Chapter

Risk-Based Decision Support for Protective Forest and Natural Hazard Management

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Abstract

Protective forests are an effective Forest-based Solution (FbS) for Ecosystem-based Disaster Risk Reduction (Eco-DRR) and are part of an integrated risk management (IRM) of natural hazards. However, their utilization requires addressing conflicting interests as well as considering relevant spatial and temporal scales. Decision support systems (DSS) can improve the quality of such complex decision-making processes regarding the most suitable and accepted combinations of risk mitigation measures. We introduce four easy-to-apply DSS to foster an ecosystem-based and integrated management of natural hazard risks as well as to increase the acceptance of protective forests as FbS for Eco-DRR: (1) the Flow-Py simulation tool for gravitational mass flows that can be used to model forests with protective functions and to estimate their potential for reducing natural hazards' energy, (2) an exposure assessment model chain for quantifying forests' relevance for reducing natural hazard risks, (3) the Rapid Risk management Appraisal (RRA), a participatory method aiming to identify IRM strengths and points for improvement, and (4) the Protective Forest Assessment Tool (FAT), an online DSS for comparing different mitigation measures. These are only a few examples covering various aims and spatial and temporal scales. Science and practice need to collaborate to provide applied DSS for an IRM of natural hazards.

Keywords: natural hazard risk, decision support tools and systems, protective forest, integrated risk management, exposure assessment

1. Introduction

The variety of available natural hazard risk mitigation measures, such as land use planning, technical measures, biological measures, and organizational directives [1], necessitates decision-making in integrated risk management (IRM) processes to recognize and incorporate social, economic, and ecological sustainability criteria as well as conflicting interests and constraints (see chapter [2] of this book). Protective forests as an effective Forest-based Solution (FbS) for Disaster Risk Reduction (DRR) must have a key role within the portfolio of IRM measures (see chapter [3] of this book). However, managing protective forests and natural hazard risks requires including different spatial and temporal dimensions such as slope and regional scales

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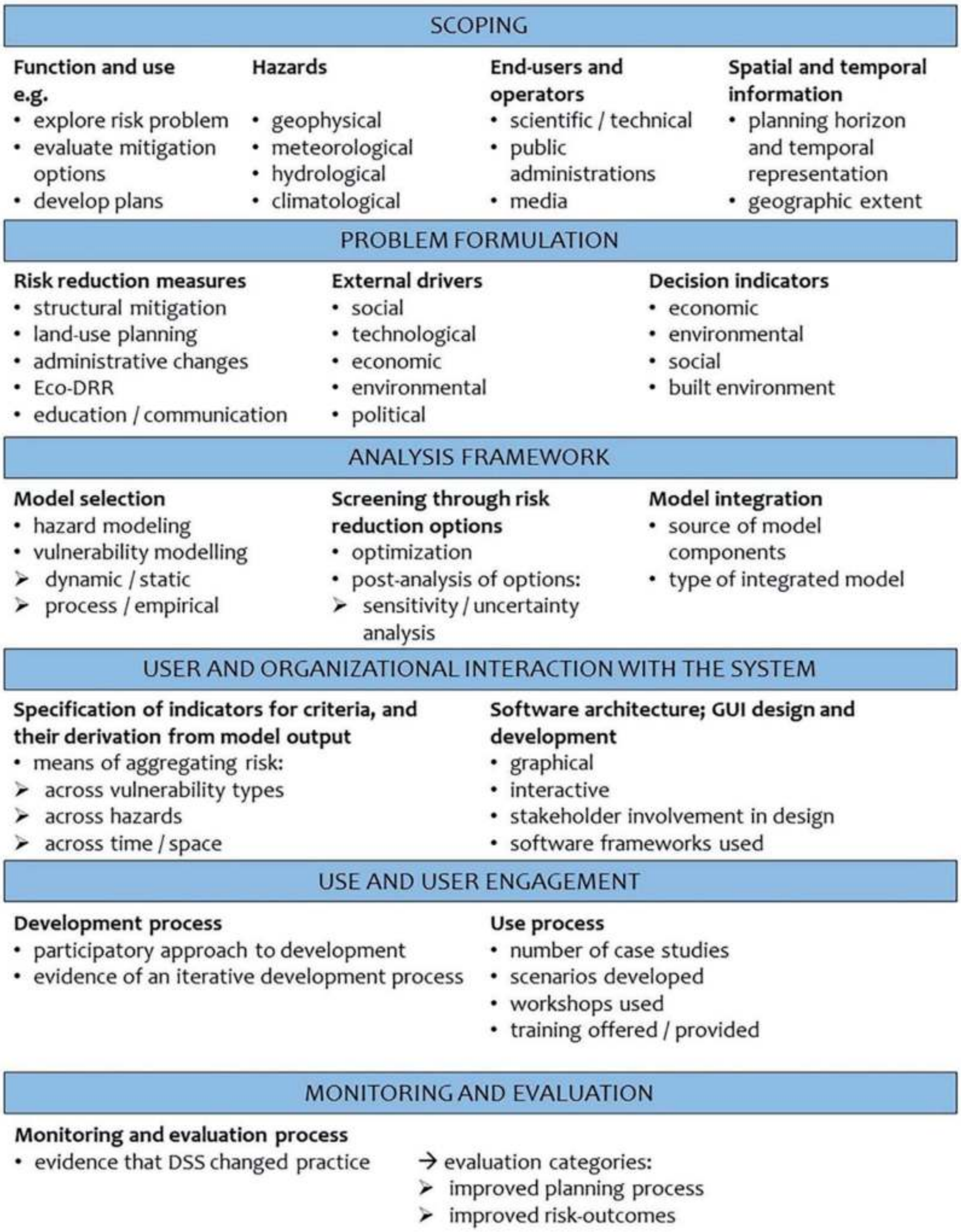
as well as short- and long-term changes in land use in the decision-making process to implement the most suitable combinations of risk mitigation measures.

Decision support tools and systems (DSS) are computer-based tools and/or techniques and methods that were developed to improve the quality of decision-making on complex issues. DSS are often applied in participatory processes by integrating decision-makers own insights with the information processing capabilities of computers [4]; however, they do not automate decisions by simply finding optimal solutions. The final decision is still left to the decision-maker [5]. For a DSS to be effective, it must present aspects of a complex system as well as the effects of changing the system in a user-friendly interface. Examples of well-established DSS are simulation models, expert opinions, and decision flowcharts. DSS are therefore also one of the most common ways to transfer knowledge from science into practice as a vehicle for communication, training, and experimentation [6]. They are often integrated within web platforms or GIS (geographic information systems), facilitating a dialogue and the exchange of information, and thus providing insights to decision-makers, which can support them in exploring, for example, potential outcomes of different policy options. Numerous DSS have been developed for forest management over the past 40 years [7, 8]. More recently, DSS have also been introduced in natural hazard risk management with the goal to communicate hazard and risk modeling results to the public, supported by improved visuals and graphical user interfaces (GUI) [6]. For example, Xu et al. [9] developed a geospatial web platform that considers combined risks of multiple water-related hazards using serious gaming techniques to involve a variety of decision-makers and to foster a holistic and collaborative planning process. Like natural hazard models (see chapter [10] of this book), the features and characteristics of risk models vary widely. For example, operating at different scales requires to adopt different approaches for data collection and model complexity as well as influences the representation and precision of the results, which determines the applicability and effectiveness of a tool itself. Based on a literature review, Newman et al. [6] proposed a classification for natural hazard risk reduction DSS based on their components and characteristics such as scoping, problem formulation, analysis framework, user engagement, and evaluation (**Figure 1**).

