RECIPE

REINFORCING CIVIL PROTECTION CAPABILITIES INTO MULTI-HAZARD RISK ASSESSMENT UNDER CLIMATE CHANGE

Report on impacts of climate change projections on wildfires, floods, storms, avalanches, rockfalls, landslides and multi-hazard risk management

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1 Introduction

This report is part of the deliverables of the RECIPE project (Reinforcing civil protection capabilities into multi-hazard risk assessment under climate change) and corresponds to the deliverable D3.1 of task 3.1. and 3.2.

RECIPE is a two-year Prevention Project (January 2020 – November 2021) founded by the Civil Protection Mechanism of the European Commission (call identifier UCPM-2019-PP-AG), with the participation of 8 institutions from 5 EU countries:

1. Forest Science and Technology Centre of Catalonia (CTFC), Spain (Project coordinator).
2. Pau Costa Foundation (PCF), Spain.
3. Civil Protection General Directorate of Catalonia (DGPC CAT), Spain.
4. Forest Research Institute Baden-Wuerttemberg (FVA), Germany.
5. CIMA Research Foundation (CIMA), Italy.
6. Austrian Research Centre for Forest Natural Hazards and Landscape (BFW), Austria.
7. Institute of Cartography and Geology of Catalonia (ICGC), Spain.
8. Higher Institute of Agronomy (ISA), Portugal.

The RECIPE project seeks to develop operational recommendations and tools to reinforce Civil Protection capabilities into emergency management and risk planning of different natural hazards across Europe to address climate change impacts by using an integrated risk management approach and the exchange of lessons learned and best practices.

By means of putting together multi-hazards' expertise from science and practice of wildfires, floods, storms, avalanches, rockfalls and landslides, main impacts of climate change in risk management will be identified. The potential scenarios of unprecedented multi-risk events will be considered. The interactions between prevention-preparedness-response-recovery actions in projected climate change scenarios will be analysed with an active participation of practitioners and other users. Accordingly, Civil Protection requirements to face new risk management challenges about climate change impacts will be identified.

Based on the above, transferable guidelines will be edited to incorporate the projected multi-risk impacts of climate change into operational decision support systems (DSS) that are used for risk management. Complementary, specific operational tools will be developed at pilot site level for each natural hazard to reinforce Civil Protection capabilities. Participation of public agencies will be promoted from the beginning to achieve an end-user oriented focus. Results will be actively disseminated into Civil Protection systems.

Furthermore, the project's workshops will promote the knowledge exchange in the existing networks to reinforce European landscapes' resilience to natural hazards.

The project is divided in 5 work packages (WP) as follows:

1. WP1 Management and coordination of the action.
2. WP2 Framing Civil Protection requirements for integrated multi-hazard risk management.
3. WP3 Impacts of climate change projections on multi-hazard risk management.
4. WP4 Guidelines and decision support tools for integrate climate scenarios into risk assessment and planning.
5. WP5 Publicity and project outcomes transference.

2 Objective

This deliverable aims at **reviewing the emergency management requirements to face unexpected or new risk situations posed by the climate change**, and how to fit them into the risk assessment and planning process of wildfires, floods, storms, avalanches, rockfalls, landslides and potential multi-hazard interactions.

In particular, the analysis has been developed in three steps corresponding to tasks 3.1 (step one and two) and 3.2 (third step) of the project Action Plan:

- A review of literature, R+D+I projects, operational guidelines, etc. about impacts of climate change on natural hazards and risk management;
- a qualitative gap analysis about climate change scenarios integration into disaster risk management*;*
- the identification of potential situations of single and multi-hazard interactions under climate change.

In the two first steps (task 3.1.State of the art of climate change impacts on natural hazards and risk management), by means of sharing solid practical knowledge and the literature review, the climate change impacts on natural hazard and on risk management and multi-hazard cascade effects of wildfires, floods, storms, avalanches, rockfalls and landslides have been identified (chapter 3.1 and 3.2). Moreover, the transferable information available at operational level (such as guidelines, consolidated risk assessment tools, etc.) about climate change impacts have been identified. Finally, a qualitative survey on main constrains and challenges to integrate climate change projections into risk management policies have been done with the participation of end-users (chapter 3.3).

The main findings have been capitalized and discussed in a 2nd technical workshop (November 9-11th 2020) where risk managers and civil protection practitioners have been invited, as well as external experts.

