of the marteloscope. The marteloscope was implemented on the field during a student project by four students of the AgroParisTech forest engineer school under the supervision of INRAE.

For the trainings, we will use a combination of tools: the European Forest Institute I+Trainer to select trees on the field and the Samsara marteloscope package to simulate the evolution of the stand structure and the ecosystem services over 50 years.

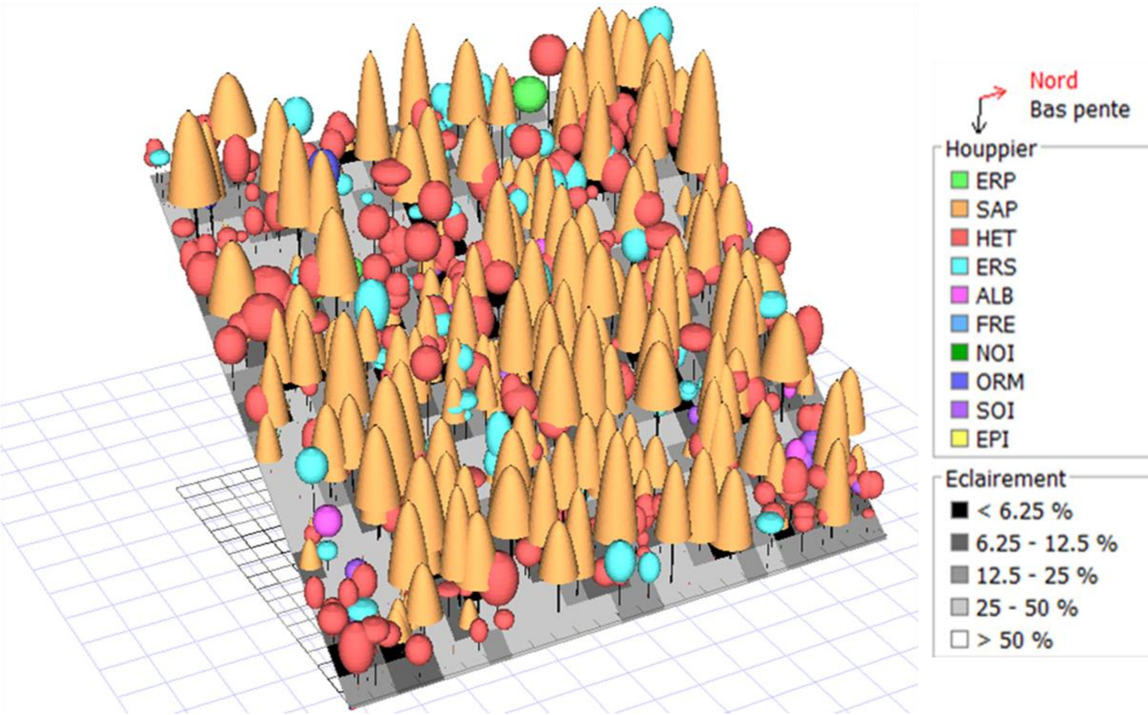


Figure2: View of the marteloscope of Prelenfrey in the simulation software Samsara