The application of risk-based approaches that are not only hazard-focused in decision-making processes regarding Ecosystem-based Disaster Risk Reduction (Eco-DRR) is increasing [11]. Risk-based approaches have been developed to estimate the economic value of mountain forests' protective functions and effects by reducing the risk from natural hazards that endanger people and assets, considering all three risk components, hazard, exposure, and vulnerability (see chapter [3] of this book). These studies were conducted at different spatial scales from local [12–15] to regional [16, 17] as well as national evaluations ([18]; see also chapters [19–21] of this book). Other studies integrated Eco-DRR in hazard and risk models into more complex online DSS, for example, Grandjean et al. [22] created a multi-risk tool for identifying management strategies to reduce potential impacts of global change by considering short- and long-term changes in land use, climate change scenarios, and alternative socio-economic development pathways. Bebi et al. [21] highlight how scenario-specific avalanche protective forest maps can be developed by collaborating with avalanche modelers and practitioners, and implemented into an interactive, web-based DSS providing combined information about natural hazards and effective avalanche protective forests. However, for ecosystem-based and integrated natural hazard risk management, few economic evaluation methods and/or DSS are currently available in practice to compare the effectiveness and/or cost-efficiency of protective forests with technical measures. One reason could be that the remaining considerable uncertainties in assessing the protective effects of forests against natural hazards are affecting the confidence in FbS in contrast to technical



SCOPING

Function and use e.g.
- explore risk problem
- evaluate mitigation options
- develop plans

Hazards
- geophysical
- meteorological
- hydrological
- climatological

End-users and operators
- scientific / technical
- public administrations
- media

Spatial and temporal information
- planning horizon and temporal representation
- geographic extent

PROBLEM FORMULATION

Risk reduction measures
- structural mitigation
- land-use planning
- administrative changes
- Eco-DRR
- education / communication

External drivers
- social
- technological
- economic
- environmental
- political

Decision indicators
- economic
- environmental
- social
- built environment

ANALYSIS FRAMEWORK

Model selection
- hazard modeling
- vulnerability modelling
  - ➢ dynamic / static
  - ➢ process / empirical

Screening through risk reduction options
- optimization
- post-analysis of options:
  - ➢ sensitivity / uncertainty analysis

Model integration
- source of model components
- type of integrated model

USER AND ORGANIZATIONAL INTERACTION WITH THE SYSTEM

Specification of indicators for criteria, and their derivation from model output
- means of aggregating risk:
  - ➢ across vulnerability types
  - ➢ across hazards
  - ➢ across time / space

Software architecture; GUI design and development
- graphical
- interactive
- stakeholder involvement in design
- software frameworks used

USE AND USER ENGAGEMENT

Development process
- participatory approach to development
- evidence of an iterative development process

Use process
- number of case studies
- scenarios developed
- workshops used
- training offered / provided

MONITORING AND EVALUATION

Monitoring and evaluation process
- evidence that DSS changed practice

→ evaluation categories:
- ➢ improved planning process
- ➢ improved risk-outcomes

Figure 1.
Classification system for reviewing natural hazard risk-reduction decision support tools and systems (DSS) proposed by and adapted from Newman et al. [6]. The listed examples are not exhaustive; for the complete list see [6].

measures (e.g., [23]; see also chapters [3, 20, 24] of this book.). These uncertainties could be addressed, for example, with Bayesian probability theory and Bayesian Networks [25]. However, there is a lack of openly available and easy-to-use tools to apply Bayesian Networks as a DSS for an IRM in practice, which also includes the essential spatial and temporal dimensions to implement the most suitable combinations of risk mitigation measures [26].

In this and two other chapters of this book [10, 27], we introduce four easy-to-apply DSS that were developed in the frame of the Interreg Alpine Space project GreenRisk4ALPs [28] to support and foster ecosystem-based and integrated

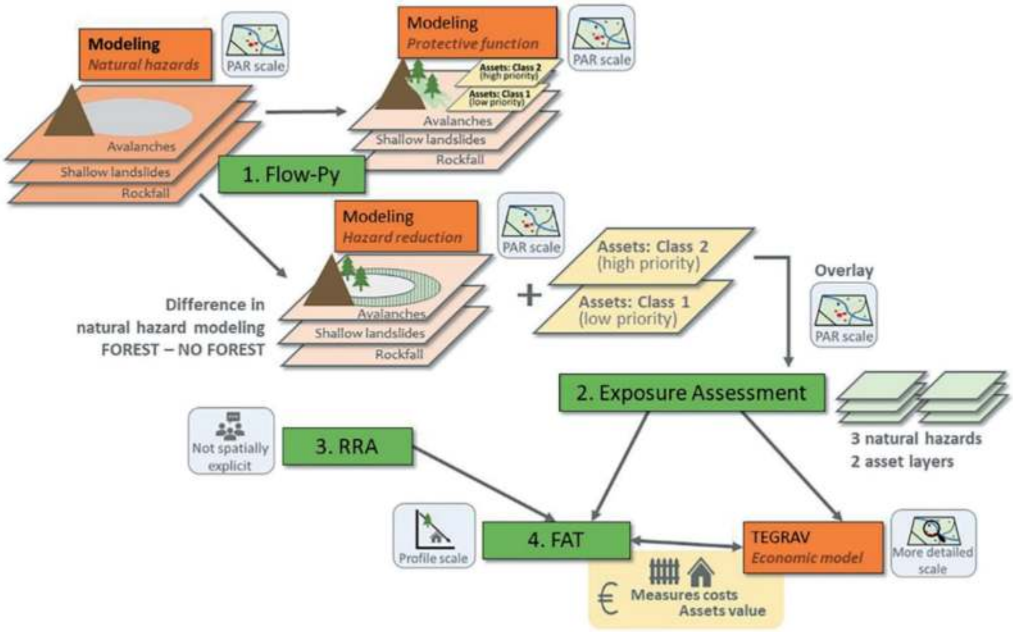


Figure 2.
Overview of the different components and analysis conducted in the GreenRisk4ALPs project for developing decision support tools and systems (DSS) for an integrated risk management (IRM) of natural hazards in the Alpine Space. Green rectangles = DSS, orange rectangles = model chains, yellow rectangles = generated input data. PAR = GreenRisk4ALPs Pilot Action Region [29]. FAT = Protective Forest Assessment Tool; RRA = Rapid Risk management Appraisal (see chapter [27] of this book); TEGRAV = TEchnical—GReen—AVoidance (see subsection 2.3).

management of natural hazard risks as well as to increase the acceptance of FbS for Eco-DRR (**Figure 2**):

1. the Flow-Py simulation tool for gravitational mass flows (GMF; [30, 31]) can be used to model forests with a direct object protective function and to estimate their potential for reducing natural hazards' energy (see also chapter [10] of this book),

2. an exposure assessment model chain to quantify potential forest relevance for reducing natural hazard risk to people and assets,

3. the Rapid Risk management Appraisal (RRA), a participatory tool aiming to identify strengths and points for improvement of IRM, supporting municipalities to increase their resilience to natural disasters (see chapter [27] of this book), and

4. the Protective Forest Assessment Tool (FAT), an open-access online DSS for profile-based comparisons of different mitigation measures to support local risk management strategies.