The workshop has been focused on the following central themes: Factors and Components of Risk, Civil Protection Requirements, and Climate Change Impact. Minutes and presentations of the 2nd workshop are available at the project website.

In the third step (task 3.2. Integration of climate change scenarios into multi-hazard risk assessment and planning), new single and multi-risk situations posed by climate change have been identified and risk components and data requirements for civil protection and emergency management identified in previous tasks (Deliverable 2.2) are evaluated in each scenario (chapter 4). By this way, gaps and new needs of operational data and risk assessment under climate change are identified, for instance: how to re-evaluate in a territory the known vulnerability to recorded avalanches, according the risk factors identified in task 2.1, to potential avalanches scenarios posed by climate change or new avalanche-wildfire risk interactions in mountain areas. Or which new operational data requirements for efficient civil protection -task 2.2- have to be included in the risk assessment in the case of increased levels of risk, unprecedented hazards interactions or multi-emergencies. Across the partnership, single/multi-risk situations are defined and analysed. The objective is to check and updated the kwon solutions of risk assessment and planning to face potential new risk situations in the climate scenarios, both at single and multi-risk level, putting together the expertise of the consortium together and, where possible, the end-users and external experts suggestions and comments.

3 State of the art of climate change impacts on the natural hazards and the risk management

This chapter summarize the state of the art of climate change impacts on the risk of wildfires, floods, storms, avalanches, rockfalls, landslides and multi-hazard interactions.

The methodology proposed to obtain the requested information is based on:

- a review of literature, R+D+I projects, operational guidelines, etc. about impacts of climate change on natural hazards and risk management, carried out by a desk work;
- a qualitative gap analysis about climate change scenarios integration into disaster risk management, carried out by online interviews with risk managers and civil protection and emergency management stakeholders.

The first component wants to analyse the robustness of available data on climate change effects for risk assessment and planning at operational level. The second, seeks to analyse up to what extent climate change is being integrated into risk management strategies, identifying main successes, challenges and constrains (i.e., legal frame/economic dimension, etc).

All partners have contributed to the assessment, according to each one's expertise in the corresponding natural hazard and main geographical/territorial context (as can be seen in Table 1).

Table 1. Expertise and territorial context of each partner

Partner	Risk	Context
CIMA	Flood	Europe and Italy
	Wildfire	Italy
ISA	Flood	Portugal
	Wildfire	Portugal
BFW	Landslides and rockfalls	Austria
CTFC	Wildfire	Europe, Spain and Catalonia
FVA	Storm	Europe
ICGC	Avalanche	Catalonia
PCF	Wildfire	Europe

3.1 Documentary review on climate change impacts on natural hazards

For better understanding and socializing the climate change impacts on different hazard, to be analysed in the project, an analysis of the following elements has been carried out:

- Climate change impacts on each natural hazard.
- The cascade effects or feedback effects triggered.
- Climate change modelling chain;
  - Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2);
  - Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models);
  - The scale of analysis (scale and temporal resolution);
  - Level of uncertainties in predicting changes (if possible).

The description and narrative of previous elements contribute to give an overview of the state of the art of the climate change studies and analysis on different natural hazards at European level, also exploring the role of the climate model uncertainties on the possible impacts and the interactions among different hazards.

These two elements are very useful for giving a consistent framework for better framing the climate change impacts and so individuating a more reliable measures or actions to face climate change impacts.

3.1.1 Wildfires

3.1.1.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

3.1.1.1.1 Europe

Climate change impacts on natural hazards are almost not mentioned in EU Strategies. It only appears as general comments, as the increase of frequency and intensity of extreme weather events. However, other publications describe quite exhaustive the climate change effects on risk events.

In the existing literature, there are hundreds of recent studies and authors analysing the effects of climate change on wildfires in different biomes, timespans, climate change scenarios, variables, etc.

The following sections summarizes the main findings of EU strategies and of some of the studies.

EU Strategies or documents

The *UN 2030 Agenda for Sustainable Development, EU Green Infrastructure Strategy* and the *European Green Deal*, do not make any specific mention to climate change impacts on natural hazards.

The *EU Forest Strategy*, recognizes that climate change exacerbates the effects of storms, and wildfires, pests and increasingly will make water resources scarce. Additionally, recognizes that these threats do not respect national borders.