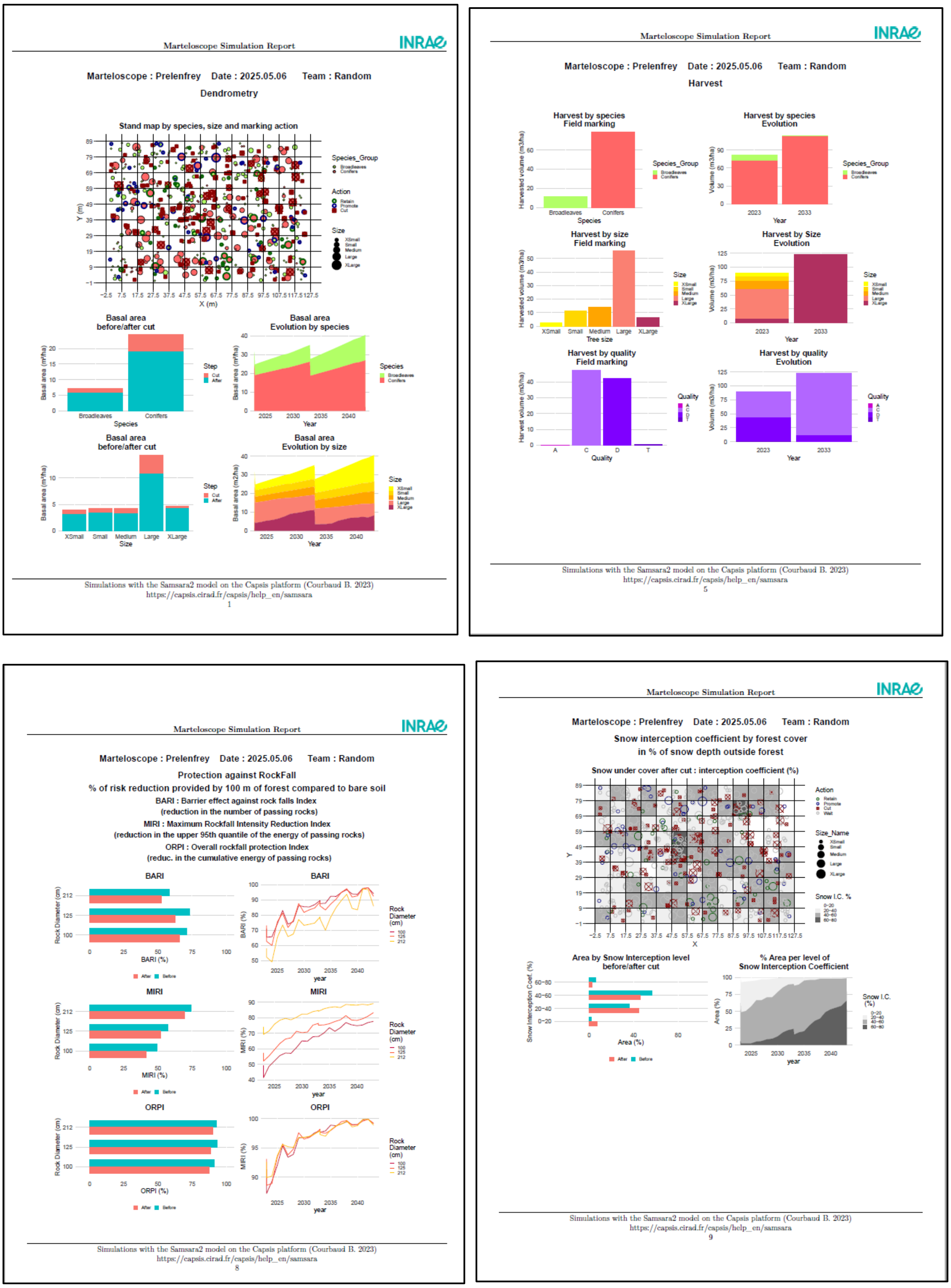


Figure 3: Four examples pages of the report of a Samsara simulation after the thinning corresponding to the field marking and over 20 years : changes in stand structure, harvests, changes in the protection against rockfalls indicator, changes in the snow interception indicator.

Stakeholder involvment and knowledge transfer

Stakeholders who will be included in the FLL will be :

- Researchers and instructors: Researchers, professors in forestry schools and marteloscope trainers interested by the development of innovative forestry training tools (at a French and international level).
- Forest managers: Forest managers of the public forests of the Grenoble area (National Forest Office), advisers for private forest owners (National Center for Private Forest), private forest experts, and forestry students.
- Stakeholders: Elected representatives of the Grenoble community of municipalities, nature conservation associations, people involved in the terrestrial development of the Grenoble area.

Knowledge transfer will be provided by one day long training and discussion sessions on the field, adapted to the different groups of stakeholders. A training session will be composed of (1) a presentation of the issues of the protection role of the forest from natural hazards and the specificities of the site of Prelenfrey, (2) a virtual marking of trees on the field by the participants (3) a presentation of the results of a simulation of the different marking strategies over 50 years (4) a discussion about forest management solutions and regional planning issues.

Agenda:

- A first workshop has been conducted the 4th November 2024 to demonstrate the simulation tools to MOSAIC partners. 19 people have participated (2 from BFW, Austria; 2 from University Padova, Italy; 2 from University Torino, Italy, and 3 from The Slovenia Forest service, Slovenia; 10 from INRAE, France).
- A Second workshop will be conducted the 11 June 2025 to demonstrate the pedagogical approach to forestry school professors. 12 people will participate (2 from AgroParisTech Nancy, 1 from AgroParisTech Montpellier, 3 from BordeauxSupAgro, 1 from University Toulouse, 2 from University Montpellier, 3 from INRAE Grenoble).
- A third workshop is planned at the fall 2025 for the forest mangers of the National Forest Office, the National center for private Forest and the municipality of Prelenfrey.
- Other workshops will be organized as soon as the simulation tools will be more operaitional and we can transfer the approach to forest instructors.

Attachment 7: Presentation of forest living lab »Davos, Switzerland«

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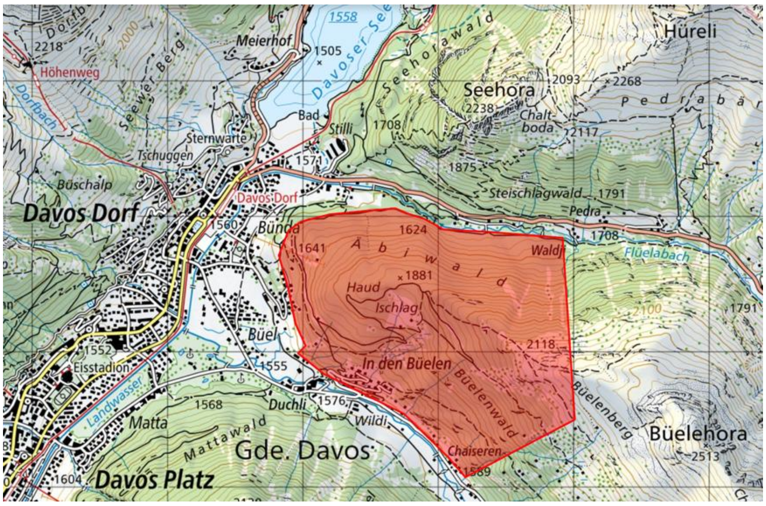

Fig. 1. Location of the Forest Living Lab 'Davos' near Davos Dorf in Switzerland. Background map data © swisstopo 2025.