Considering the differences in DSS for natural hazard risk management (see **Figure 1**), these tools were developed following a complementary approach that allows for robust and comprehensive risk analysis at different scales. They are still addressing rather an expert audience than non-experts or the general public; however, an extended group of stakeholders and policy makers was involved in their development, evaluation, and testing within the GreenRisk4ALPs project.

2. GreenRisk4ALPs' risk-based decision support tools and systems (DSS)

2.1 Flow-Py: regional mapping and modeling of protective forests

Flow-Py is a simulation tool to model runout and intensity of gravitational mass flows (GMFs) based on a runout angle model (also referred to as travel or α-angle [32]) at regional scales [30, 31]. The required input data are a digital elevation model (DEM) and a release raster containing one or several starting cells. Together with two developed custom extensions, post-processing routines, and recommendations for the visualization of simulation results (see chapter [10] of this book), Flow-Py can be used as DSS to support protective forest and risk management-related decisions. To develop an easy-to-apply procedure we asked: Where does the presence of forest reduce the impact of GMFs on elements potentially at risks such as exposed buildings, transport, or recreational infrastructure?

The objectives to answer this question are:

1. to map the forest areas that may reduce the natural hazard risk for people and assets,

2. to model potential GMF runout and intensity reductions due to the presence of forest and to quantify forest effects in reducing risk by assessing the reduced impact each GMF has on different types of assets, and

3. to identify and visualize areas where the risk-reducing effect of forests is greatest within a region.

To test the DSS, five types of protective forest-related map products were developed for the three GMFs snow avalanches, rockfall, and shallow landslides, and applied in five of the six GreenRisk4ALPs Pilot Action Regions (PARs; [29]). The freely available and open-source Flow-Py code allows users to customize GMF simulations by adjusting the parameterization or developing extensions to adapt calculations, input data, and model outputs as well as to apply their own post-processing routines and visualizations based on their specific questions and problems. **Figures 3**–7 show example maps of the PAR "Wipptal South" in South Tyrol, Northern Italy, and the snow avalanche hazard that were created from Flow-Py simulation results, providing relevant information to support decision-making in protective forest and natural hazard management.

The map shown in **Figure 3** was created based on Flow-Py simulations with the "back-tracking" custom extension. This extension changes Flow-Py from a pure runout model to one that can identify terrain associated with endangering assets by storing the path that a GMF traveled to reach an infrastructure in computer memory (see also [33]). To apply the back-tracking extension an input raster including the location of infrastructure in the modeling domain is therefore required. The simulation output is a spatially explicit subset of the GMF release areas, transit, and runout zones that were modeled to endanger infrastructure, which can be united with the spatial distribution of forested areas (for details see chapter [10] of this book). The resulting map highlights the location of forests with a direct object protective function (for definitions see chapter [3] of this book). In other words, it shows those forested areas located between physical assets and a hazard's release area. The map provides information at a regional scale about the approximate geographic extent of protective forests and how they are distributed in the landscape. Similar maps have been produced in Switzerland [34, 35] and Austria [36, 37]; however, such protective forest maps are not available for all Alpine Space countries.

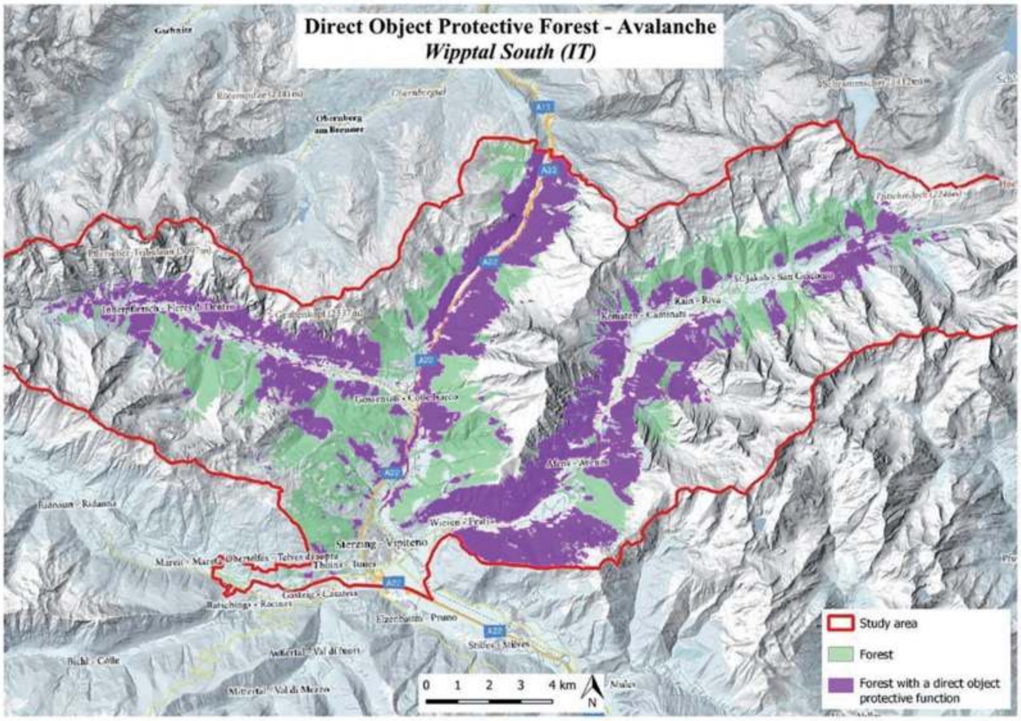


Figure 3.
Example for a direct object protective forest map based on Flow-Py simulations. Purple shaded areas were modeled as forests with a direct object protective function, which can protect people and assets from large and very large dry snow slab avalanches. Green shaded are forested areas that are not considered protective forests against snow avalanches.