In the review *Climate change impact on future wildfire danger and activity in southern Europe*, they found that despite the heterogeneity in methods and results of reviewed studies, all projection studies based on the FWI[1] System agreed on a generalized future increase in fire danger and fire season length in southern Europe. The relative increase in mean seasonal fire danger ranges between 2 and 4% per decade in the Mediterranean regions of Europe, and it reaches 7% per decade in France, where the fire-prone area is currently limited to the south. The projected increase in severity of the fire season, as measured by the SSR[2], is even higher (3–7% per decade in the Mediterranean area), and fire season lengths are projected to increase by 3–4 days per decade for the whole area of southern Europe. When fuel load/continuity dynamics are ignored, burnt areas are projected to increase everywhere in southern Europe, just as the potential fire danger does but with substantially higher rates of increase (15 to 25% per decade for most areas, and much more for Spain). Large uncertainties remain when considering fuel dynamics. The area at risk should expand to new fire-prone regions, such as western and central France, the mountains surrounding the Mediterranean basin or central-eastern Europe, where fuel load is not expected to be a limiting factor. In the warmest and driest fire-prone regions (e.g., central and southern Iberian Peninsula), fuel availability is or would become the main limiting factor of fire activity.

According to *Global fire challenges in a warming world*, based solely on meteorological aspects it is expected a more fire occurrence, a longer fire season, more high intensity fires, increased fuel consumption (i.e., more emissions) and more area burned. Climate change is leading to more extreme weather events which means more fires since extreme weather drives fire activity. One of the consequences will be for fire management as high intensity fires will occur also outside the traditional/historical fire season challenging their response. Global projections depict also more extreme droughts and a general increase in global aridity.

According to *Global assessment report on Disaster Risk Reduction*, global warming triggers climate change effects that are not linear. Climate change amplifies risk and creates new ones including the direct consequences of a warming planet. It affects the intensive and extensive nature of risk, can generate more powerful storms, exacerbate coastal flooding, and bring higher temperatures and longer droughts. Drought is highly destructive and is projected to become more frequent and more severe in many parts of the world due to climate change. Particularly vulnerable are countries located in arid and semi-arid regions where water stress will be further exacerbated due to strain from overexploitation and degradation already tangible under the present conditions. Climate change exacerbate disasters, increasing their frequency, irregularity and intensity, significantly impede progress towards sustainable development. With the effects of climate change warming the planet, the incidence of fires will increase, and fires will arise in areas that have not previously been fire-prone.

The document *Sparking firesmart policies in the EU* classified climate change effects as direct or indirect. Direct effects through fire season length and intensity increased; extreme fires events; changes in fire frequency, size, and intensity; more frequent and intense heat waves and drought episodes. Indirect effects through flammability changes in vegetation and fuel availability as well as in ecosystem dynamics.

[1] FWI Fire Weather Index is designed to provide a uniform numerical rating of the relative fire potential, by dynamically combining the information from local temperature, wind speed, relative humidity, and precipitation values. If a daily time series for each of these weather data variables is available, the system can process either actual observations or future simulated estimates (JRC, 2017).

[2] SSR: Seasonal Severity Rating

Research studies

In the same line, a study carried out by *Turco et al. 2018* projects changes in summer burnt areas for +1°C, +2°C and +3°C warming scenarios considering reference data from the period 1971-2000 in Mediterranean countries. Results conclude that burned area is expected to increase. The higher the warming level, the larger will be the increase of burned area (from 40% to 100% more depending on the scenario).

Annual burnt area was assessed by *Wu et al. 2015* for the whole Europe. It seems that Eastern Europe will increase the number of hectares burned and become a fire-prone area. Mediterranean and western countries will moderately increase their burned area, while results are not that clear for Northern Europe. It is pretty clear that, at continental scale, burned areas will increase by 2100. Under RCP8.5 scenario is expected an increment between 1.8 and 3.6 times the present values, while for the 2.6 scenario the increment is expected to be under 60%.

Kalabokidis et al. 2015 assessed monthly FWI statistics, number of days with extreme fire danger, maps of conditional burn probability and flame lengths and fire size distribution at Greece scale using data from the period 1961-1990 and projections from 2071-2100. Results reveal that larger wildfires that overcome the initial control will be more frequent in the future. Fire intensities are projected to increase as well. FWI will be in higher values with more frequency. Apart from that, FWI will be from 60% to 80% higher during fire season.