Name of FLL and of the Marteloscope: *Davos* (FLL) and *Dischma* (Marteloscope)

Country, Region: Switzerland, Canton of the Grisons, Davos

Coordinates: 46.8044540, 9.8585037 (FLL) and 46.7707624, 9.8769676 (Marteloscope)

Main risks: Snow avalanches, bark beetle outbreaks

Characteristics of this area: It was a pasture until the early 20th century; mixed property (private, municipality of Davos); forest management mainly using cable roads (strip cuts) and thinning; where the forest has no protective effect it is used for wood production.

Needs and problems to be Addressed: Browsing (red zone - also Norway spruce has problems regenerating); adaptation (spruce-dominated but wish to introduce climate-adapted species); increasing bark beetle damage.

Goal of FLL: To improve stand resilience against climate change impacts and compound disturbances, thereby enhancing protective effects; use it for research, training, raising awareness and knowledge dissemination about

Background and description of the problem

Mountain forests in the Central Alps play a crucial role in protecting settlements, infrastructure, and human activities from natural hazards such as avalanches, rockfall, and shallow landslides. In Switzerland, a large share of forests fulfils a direct or indirect protective function, and their stability is of high societal importance. In the Davos region (canton of the Grisons), protective forests are particularly relevant due to steep terrain, high elevation, and intensive recreational use.

However, protective forests in this region are increasingly exposed to multiple and interacting stressors. Climate change is altering temperature and precipitation regimes, affecting tree species suitability and disturbance dynamics. Norway spruce–dominated stands, which are widespread in the area, show growing vulnerability to bark beetle outbreaks, drought stress, and storm damage. At the same time, browsing pressure by ungulates significantly constrains natural regeneration, even for traditionally resilient species.

In addition to ongoing biotic disturbances, the Davos landscape also bears the legacy of past land use and historical disturbances. Many forest areas were used as pasture until the early 20th century, shaping current stand structures and species composition. Furthermore, a high-severity forest fire in 1952 affected parts of the south-eastern area of the Forest Living Lab (FLL, Fig. 2), resulting in extremely slow post-fire regeneration that remains incomplete more than 70 years later. This long-term recovery trajectory highlights the limits of natural regeneration under harsh subalpine conditions and raises critical questions about future forest resilience and protective function.

Against this background, there is a clear need for long-term, practice-oriented learning environments where forest dynamics, disturbance interactions, and management options can be jointly explored by researchers, practitioners, authorities, and other stakeholders. The Forest Living Lab *Davos* addresses this need by providing a real-life setting for research, training, and knowledge exchange on the development and management of protective forests under changing environmental conditions.

Fig. 2. *Location of the forest fire from 1952 within the FFL 'Davos'. Historical photos from before (left, 1945) and after (right, 1955) the fire.*

Introduction of the area

The Forest Living Lab *Davos* is located in and around Davos Dorf, municipality of Davos, in the canton of the Grisons, Switzerland. The area lies in the Central Alps and spans subalpine elevations, typically ranging from approximately 1,700 to over 2,100 m a.s.l. The terrain is steep and topographically complex, creating a high exposure to gravitational natural hazards.

Forest cover in the municipality of Davos amounts to roughly 25% of the total area and is dominated by Norway spruce (*Picea abies*), with significant shares of European larch (*Larix decidua*) and Swiss stone pine (*Pinus cembra*) at higher elevations. A substantial proportion of these forests is officially classified as protective forest, often with a high or very high protection priority. Forest ownership is mixed, comprising municipal, other public, and private forest owners, which adds complexity to management and governance.

The forests of the FLL area fulfil multiple functions. While protection against avalanches and rockfall is the primary function in many stands, forests are also used for timber production where protective effects are limited, as well as for recreation, tourism, biodiversity conservation, hunting, and carbon storage. The area is intensively used by the public year-round, which further increases the importance of maintaining stable and resilient forest structures.

A defining feature of the FLL area is the presence of contrasting forest development trajectories (Fig. 3): from long-established subalpine stands influenced by avalanche and rockfall dynamics, to areas affected by historical fire disturbance, where forest recovery has been exceptionally slow. This diversity of conditions makes the area particularly suitable as a Forest Living Lab.

Fig. 3. *Examples of dense Norway spruce forest with little to no regeneration (left); regeneration following windthrow disturbance (middle); view from the top of the forest fire (right). Photos: A. Bottero.*

Current management with protective forests

Protective forest management in the Davos region follows the principle of maintaining or restoring forest structures that provide long-term protection with minimal technical interventions. Management is strongly guided by cantonal and federal policy frameworks, which provide co-financing mechanisms for protective forest measures, including regeneration support, planting, and early interventions.