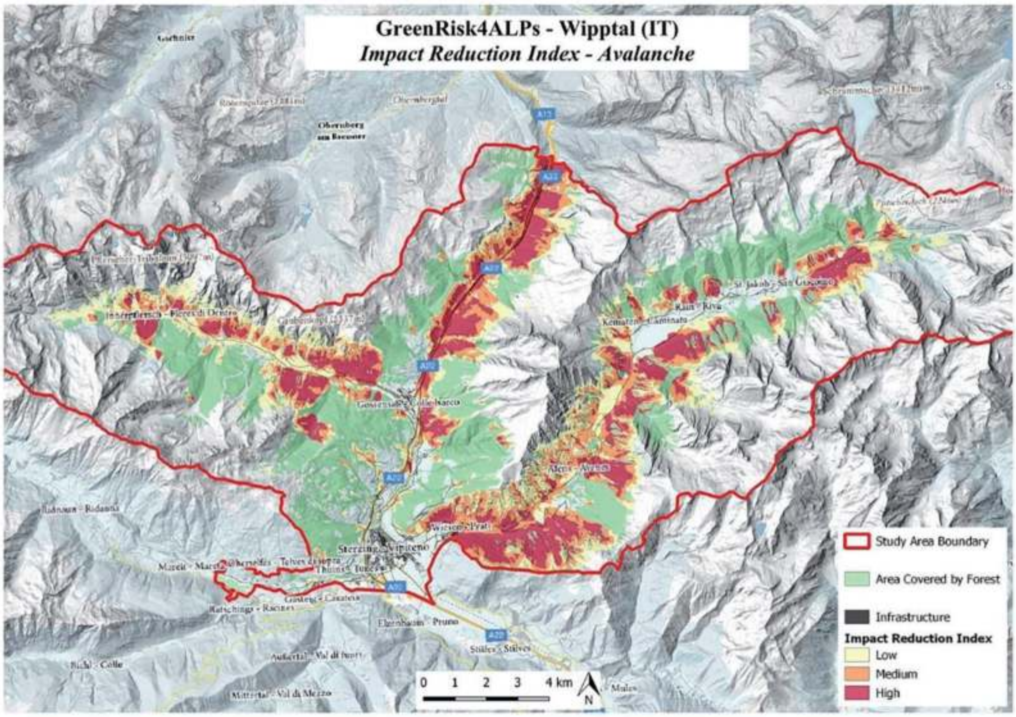


Figure 4.
Example for a map quantifying the magnitude of snow avalanches' kinetic energy potentially reduced by forest based on Flow-Py simulations. Yellow to red colors show the difference in the kinetic energy from simulations with and without the effect of the forest. The Impact Reduction Index (IRI) is only shown for areas where elements are potentially at risk.

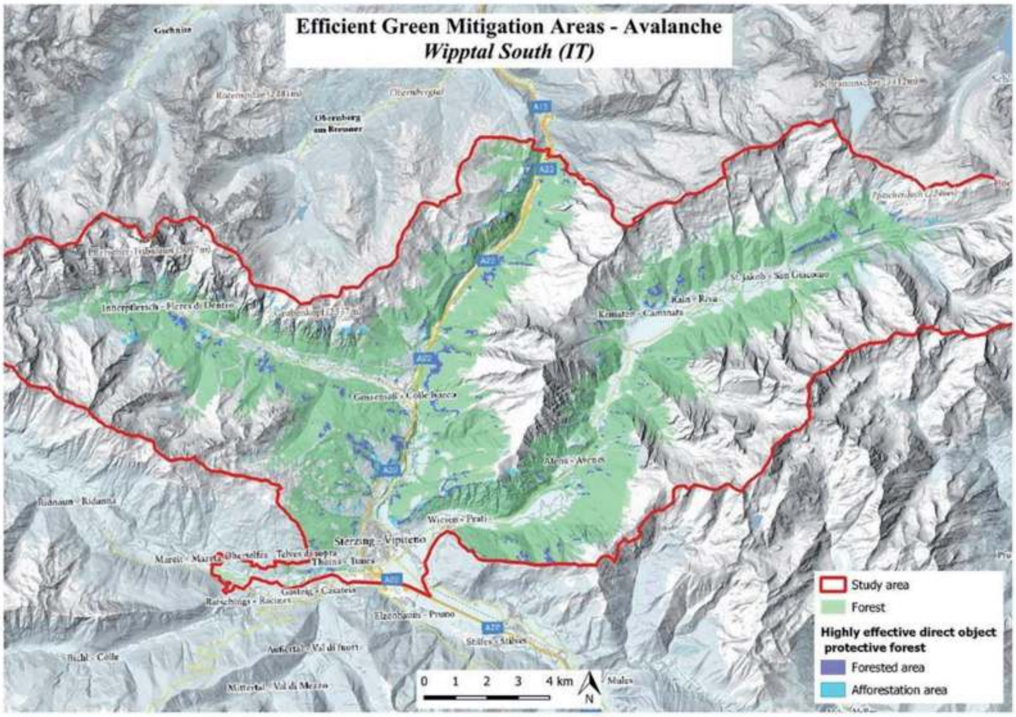


Figure 5.
Example for a map delineating locations of potentially highly effective protective forests against snow avalanches based on Flow-Py simulations. Dark blue are forested locations that were identified as highly effective for reducing the kinetic energy by forests of large and very large dry snow slab avalanches. Light blue are non-forested locations that were identified as highly effective for reducing snow avalanche's kinetic energy by forest; it was not considered whether it is possible to grow forests at these locations in terms of, e.g., land use, soil, or climatic conditions (except altitude and slope).

The Impact Reduction Index (IRI) shown in **Figure 4** quantifies the magnitude of the potential hazard's energy reduction by forests, which depends on forest structure and tree species composition by comparing the difference in kinetic energy in simulations with and without forest effects. The IRI was calculated based on Flow-Py simulations with the "forest" custom extension and a developed post-processing workflow (see chapter [10] of this book for details). That is, this map shows which areas are benefiting most from the surrounding protective forests in terms of reduced GMF's kinetic energy. To account for the increase in energy dissipation (or friction) in the parts of a GMF path that are located in a forest, the forest extension adjusts the runout angle to a steeper angle dependent on the length of the forested slope, the forest structure and the kinetic energy of the GMF. For this, an additional Forest Structure Index (FSI) input raster ranging between 0 and 1, which summarizes how developed a forest is regarding its optimal protective effect is needed. For example, the optimal protective forest for snow avalanches is an evergreen conifer forest with a high stem density and dense canopy cover (FSI = 1), which can hinder avalanche formation and significantly reduce runout lengths of small-to-medium avalanches ([38]; see chapter [24] of this book). A broad-leaved forest has a reduced effect (FSI = 0.8) as well as a forest with lower stem densities and less dense canopy cover, which needs to be reflected in the choice of the FSI values. However, the parameterizations of forest-GMF interactions to model the forest's potential to reduce the kinetic energy of natural hazards with Flow-Py and the forest extension as well as FSI-values were developed and estimated based on a literature review but can and should be further refined with observations.