Frequency distributions of FFMC[3] and DC[4], mean values and maps of burn probability, flame length and fire size were projected in Italy and Corsica using data from the period 1981-2010, and projections for 2011-2070 by *Lozano et al. 2017*. Wildfire simulations showed very slight changes in flame length, while other outputs such as burn probability and fire size increased significantly by 2070, especially in the southern portion of the study area. The projected changes fuel moisture could result in a lengthening of the fire season.

3.1.1.1.2 Portugal

Wildfires are a serious problem in Portugal. In average, more than 100 thousand hectares are burning in Portugal every year. Since 1980, an area equivalent to 3/5 of the forested area has been burned *(EC 2000 – 2018)*.

A study about fire weather risk (*Carvalho et al., 2011*) shows that climate change in the coming decades will lead to higher temperatures in Portugal for all seasons, especially in the Summer and the beginning of Autumn. According to the study, by 2050 the amount of Spring and Summer precipitation will decrease, but at the same time it is predicted to increase in February and March. Also, depending on the month, the temperature is predicted to rise from 2 to 6°C. Temperature lower and upper extreme values (5th and 95th

[3] FFMC: fine fuel moisture code represents fuel moisture of forest litter fuels under the shade of a forest canopy. It is intended to represent moisture conditions for shaded litter fuels, the equivalent of 16-hour timelag. It ranges from 0-101

[4] DC: drought code r epresents drying deep into the soil. It approximates moisture conditions for the equivalent of 53-day (1272 hour) timelag fuels. It is unitless, with a maximum value of 1000.

percentiles) at 12h will be higher in future climate. Precipitation will decrease in all simulated months, except in October.

A similar scenario was also achieved by *Carvalho et al., (2010)* modelling on their paper about the impact of special resolution on area burned and fire occurrence projections in Portugal. Results show that the daily precipitation will decrease across Portugal in all seasons. Spring will be the most affected, with reductions reaching almost 2.2 mm in the northwest region of the country. The north and centre of Portugal will register the highest reductions in rainfall amounts. The northwest of Portugal will experience the greatest precipitation reduction (1.5 mm).

The low values of precipitation that follow in May and June, together with the high values of temperature, will provoke the more abundant vegetation, which contributes to a larger amount of burnt area, especially if, during the fire season, Portugal will be affected by atmospheric circulation. Consequently, the projected changes for temperature and precipitation will deeply impact the fire weather risk at centre of Portugal, namely higher fire weather risk in Portugal and a longer fire season.

All modelling results indicate that for all fires at the end of the 21st century, a larger increase in burnt area should be expected *(Amatulli et al., 2013; Carvalho et al., 2011, 2010; Pereira et al., 2013)*. However, the final values of these models differ.

For example, *Pereira et al. (2013)* modelled the burnt areas behaviour for two periods (2051−2080 and 2071− 2100) with B1 climate scenarios. The results pointed to a future increase in area burned of 7 to 11%. The largest increase in the area of fires (up to 35%) is expected to be observed in the periods from July to August.

Studies of *Carvalho et al., (2010)*, using historical relationships and simulations of the High Resolution Hamburg Model (HIRHAM), have estimated an increase of 280% in the number of fires and of 480% in burnt area in the case of a 2× CO2 scenario, which equates to an increase from 1.4% to 7.8% of the available burnable area burning annually. Additionally, future fire seasons are predicted to start earlier and end later.

A similar study was carried out at the international level by *Amatulli et al. (2013)*. Their results showed that Portugal will be one of the most affected Mediterranean regions in absolute terms of increased fire danger, with an average SSR of over 9 in both scenarios. In the 2 × CO2 scenarios, the projected increase in burned area was estimated at 504%. In the 3 × CO2 scenarios, the projected increases in burned area was 169% in Portugal (Table 2).

Table 2. Seasonal Severity Rating (SSR) averages, computed from historical (ERA-40) and projected climatic conditions under B2 and A2 emission scenarios. Between brackets the % projected increase of SSR against observed historical average is shown.