In protective forests, management objectives clearly outweigh timber production goals. Interventions focus on:

- maintaining continuous forest cover,
- promoting structurally diverse and stable stands,
- ensuring sufficient regeneration of suitable tree species,
- and reducing vulnerability to disturbances.

Where forests do not fulfil a protective function, management may prioritise wood production, depending on accessibility and ownership objectives. Due to steep terrain, harvesting is often conducted using cable crane systems, typically through strip cuts and targeted thinning.

A major management challenge across the FLL is high browsing pressure (Fig. 4), which severely limits regeneration success. This constraint applies not only to broadleaved species but increasingly also to Norway spruce and other conifers. Climate change adaptation is therefore closely linked to wildlife management, hunting regimes, and regeneration protection measures.

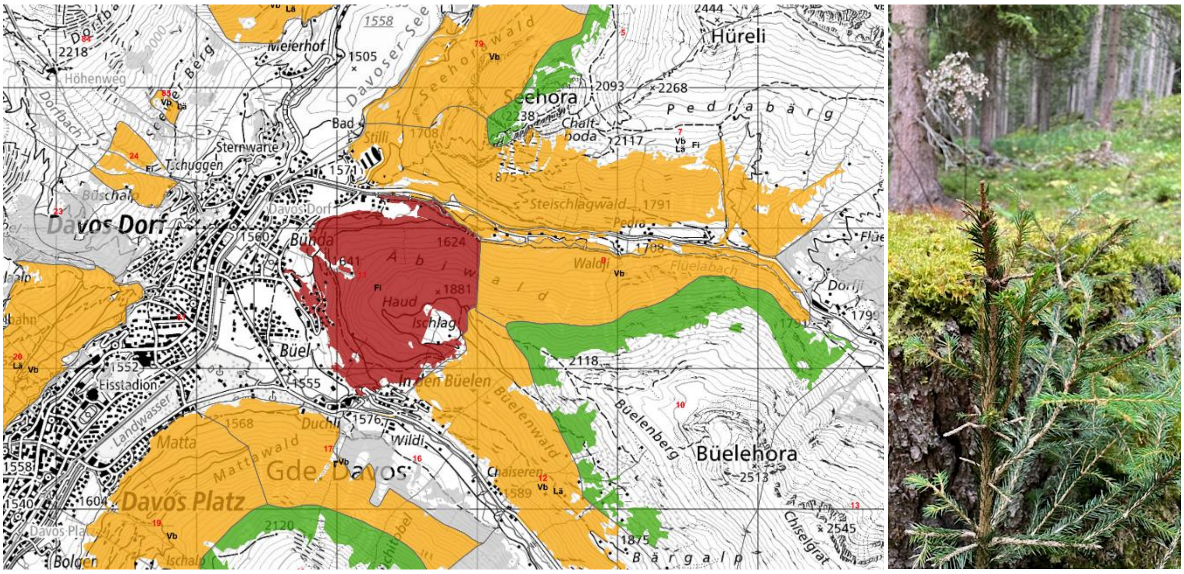

Fig. 4. *Assessment of wildlife impact (left): green = low, orange = significant, red = very high, grey = not assessed. Map from geo.gr.ch. Example of browsed Norway spruce regeneration (right). Photo: A. Bottero.*

Living lab concept and objectives

The Forest Living Lab *Davos* functions as a real-life experimentation and learning platform that brings together research, practice, policy, and education. Its overarching goal is to improve understanding and management of protective forests under compound disturbance regimes and changing climatic conditions.

Key objectives of the FLL include:

- investigating long-term forest dynamics under avalanches, rockfall, bark beetle outbreaks, and historical fire disturbance (Fig. 5),
- analysing regeneration processes and limitations in subalpine protective forests,
- supporting the development and testing of management strategies for climate adaptation (Fig. 6),
- providing training and demonstration opportunities for forest practitioners and students,
- and facilitating knowledge exchange between science, policy, and practice.

The FLL follows core living lab principles such as multi-stakeholder participation, active user involvement, co-creation of knowledge, and operation in a real-life setting.

Fig. 5. *Bark beetle disturbed stand (left), example of burned tree inside the forest fire perimeter (right). Photos: A. Bottero.*

Fig. 6. *Sheep wool to protect planted silver fir (Abies alba) regeneration from browsing (left), planted climate-adapted broadleaf species in a fence following management intervention (right). Photos: A. Bottero.*

Case studies, research, test and demonstration sites for FLL Davos

Marteloscope Dischma – demonstration and training site

A central element of the Forest Living Lab *Davos* is the *Dischma* Marteloscope, established in 2015 by WSL and SLF in the Dischma Valley near Davos (Fig. 7).