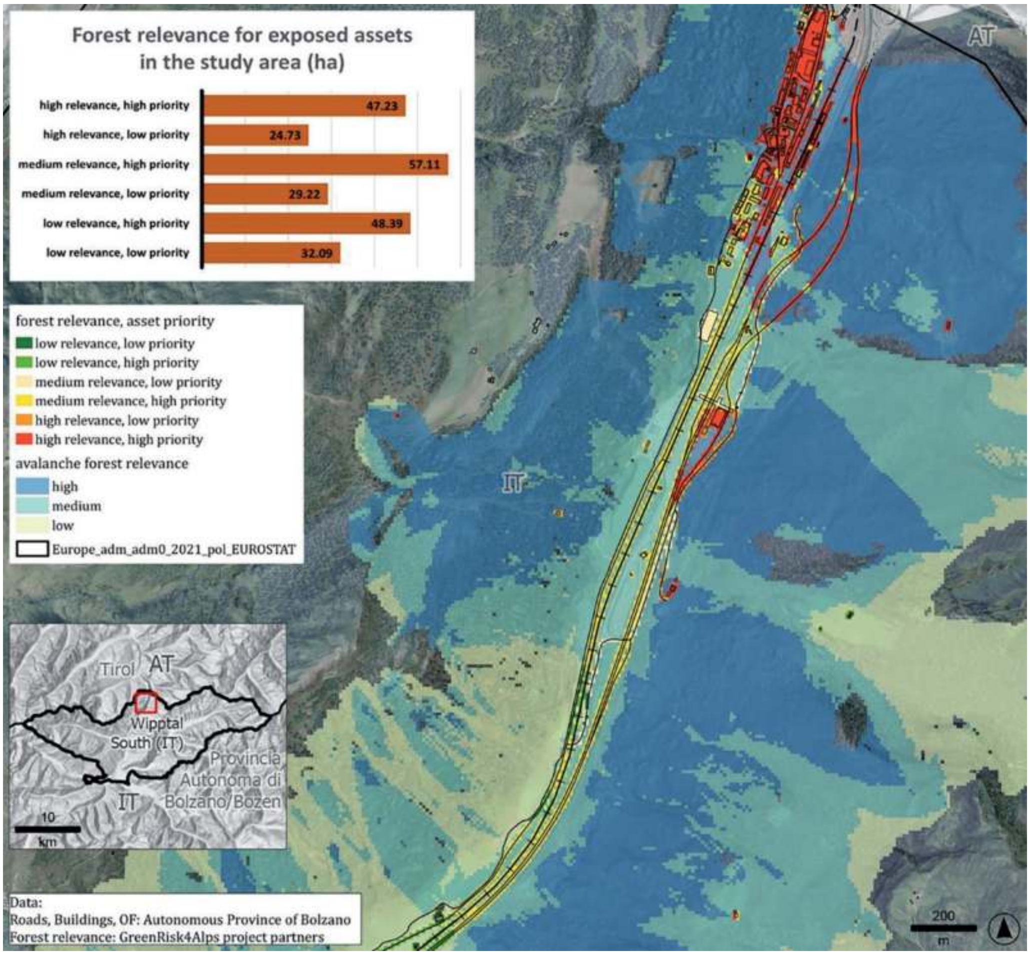


Figure 6.
Forest relevance in reducing the impact of snow avalanches is classified into three levels in the far north of the GreenRisk4ALPs Pilot Action Region (PAR) Wipptal South (IT), and forest relevance levels are combined with the building and infrastructure priority classes. The bar chart indicates for the entire PAR the square meters of assets for which the forest has relevance in reducing the potential risk from snow avalanches. Building and transport infrastructure footprints are shown with black outlines.

Figure 5 shows areas where forests are assumed to be highly effective in reducing GMF runout and intensity based on maximum thresholds in the kinetic energy of a GMF calculated with the Flow-Py simulation tool. To be considered as highly effective (or having the potential to be), the location must lie between a release area of a GMF and elements potentially at risk. The maximum kinetic energy threshold, which indicates where forests can reduce GMF runout and intensity considerably, is dependent on the GMF type and dictated by the different forest-GMF interactions. For example, a threshold of ~105 m in kinetic energy (velocity of ~30 m s^{-1}) was applied for snow avalanches above which a forest is no longer capable of reducing the avalanches' energy considerably since trees can be easily uprooted [39, 40]. In contrast, a threshold of ~75 m in kinetic energy was assumed for rockfall, which also translates to a velocity of ~30 m s^{-1}, above which forest is considered to have no energy dissipating effect on a falling block [41]. Other criteria used to identify such locations are the same for all GMF types since they characterize the forest growing conditions by simple terrain characteristics. For example, we assumed that an effective protective forest cannot grow above 2000 m in elevation and on slopes steeper than 45°. However, these criteria and thresholds can be adjusted easily and added to dependent on specific questions and/or, for example, land use, growing region, soil, and climatic conditions.

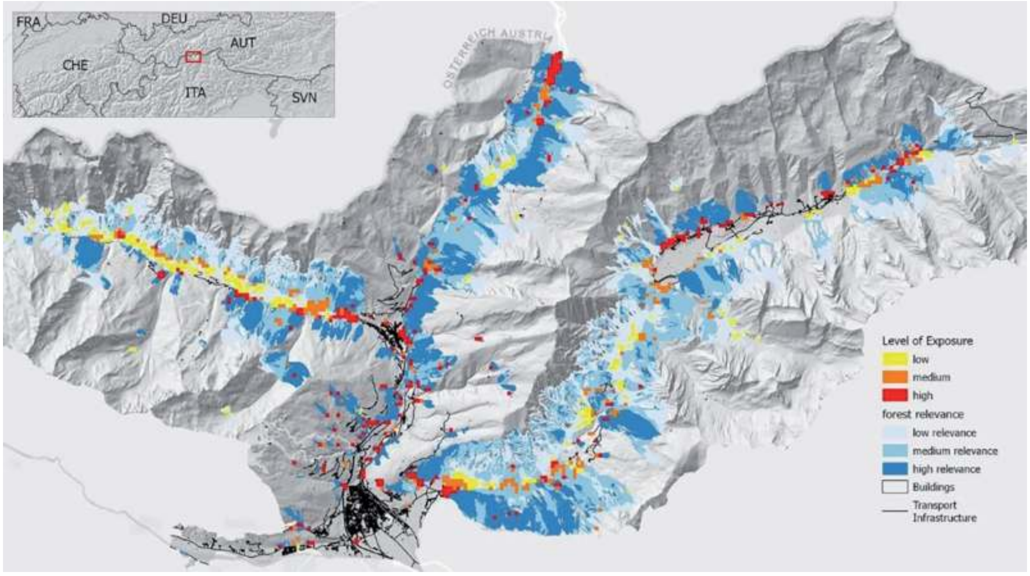


Figure 7.
Hotspots where protective forests are particularly relevant for reducing risk for the GreenRisk4ALPs Pilot Action Region (PAR) Wipptal South (IT). Building hotspots are shown for three levels of forest relevance to reduce the risk of snow avalanches.

2.2 Exposure assessment: relevance of forests in reducing natural hazard risk

Exposure is, together with hazard and vulnerability, one of the three components determining the risk (see chapter [2] of this book). As defined by the Intergovernmental Panel for Climate Change (IPCC), exposure refers to "the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected" [42].