Region	Average SSR		
	ERA-40 (1958–2004)	Scenario B2 (2070–2100)	Scenario A2 (2070–2100)
EU-Med	5.30	6,64 (+ 25%)	7,34 (+ 38%)
Portugal	6.23	9.04 (+ 45%)	9.37 (+ 51%)

Region	Average SSR		
	ERA-40 (1958–2004)	Scenario B2 (2070–2100)	Scenario A2 (2070–2100)
Spain	6,95	9,63 (+ 39%)	10,08 (+ 45%)
France	2,16	2,83 (+ 31%)	3,23 (+ 49%)
Italy	3,27	3,78 (+ 16%)	4,15 (+ 27%)
Greece	7,13	8,55 (+ 20%)	10,08 (+ 41%)

Also, results showed that significant increases, 66% and 140% of the total burned area, can be expected in all EU-Med region.

3.1.1.1.3 Spain and Catalonia

Law 16/2017 on Climate Change (Catalonia) mentions that climate change will alter climatic variables like temperature, precipitation, humidity, wind speed and sea water's temperature among others as well as increase the frequency and intensity of extreme meteorological events (droughts, floods, waves heat). All these situations pose a risk to ecosystems, to the preservation of biodiversity and to people. It also quantifies some of the costs, according to it the damage and losses from natural phenomena have gone from €50 billion in the 1980s to more than €200 billion in the last decade, three-quarters of which are the results of extreme weather events.

Regarding the *Project of Law on Climate Change and Energy Transition (Spain)*, a special section is addressed to water related risks and impacts. Specifically, on water availability (measures to assure basic supply for society, biodiversity and socio-economic activities). Other impacts identified are: changes in frequency and intensity of extreme events (droughts and floods), increase of water temperature and increase sea level; wildfire risk with special attention to wildland-urban interface; extreme weather events that might affect basic supplies like water, power or emergency services; among others.

Finally, the *Third report on climate change in Catalonia* mention specific impacts for fires, avalanches and floods. It is also analysed rockfalls and landslides, but without a specific climate change impact associated. In general terms, mention that climate change can have direct consequences and can increase the level of hazard in almost every risk, and can also affect the vulnerability and exposure, producing feedback effects. Even so, there are no clear tendencies about how climate change is affecting natural hazards or extreme meteorological events in Catalonia. Nevertheless, there is identified an increase tendency of floods, flash floods and wildfires according that effects. Also, it is stated that climate change can affect the occurrence and type of avalanches.

3.1.1.1.4 Italy

At Italian level according to the *Risk analysis: climate change in Italy* (CMCC, 2020), forest fires represent one of the main threats to the Italian forest sector. The increase in temperatures and the reduction in average annual rainfall, and at the same time the greater frequency of extreme weather events such as heat waves or prolonged drought, interact with the effects of the abandonment of cultivated areas, pastures and those that were once managed forests, of the strong exodus towards cities and coastal areas, and of monitoring, prevention and active struggle activities increasingly efficient. Climate change is expected to further exacerbate specific components of fire risk, resulting in impacts on exposed people, assets and ecosystems in the most vulnerable areas. Increases in the fire hazard, altitude shift of vulnerable areas, extension of the fire season and an increase in extremely dangerous days are expected which, in turn, could translate into an increase in the surfaces travelled with a consequent increase in gas emissions. greenhouse and particulate matter, therefore with impacts on human health and the carbon cycle.

A study carried out by *Faggian (2018)* projects the number of fire danger days in Italy for the period 2021-2050 considering data from 1971-2000. Results highlight an alarming increasing fire probability: in line with previous experiments, fire danger is expected to increase of at least 20% by 2050 in most of Italy regions in summer, projected drier and warmer for the next decades.

According to *Michetti and Pinar (2019)* by projecting fire regime as a function of future climate change, it could be possible observe that in Italy it will be an annual increase in the number of events and area burnt between 2016 and 2035. The most affected area will be the central-south of Italy, with fire events and area burnt are projected to increase by 25% and 75%, respectively. Northern Italy will experience a higher fire frequency during the winter period, while in the central-north the annual rise in frequency is mostly driven by the projected fire events during the summer season. Central-south is projected to experience 30% and 20% increase in the number of fires during the summer and autumn periods, respectively. Overall, while most frequent fire events will occur mainly in summer, confirming the past trends, a new path is reported for fires taking place in the central-south and south of Italy during the autumn period, which highlights the importance of more fire suppression efforts during autumn period in the central-south and south of Italy than the ones observed in the past. Finally, it is worth noting that the projected increases in area burnt in the northern Italy is expected to increase even though the projected increase in fire events is at modest levels. This increase in spread of fire could be a result of the impact of climate change on soil conditions, moisture content of litter and other fine fuels. The fire season could then become longer, more intense and extreme as reduced rainfall, heat waves, and drought events increase the water stress of the vegetation making it highly flammable. In sum, compared to the past, our findings suggest that there is clear change in the forest fire phenomenon across different seasons and geographical clusters and the interactions of climatic factors and forests have new connotations.