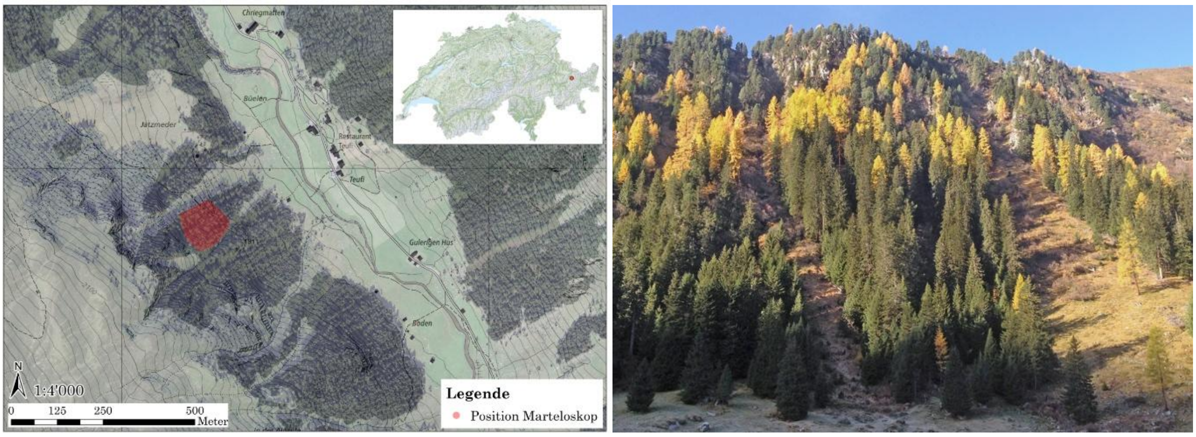

Fig. 7. *Location of the marteloscope plot in the Dischma Valley (left) and view of the area (right). The marteloscope area is bounded by forest clearings on both sides. (Orthophoto and map: © Federal Office of Topography swisstopo). Map and photo: G. Könz 2018.*

The marteloscope is located on a steep, north-eastern exposed slope at subalpine elevation and is influenced by avalanche paths and regular rockfall activity. All trees above a defined diameter threshold (min. DBH class: 10 cm) are mapped and characterised with respect to species, dimensions, habitat value, and economic parameters (Fig. 8). The plot is fully integrated into the I+ marteloscope software, enabling virtual tree marking, scenario analysis, and training exercises (http://iplus.efi.int/marteloscopes-data.html).

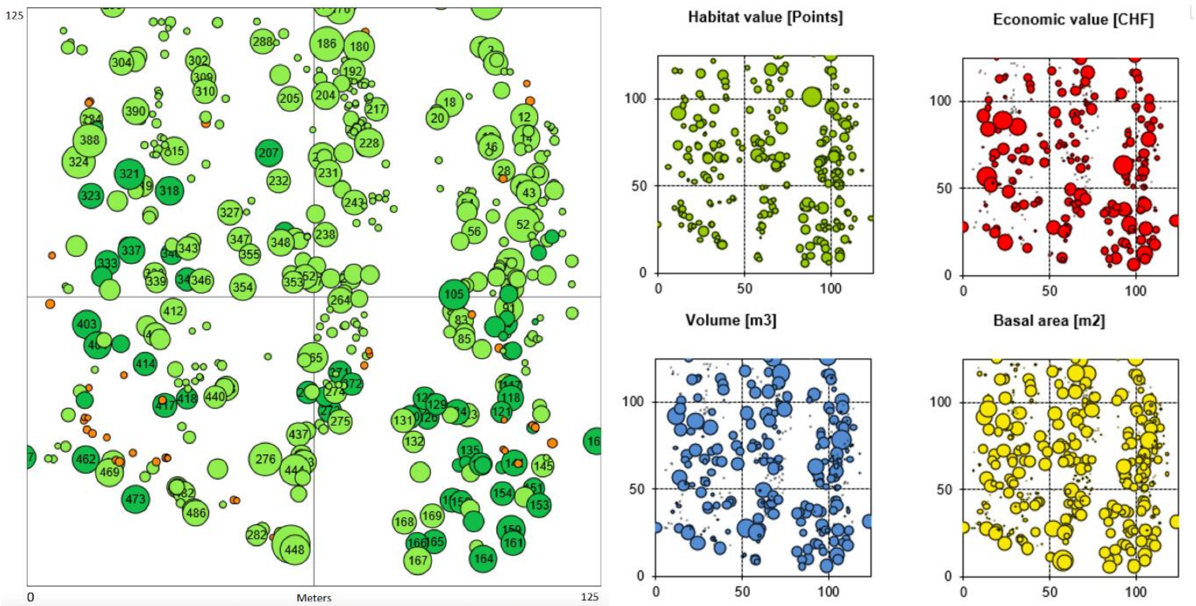

Fig. 8. *Map of the Marteloscope 'Dischma' (1.5 ha, left) and related thematic maps (right).*

The *Dischma* marteloscope (Fig. 9) has been used extensively for:

- university teaching and field courses,
- professional training of forest practitioners,
- applied research on regeneration, stand dynamics, and disturbance history,
- and simulation studies combining field data with avalanche and rockfall models.

Several academic theses and research projects have been conducted on this site, including detailed studies on regeneration dynamics, dendrochronological reconstruction of disturbance history, and the interaction between forest structure and natural hazards. This long-term and multi-method use makes the marteloscope *Dischma* a cornerstone of the FLL *Davos*.