The aim of the exposure assessment was to spatially identify those forest areas that have significant relevance in reducing the impact of GMFs on assets. We considered buildings, transport, and recreational infrastructure as exposed assets and classified each asset type into high and low priority (provided the required input data was available) following the recommendations of Perzl et al. [43] to acknowledge the commonly existing public interests in the protection of assets that are used frequently [44]. Perzl et al. [43] thoroughly discuss the challenge of a common classification scheme based on existing laws and regulations and applied a much more detailed classification of assets potentially at risk to model forests with a direct object protective function in Austria. However, the simplified scheme fits our purpose and goal to produce an overview of assets potentially at risk enabling to compare model outcomes of different PARs and countries that can be followed by a more detailed risk assessment. Accordingly, buildings used for residential, commercial, and industrial purposes were categorized as high priority and all other buildings (e.g., garages, stables, derelict buildings) were classified as a lower priority. Regarding transport infrastructure, highways, and primary and secondary roads were assigned a high priority whereas tertiary roads, for example, roads within settlements were categorized as a lower priority; forest roads were excluded from the analysis. Recreational infrastructure, such as cable cars, campgrounds, ski runs, golf courses, and sports grounds were considered assets of lower priority.

The spatial data needed for the exposure assessment were available in different formats representing different levels of detail (thematic and spatial) for five PARs of the GreenRisk4ALPs project. In the first step, the required features, buildings, transport, and recreational infrastructure, were extracted from the original data sets. In a second step, the assets were attributed categories of importance as defined and according to their priority, that is, high priority = 2 and low priority = 1. All asset information was subsequently converted into 10-m resolution gridded data sets. To spatially identify those areas where the forest has significant relevance in reducing the impact of GMFs, the IRI data sets that were computed based on Flow-Py simulation results (for method and result description see subsection 2.1 and chapter [10] of this book) were translated into forest relevance levels and intersected with the classified asset information. Building and infrastructure classes combined with forest relevance levels were visualized on maps. This spatial overlay allowed to quantify for the entire study area the square meters of each combination of forest relevance and asset priority level (**Figure 6**).

The forest relevance maps were used to identify hotspots where protective forests are particularly relevant for reducing risk (**Figure 7**). To define these hotspots of forest relevance, we considered those building types and infrastructure of a higher priority and combined them with the high level of forest relevance. Aggregating those features to larger pixel sizes allows to increase their visibility in a map showing a region at a scale of approximately 1:135,000 and for a qualitative consultation and discussion with local stakeholders.

2.3 The Protective Forest Assessment Tool (FAT)

The Protective Forest Assessment Tool (FAT) is a DSS in form of an interactive web platform, which consists of a model chain provided with a dedicated and easily accessible web interface. It serves for assessing the protective effect of a forest along a natural hazard process path/profile by comparing it to alternative mitigation measures to determine the best risk reduction measures in terms of cost-benefit ratio [45]. The FAT model chain consists of a GMF model that is connected to the risk assessment and economic model TEGRAV (TEchnical – GReen – AVoidance; [46]; **Figure 8**). FAT is targeted at different stakeholder groups, for example, local/regional decision-makers, forest managers, safety and infrastructure managers, planning officers, and local/regional public authorities. The aim of the tool is to present an assessment of the effectiveness of protective forest and ecosystem-based risk management compared to other solutions such as technical measures or avoidance strategies.

The Protective Forest Assessment Tool is freely available through a web interface [45], which enables users to perform an ad hoc risk analysis by uploading and entering input data, running the model chain, and viewing the results in a user-friendly way. Most of the user's inputs are predefined via dropdown menus, and graphical results are apparent and intuitive (**Figures 9** and **10**). Furthermore, detailed instructions guide the user through the modeling process as needed via the info buttons on each page.

To maximize its applicability, FAT's GMF model is based on a simple empirical relationship, which requires minimal input data and parameterization. Three GMFs, snow avalanches, rockfall, and shallow landslides, are parameterized with a runout angle model [32], which calculates the runout and intensity of the natural hazard process. The GMF model considers two types of effects that forest exhibit: (1) the forest effect in the release area, and (2) the forest effect in the process path of the natural hazard by increasing the runout angle dependent on forest type (broadleaved or coniferous forest) and forest structure. The forest effect in the process path applies to snow avalanches and rockfall, while forest effects in release areas are considered for snow avalanches and shallow landslides. The forest effect is parameterized with the FSI (see subsection 2.1), which is a relative measure characterizing the current structure of the forest in relation to the most robust and dense forest possible for the respective forest type and selected natural hazard (see **Figure 10**,