Beyond weather parameters, socio-economic factors also contribute to the explanation of forest fire regimes. Higher levels of education lead to decreases in the number of fire events and total area burnt in all geographical clusters with the exception of southern Italy. Whereas, a major contribution to fire regime in the southern Italy is due to the existence of criminal activity, exerting pressure on forest land. These two socio-economic factors are found to be important in explaining yearly variation in forest fires and area burnt after controlling for regional effects and weather variables.

3.1.1.2 The cascade effects or feedback effects triggered

3.1.1.2.1 Europe

With regards of EU strategies or documents the cascade effects are not mentioned in the *UN 2030 Agenda for Sustainable Development*, the *EU Green Infrastructure Strategy*, the *European Green Deal*, the *EU Forest Strategy* and the document *Sparking firesmart policies in the EU.*

As highlighted in *Climate change impact on future wildfire danger* review, important shifts in the potential vegetation distribution are projected in Europe owing to changes in climate conditions (e.g., *Hickler et al. 2012; Costa et al. 2015*), although trends are still uncertain (e.g., *Cheaib et al. 2012; Lindner et al. 2014*). These shifts could alter fuels, and changes in fire regimes could accelerate such shifts. So far, spatial and temporal fuel variations and fire-vegetation feedbacks have largely been ignored in reviewed projection studies.

In the *Global fire challenges in a warming world* document several feedbacks are identified. In rainforest there is a positive feedback of increasing fire frequency, forest desiccation, and increased fire severity continues leading to complete deforestation. In mountain areas small-scale fires often penetrate litter and humus layers, exposing the soil and leading to rockfalls, landslides and mudslides on steep slopes. More generally, the opening up of the canopy caused by fires may lead to the landscape drying out, in particular through the loss of soil moisture storage. This then could affect the future loss of evapotranspiration outputs to downwind locations and reduce precipitation. In forests, a vicious circle between fire and pests then takes place, with fire damaged trees being more likely to be infected, the insects spread and attack healthy trees which in turn create dead dying and dry trees creating a more acute fire hazard. Other positive feedbacks can allow the invasive plant to increase its presence by increasing fuel availability resulting in increased fire intensity that could in turn allow the more fire resistant invasive species to dominate more components of the native ecosystem, further influencing the fire regime in favour of the invasive plant.

In the *Global assessment report on Disaster Risk Reduction*, the document recognizes that the atmosphere alterations are predicted to cause new, more-frequent and intensive disasters ranging from drought and flooding all the way to changes in seismic activity. Some of these disturbances lead to feedback loops such as increased frequency of forest and savannah burning, and permafrost thawing, which further accelerate the build-up of carbon stocks in the atmosphere and cause increased warming, potentially triggering even more catastrophic abrupt climate change phenomena. Societies continue to create wealth at the expense of declining ecological life support functions in a positive spiralling feedback loop that creates systemic risks with cascading effects and makes overarching economic, ecological and social systems increasingly susceptible to collapse.

Triggering effects are slightly considered in the **literature reviewed** under the current document.

Lozano et al. 2017 states that vegetation distribution may change during the coming decades, without precising how this distribution change could be. On the other hand, more severe erosion processes can occur under climate change effects.

The effect of population was considered in the study of *Wu et al. 2015* as a variable that may influence future burned area. As expected, an increment of population is linked to an increment of the annual burned area because of the increment of ignition probabilities. Two vegetation models were also assessed (LPJ-GUESS-SIMFIRE and LPJmL-SPITFIRE).

3.1.1.2.2 Portugal

In total, there were few attempts to understand the triggering effects of future changes in wildfires and increase of burned areas. Nonetheless, *Carvalho et al. (2010)* analysis suggests that a future surge in fire activity across Portugal would have environmental, social, and economic impacts and would dramatically impact the organizational structures that deal with wildland fire and also society in general. *Dias (2009)* points to an increase in the loss of forest goods and services; human losses; among others. In social terms, the effects on human health caused by smoking and stress are highlighted; the interruption of the electricity supply; water supply problems; burning agricultural productivity due to soil dehydration and loss of nutrients; increase in food prices, among others. Results of the report done by *de Rigo et al. (2007)* indicates that the combined effects of fire and global environmental changes can exceed their effects in uneven influence on the level of species richness and on productivity recovery after forest fires; changing the types and conditions of fuel; abiotic and biotic disturbances, etc.