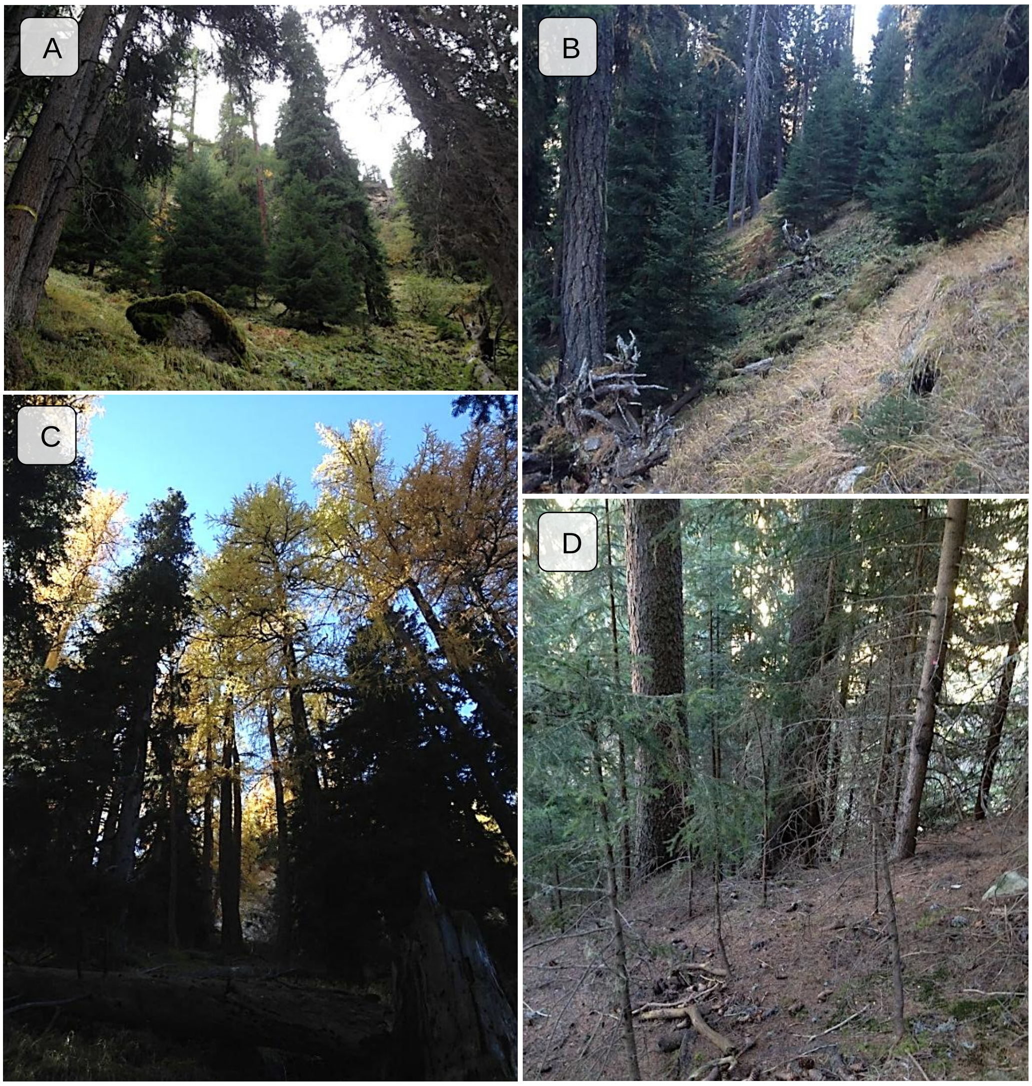

Fig. 9. *Impressions from the marteloscope 'Dischma'. (A) tall-forb–rich forest area; (B) Calamagrostis villosa–dominated forest area; (C) larch-dominated forest area; (D) dense forest area. Photos: G. Könz 2017.*

Long-term fire legacy and post-fire regeneration research

An additional key component of the Forest Living Lab *Davos* is the area affected by a high-severity forest fire in 1952 at Büelenberg, located in the south-eastern part of the FLL (Fig. 10). This site represents a rare opportunity to study very long-term post-fire regeneration in subalpine protective forests.