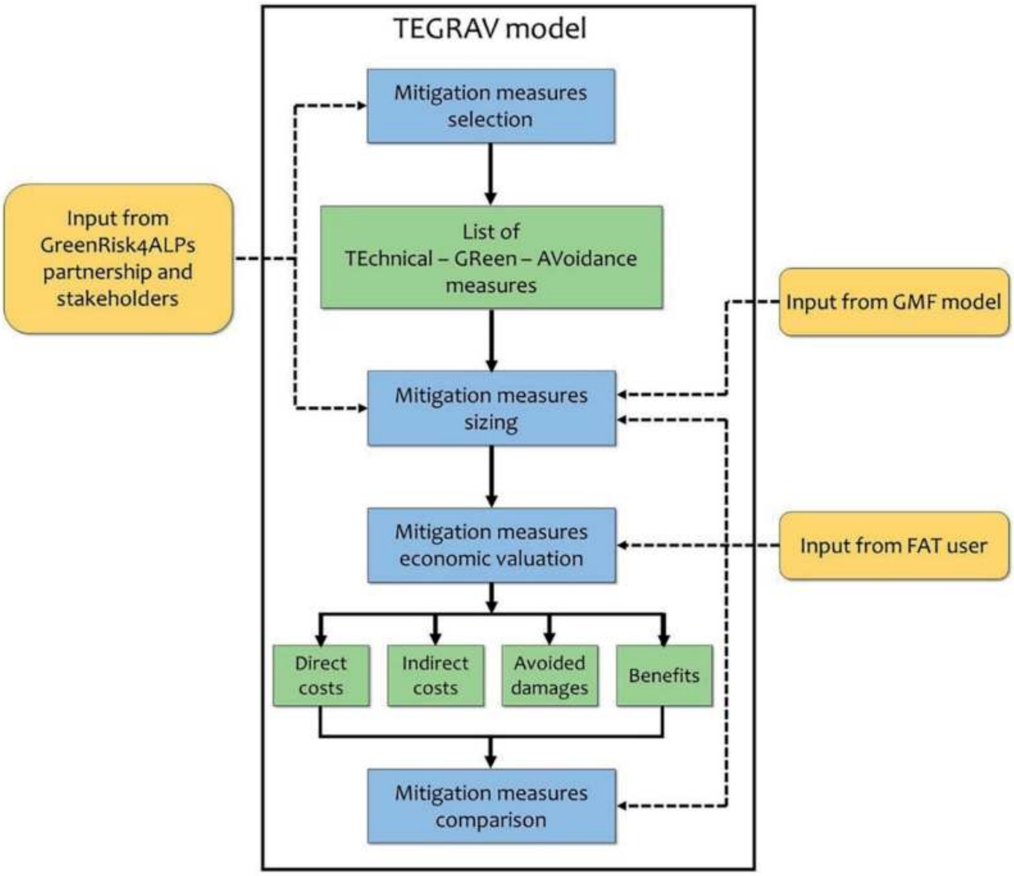
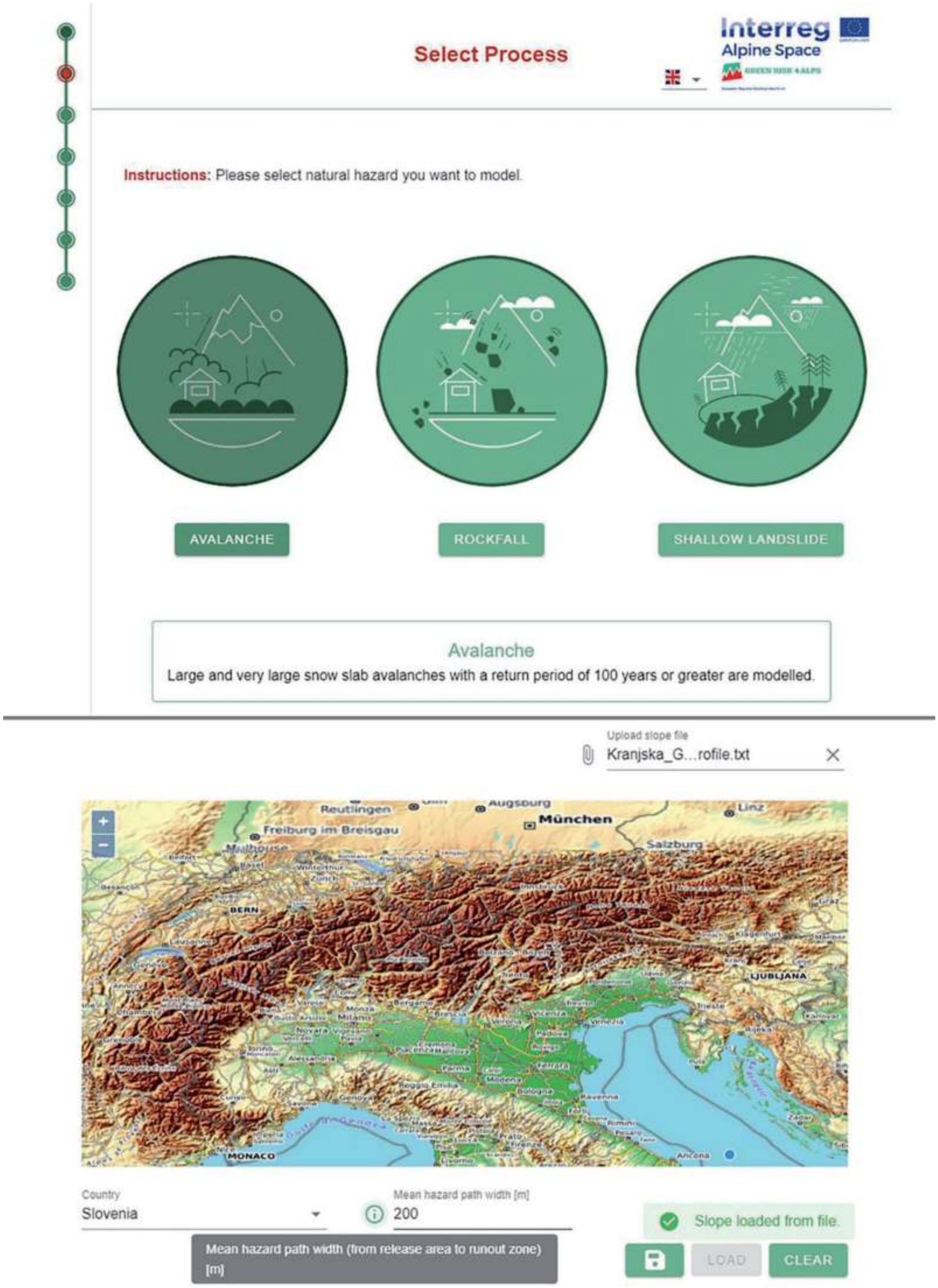


Figure 8.
TEGRAV (TEchnical – GReen – AVoidance) risk assessment and economic model workflow: modeling steps in blue, model outputs in green, external inputs in yellow. GMF = gravitational mass flow, FAT = Protective Forest Assessment Tool. Adapted from [47].

and chapter [10] of this book for details). Forest type and FSI as well as the forest's location along the process profile need to be defined by the FAT user. Based on this information, the runout angle associated with the chosen natural hazard is adjusted to a steeper angle, which can immediately stop or shorten the simulated runout. To quantify the forest's protective effect as the resulting difference in kinetic energy and thus simulated runout, the GMF model runs two times: 1) accounting for forest effects along the GMF profile, and 2) without considering forest.

Using the simulation results of the GMF model, the risk assessment and economic model TEGRAV performs a cost-benefit analysis of FbS (green measures), technical measures (grey measures), and land use avoidance (avoidance measures), allowing for their comparison [47, 48]. Risk assessment and cost-benefit analysis are carried out by integrating costs and effects of mitigation measures and damage potentials (i.e., the estimated values of assets that are potentially at risk; **Figure 8**). The TEGRAV model assesses the costs and benefits of each mitigation measure selected by the FAT user among an extensive list of possible solutions, which was established with the goal to cover the most frequent solutions currently used in the Alpine Space (**Figure 11**). Standard economic values were assigned to each technical and avoidance measure as well as to average afforestation costs based on the country or region in which they are implemented to obtain results in line with the geographic location of the natural hazard process path defined in FAT (see **Figure 9**). Costs for protective forest maintenance and rehabilitation need to be defined by the user based on their experience. These standard or regional values are then



Instructions: Please select natural hazard you want to model.

Avalanche
Large and very large snow slab avalanches with a return period of 100 years or greater are modelled.

Upload slope file: Kranjska_G...rofile.txt

Country: Slovenia

Mean hazard path width [m]: 200

Mean hazard path width (from release area to runout zone) [m]

Slope loaded from file.

Figure 9.
Protective Forest Assessment Tool (FAT) web interface. Upper panel: selection of the natural hazard process to be modeled. Additional information about the type and characteristics of each process is provided by moving the cursor to the respective process. Lower panel: the hazard process profile can be uploaded from a .txt file or drawn on a map. Info buttons guide the user through each step.

combined with the input data provided by the FAT user such as asset location and type, path width, maximum snow depth, or which assets should be protected to provide path-specific economic estimates (see **Figures 9** and **10**). For example, the costs for steel snow bridges depend on the maximum depth of the snowpack that they should stabilize. The sizes of rockfall nets and retention dams are estimated

Forest and infrastructure information

Forests

F1: Forest Type: Coniferous forest; Forest structure index: 0.85; Start[m]: 0; End[m]: 495

Roads

R1: Road Type: Primary road; Traffic: High; Value of infrastructure[€]: 1; Deroute[€]: 1; Start[m]: 539

The costs associated with the extra distance that must be traveled due to the road or railway closure.