3.1.1.2.3 Spain and Catalonia

Not mentioned in *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)*, and *Third report on climate change in Catalonia.*

3.1.1.3 Climate change modelling chain

3.1.1.3.1 Europe

The climate change modelling chain are not mentioned in any of the EU Strategies and there are only general comments about climate change scenarios in *Sparking firesmart policies in the EU*. The *Global assessment report on Disaster Risk Reduction* does not mention it neither.

In *Climate change impact on wildfire danger* review they incorporated studies with FWI System; Statistical-correlative fire models; Spatially explicit fire spread models and DGVM-fire models.

In the *Global fire challenges in a warming world* established to use the Canadian FWI System — measuring the combined influence of surface temperature, relative humidity, wind speed and precipitation —.

Turco et al. (2018): Regression-type models for summer burnt area by administrative regions (NUTS3) based on a drought index (SPEI, standardized precipitation evapotranspiration index).

Wu et al. (2015): Integrated fire vegetation models LPJ-GUESS-SIMFIRE and LPJmL-SPITFIRE.

Kalabokidis et al. (2015): FWI, Randig (FLAMMAP fire simulator).

Lozano et al. (2017): FFMC and DC (FWI system), Randig (~FLAMMAP fire simulator).

3.1.1.3.1.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

The most common IPCC scenarios used are RCP 8.5 and RCP 6.0 (or equivalent) because these scenarios show the 2 worst cases of emissions and projects the situations that can drive severe disasters. Scenarios 4.5 and 2.6 are less frequent.

In *Sparking firesmart policies in the EU* talk about different scenarios but are not specified.

The different studies included in *Climate change impact on future wildfire danger* review studies considered several scenarios, however it is specifically mentioned that thirteen studies considered the A2/RCP8.5 scenario and eleven considered the A1B scenario; additionally two considered RCP 4.5 and one RCP 2.6.

In *Global fire challenges in a warming world* and *Global assessment report on Disaster Risk Reduction* it is used the RCP4.5 and RCP8.5.

Turco et al. (2018): RCP4.5, RCP 8.5.

Wu et al. (2015): RCP 2.6, RCP 8.5.

Kalabokidis et al. (2015): A1B (Eq. RCP 6.0).

Lozano et al. (2017): A1B (Eq. RCP 6.0).

3.1.1.3.1.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models)

Not mentioned in the *UN 2030 Agenda for Sustainable Development*, the *EU Green Infrastructure Strategy*, the *European Green Deal*, the *EU Forest Strategy*, *Sparking firesmart policies in the EU*, *Global fire challenges in a warming world* and neither in *Global assessment report on Disaster Risk Reduction*.

The different studies reviewed by *Climate change impact on future wildfire danger* apply several different models. For climate models apply: RCM, GCMs, ESM.

Turco et al. (2018): 9 simulations from 4 RCM and 5 GCM combinations (EUROCORDEX).

Wu et al. (2015): 4 ESM (CMIP5 EXPERIMENT).

Kalabokidis et al. (2015): One RCM (RACMO2) driven by one GCM (ECHAM5) (ENSEMBLES project).

Lozano et al. (2017): One RCM (CMCC-CLM).

3.1.1.3.1.3 The scale of analysis (scale and temporal resolution)

In terms of spatial scale, most of studies focus the efforts on 25-50 km resolution, while for temporal scale, the daily unit is the more frequent one.

Not mentioned in the *UN 2030 Agenda for Sustainable Development*, the *EU Green Infrastructure Strategy*, the *European Green Deal*, the *EU Forest Strategy*, *Sparking firesmart policies in the EU* and in *Global fire challenges in a warming world*, however in this last case, they talk in a global sense and there are various sections corresponding to some big regions (Mediterranean, Boreal, Tropical, etc.).

For most of the studies included in *Climate change impact on future wildfire danger* review, daily climate datasets were generally used, and spatial resolution was often 25 km, ranging between 10 and 50 km.