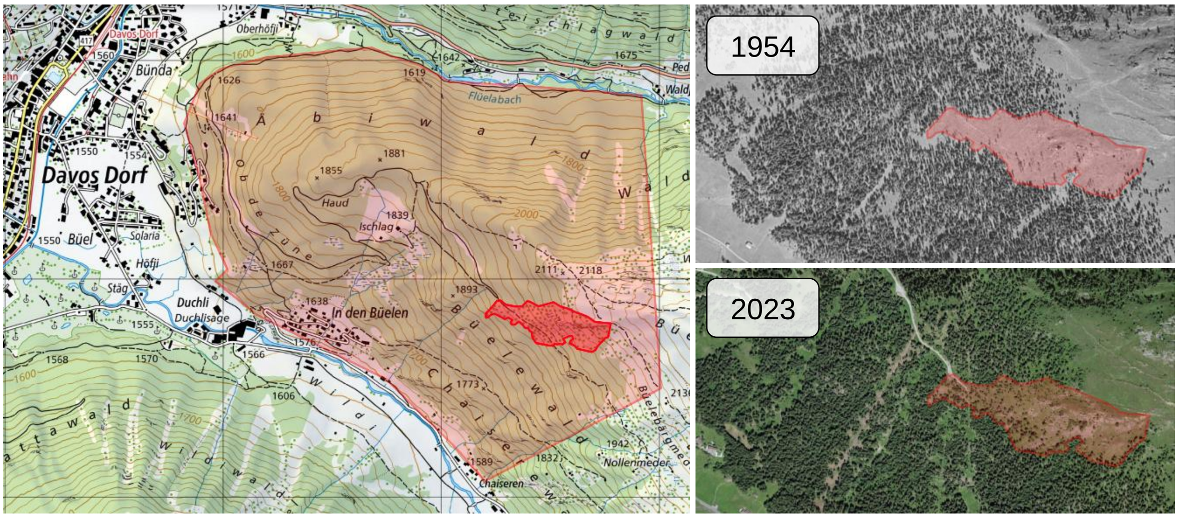

Fig. 10. *Location of the forest fire within the FLL Davos (left); 1954 orthophoto of the forest fire area (top-right); current orthophoto of the forest fire area (bottom-right). Background map data © swisstopo 2025.*

Recent field studies conducted more than 70 years after the fire show that forest recovery has been extremely slow and highly variable (*unpublished data*). Basal area and regeneration density within the fire perimeter remain far below those of neighbouring unaffected forests. Regeneration patterns are strongly influenced by elevation, slope, exposure, distance to seed sources, browsing pressure, and the presence or absence of sheltering trees.

European larch has proven to be particularly resilient, dominating both surviving trees and regeneration, while Norway spruce shows lower post-fire recovery (Fig. 11). These findings underline the importance of species selection, disturbance legacies, and post-disturbance management decisions for long-term forest development and protective function.

Within the FLL framework, the fire site serves as a research and demonstration area to discuss post-fire management options, regeneration limitations, and the implications of increasing fire risk under climate change.

Fig. 11. *Swiss stone pine that survived the fire in 1952 (left); dead tree from the fires (middle); sparse regeneration within the fire perimeter (right). Photos: A. Bottero.*

Bark beetle dynamics and early detection: the earlyBEETLE project

Another important research pillar within the Forest Living Lab *Davos* is the earlyBEETLE project, which addresses the increasing pressure of European spruce bark beetle (*Ips typographus* L.) in mountain spruce forests of the canton of the Grisons. Over recent decades, warmer and drier conditions have substantially increased the frequency and intensity of bark beetle outbreaks across the Alps, posing a serious threat to Norway spruce–dominated forests and their capacity to deliver protective and other ecosystem functions.

Given the dominance of Norway spruce in large parts of the Davos region, bark beetle infestations represent a critical challenge for protective forest management (Fig. 12). Tree mortality caused by bark beetles can reduce forest stability, disrupt stand structure, and compromise protection against natural hazards such as avalanches and rockfall. In this context, the early detection of vulnerable and newly infested trees is a key element for effective, timely, and targeted management interventions.

Fig. 12. *Bark beetle-killed trees in the FFL Davos. Photos: A. Bottero.*

The earlyBEETLE project builds on and complements existing research activities at WSL by improving methods for early detection, monitoring, and interpretation of bark beetle damage in the mountainous landscapes of the canton of the Grisons. Study plots located within the Forest Living Lab *Davos* contribute empirical data to the project and allow the testing and validation of methods.

The project is structured around four interlinked modules (Fig. 13). First, retrospective analyses combine satellite data, forest structure information, and tree-ring analyses to reconstruct past bark beetle infestations and identify factors influencing infestation dynamics. Second, a remote sensing module evaluates different approaches and spectral indices for the early detection of bark beetle damage in mountain spruce forests, with a particular focus on complex terrain and heterogeneous stand structures. Third, the project develops a dedicated bark beetle database, providing a systematic basis for long-term monitoring and spatial analyses of infestation patterns. Finally, a context-dependent management module integrates information from earlyBEETLE with other datasets to support prioritisation of management measures and efficient allocation of resources in mountain and protective forests.