Buildings

B1: Building Type: Residential; Base area of the buildi...: 300; Number of people [nbr]: 4; Start[m]: 566

Mitigation measures

Forest rehabilitation

Only areas currently covered by forest will be adjusted.

rehab: Forest Type: Coniferous forest; Rehabilitation costs [€/ha/year]: 120; Start[m]: 1; End[m]: 135

Yearly costs for managing and maintaining one hectare of protective forest, including planning, monitoring, harvesting, and logging activities, and other silvicultural interventions as well as costs for forest road network maintenance.

Afforestation

Figure 10.
Protective Forest Assessment Tool (FAT) web interface. Upper panel: information about the existing forest, buildings, and roads to be protected need to be entered by the FAT user. Lower panel: green, technical, and avoidance mitigation measures can be selected via dropdown menus. Info buttons guide the user through each step.

based on the kinetic energy simulated with the GMF model at their chosen location, that is, nets and dams will be higher and more costly in the middle of the transit zone in contrast to lower and less expensive measures located in the runout zone. The cross-slope width of steel snow bridges, rockfall nets, and retention dams, which is also considered in cost calculations, are equal to the path width defined by the FAT user. The path-specific costs for afforestation and forest rehabilitation depend on its location in terms of elevation, length along the profile, and the

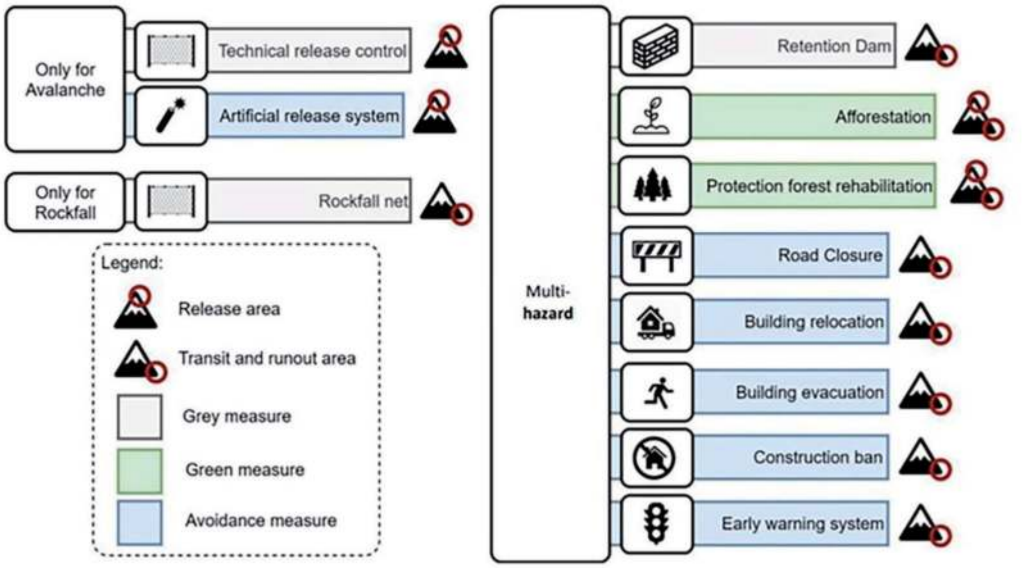


Figure 11.
Mitigation measures that are included in the TEGRAV (TEchnical – GReen – AVoidance) risk assessment and economic model and considered in the Protective Forest Assessment Tool (FAT), distinguished by hazard, area of implementation, and type. Adapted from [48].

defined path width. Since forest growth takes a considerable amount of time and dictates the development of protective effects, afforestation and forest rehabilitation measures are assessed at four (0, 25, 50, and 100 years) and three (0, 10, and 20 years) time steps, respectively. Therefore, a simplified forest growth model (based on [49]), which accounts for forest type and elevation is running in the background, estimating the forest's stage of development after a certain time, which affects the GMF runout. The costs for planting and/or maintenance are added up over time while the benefits as avoided damages will increase with the development of the forest.

Each mitigation measure included in FAT is assigned to one or more natural hazards in relation to its effectiveness. That is, in potential snow avalanche release areas, two types of measures are considered exclusively: technical release control such as snow nets or steel snow bridges and artificial release systems. For rockfall, only rockfall nets are considered in transit and runout zones. However, most measures can be applied for all natural hazards (multi-risk approach): retention dam for transit and runout zones; afforestation and protective forest rehabilitation for release, transit and runout zones; road closure, building relocation, building evacuation, and early warning system for transit and runout zones.

Based on the user's selection of mitigation measures, the model chain then calculates the remaining risk. That is, the GMF model performs simulations in the background with and without forest, adjusting the runout angle according to the protective forest type, FSI, and location along the process profile. TEGRAV then uses the simulation results to determine the damages that could be avoided thanks to the selected mitigation measures (benefits), that is, if a building or road is still reached by the simulated GMF and calculates the costs for the path-specific FbS, technical and avoidance measures.

The main output of FAT is an overview of economic metrics for each selected mitigation measure as well as for combinations of green and technical measures:

- Direct costs: originating from construction and/or implementation costs + maintenance costs + dismantling cost for the mitigation measure,

- Indirect costs: originating from constructing and/or implementing the mitigation measure, which presumably modifies an existing situation,
- Avoided damages: all damages to assets that could have happened without the mitigation measure, and
- Benefits: the sum saved or earned due to the construction and/or implementation of the mitigation measure.

The novelty of this DSS is the possibility to identify potential benefits of protective forest as a mitigation measure for natural hazard risk that can be implemented instead of or in combination with technical and avoidance measures. However, FAT's objective is neither to design real-life mitigation measures for exposed assets nor to achieve a quick, ready-to-use cost-benefit analysis for projected technical measures. The aim of FAT is to be used as DSS by displaying the potential of alternative solutions to the current practices. Forest-based Solutions and other Eco-DRR measures are often proved to be more efficient than grey measures, with little or no drawbacks from their implementation and they are, therefore, also an example of solutions that have a positive impact on livelihoods and ecosystems (see also chapter [3] of this book).

3. Conclusion

The tools and methods to support decisions in IRM of natural hazards considering protective forests that we presented in this chapter are only a few examples of different types of DSS that can cover various aims, and spatial and temporal scales, and address different user groups with specific questions and problems (see **Figure 1**). While the development of hazard and risk models has increased in number and improved in precision and effectiveness in the last years, additional effort to channel these DSS and their results into real-life risk management is still needed [50]. Indeed, several authors draw attention to the various lacks in bringing model results from science to policy and practice [51, 52], demanding the need for stronger stakeholder engagement and larger efforts to minimize uncertainties and to develop relevant indicators ([53–55]; see also chapter [56] of this book).

The next chapter of this book [27], therefore, focuses on the integration of stakeholders and decision-makers in an IRM of natural hazards. Following examples of communicating modeling results in the field of natural hazard risk management with a particular focus on mountain areas ([57, 58]; see also chapters [21, 59] of this book), the project GreenRisk4ALPs aimed to deliver openly available and easy-to-use DSS to practitioners and policy makers.

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Conflict of interest

The authors declare no conflict of interest.

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