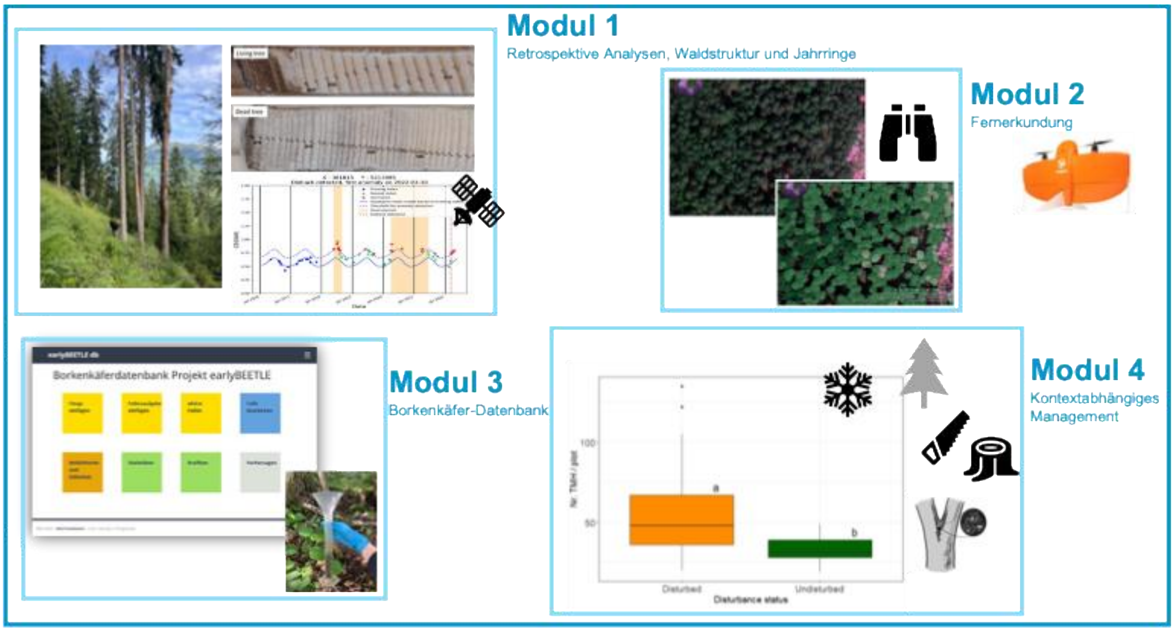

Fig. 13. Structure of the four modules part of the earlyBEETLE project. Photos: A. Bottero.

Through this integrated approach, earlyBEETLE aims to deliver a practical decision-support framework for forest and natural hazard authorities, enabling earlier intervention and more targeted responses to bark beetle disturbances. The project is financed and supported by the Office for Forest and Natural Hazards (AWN) and is closely aligned with the needs of practitioners and policymakers.

Within the Forest Living Lab *Davos*, earlyBEETLE exemplifies how applied research, monitoring technologies, and management-oriented outputs can be combined in a real-life setting. Together with long-term disturbance studies and marteloscope-based training, the project contributes to a comprehensive understanding of disturbance-driven forest dynamics and supports adaptive management of protective forests under climate change.

Stakeholder involvement and knowledge transfer

The Forest Living Lab *Davos* is embedded in a broad and well-defined stakeholder network, reflecting a quadruple helix model:

- Research and education: WSL/SLF, universities, students, and researchers using the FLL for teaching, theses, and applied research.
- Forest management and ownership: Municipality of Davos, private forest owners, local foresters, and forest enterprises responsible for daily management.
- Public authorities and policy: Cantonal and federal authorities responsible for protective forest policy, natural hazard management, wildlife regulation, and funding mechanisms.

- Users and society: Forest practitioners, hunting and wildlife managers, trainees, and the general public using the area for recreation.

Knowledge transfer is realised through field courses, professional trainings, workshops, guided site visits, and the use of digital tools such as the I+ software (Fig. 14). The FLL thus acts as an orchestrator, connecting stakeholders and ensuring that scientific insights are translated into practical and policy-relevant knowledge.

Fig. 14. *Examples of knowledge transfer events in the FLL Davos: with University students (left), with local foresters (right). Photos: A. Bottero (left) and T. Banzer (right).*

Key elements of living labs:

To check if all key elements are me

Multi stakeholder participation	***Co-creation***	***Active user involvement***	***Real life setting***	***Multimethod approach***	***Orchestration***
involving stakeholders from the quadruple helix model (government, academia, private sector, and citizens) PPPP: science, policy, practice, citizens	co-created not only for but also by all relevant stakeholders How to include them in the process?	a living lab involves relevant stakeholders 'actively' in all relevant activities, ensuring their feedback is captured and implemented throughout the whole lifecycle of the innovation	a living lab operates in the real-life setting of the end users, infusing innovations into their real life instead of moving the users to test sites to explore the innovations	Problem driven activities – searching for solutions with various methods	the living lab operates as the orchestrator within the ecosystem to connect and partner up with relevant stakeholders
• *WSL Institute for Snow and Avalanche Research SLF* • *Climate Change, Extremes and Natural Hazards in Alpine Regions Research Centre CERC* • *ETH Zurich* • *Municipality of Davos* • *Forest service of Davos* • *Local private forest owners* • *AWN GR* • *The public*	*The listed stakeholders regularly meet and exchange within the FLL.*	• *Scientists* • *Forestry professionals* • *Students from different universities* • *The public*	*Yes, see description.*	• *Field data* • *Pheromone traps & monitoring* • *Remote sensing with drone and satellite data* • *Modeling case studies* • *Research sites and forest plots with different foci* • *Marteloscope*	*The stakeholders listed previously are involved and connected.*

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