Table 3. Spatial and temporal scale defined in different publications reviewed

Study	Spatial scale	Temporal scale
Climate change impact on future wildfire danger	25 km (10-50km)	-
Turco et al. 2018	50 km	Daily
Wu et al. 2015	55 km	Daily
Kalabokidis et al. 2015	25 km	Daily
Lozano et al. 2017	14 km	6 hours

3.1.1.3.1.4 Level of uncertainties in predicting changes (if possible)

Not mentioned in the *UN 2030 Agenda for Sustainable Development*, the *EU Green Infrastructure Strategy*, the *European Green Deal*, the *EU Forest Strategy* and *Global fire challenges in a warming world.*

Sparking firesmart policies in the EU recognizes the uncertainty about climate change's effect.

According to the results of *Climate change impact on future wildfire danger*, reliability of fire danger or fire activity projections depends on the biases and uncertainties resulting from both climate projections and climate-fire models. Projected changes strongly depend on the models used to rate climate change impact, and in fact on the drivers that they incorporate. Seven of the studies included in the review consistently showed that uncertainties arising from climate models had important and significant impacts on wildfire projections. As highlighted in the review, when only seasonal fire weather or the coincident drought is considered, burnt areas are projected to increase everywhere in southern Europe. However, when the effects of fuel load/continuity are considered, through vegetation dynamics in process-based models or climatic proxies (antecedent weather or drought conditions) in statistical approaches, burnt areas generally increase at much lower rate (not exceeding a few percent per decade) and can even decrease in the current most arid regions (e.g., south Iberian Peninsula). Hence, large uncertainty exists about future trends in these regions. For the northern margins of the current Mediterranean area, fuel load/continuity is not likely to become a limiting factor and future increase in fire activity is expected there. As mentioned in the review, a thorough assessment of the respective sources of uncertainty is still missing in wildfire projections studies in southern Europe.

Global assessment report on Disaster Risk Reduction recognize large uncertainties exist in determining the causal effects of climate change across complex geospatial regions, across stakeholders and across sectors. For example, experts generally agree that the risk of extreme droughts and floods in some regions is increased by climate change, but attributing losses from any event to human-induced climate change is still unachievable.

Level of uncertainties are not well studied in the current literature. Only *Lozano et al. 2017* considered wind speed and land use as an uncertainty while predicting future wildfire behaviour and propagation.

3.1.1.3.2 Portugal

3.1.1.3.2.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

Carvalho et al. (2011):

- URL1, URL1: AMIPI - Atmospheric Models Inter-comparison Project (http://www-pcmdi.llnl.gov/projects/amip/index.php).
- URL2: SRES GCM change fields (http://www.ipcc-data.org/cgi-bin/ddcvis/gcmcf).

Pereira et al. (2013):

- For the period 1951− 2000, respecting the 20th century model simulations (20C3M), and for 2051−2100, respecting the emission scenario B1.
- Simulated meteorological data were obtained from the Model for Interdisciplinary Research on Climate (MIROC; *Hasumi & Emori 2004*). MIROC is one of the models whose outputs were used in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007).

Carvalho et al. (2010):

- In this study, the data from the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects) project were used to predict future climate in Portugal. Within PRUDENCE several Atmospheric General Circulation Models (AGCMs) and multiple Regional Climate Models (RCMs) are combined in order to predict and to get an estimate of the uncertainty for reference (1961–1990) and future (2071–2100) climate scenarios (PRUDENCE 2005).
- For future climate the changes in the radiative forcing derived from the SRES (Special Report on Emissions Scenarios) A2 scenario were used. The A2 scenario is considered a high emission scenario, and for the time period under consideration in this study, it is equivalent to a 2 × CO2 climatic scenario (IPCC 2007).

Amatulli et al. (2013):

Climatic conditions at the end of the 21st Century were simulated using results from the runs of the regional climate model HIRHAM in the European project PRUDENCE, considering two IPCC SRES scenarios (A2–B2). The MARS models were applied to both scenarios resulting in projected burned areas in each country and in the EU-Med region.

3.1.1.3.2.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models)

Carvalho et al. (2011): Melbourne University General Circulation Model (MUGCM) and a regional meteorological model (MM5) that contains comprehensive descriptions of the atmospheric motion: fields of pressure, moisture and temperature; fluxes of heat, moisture and momentum; turbulence, cloud formation, precipitation and atmospheric radiative characteristics.

Pereira et al. (2013): Burned Area Models (BAMs) based on meteorological variables and/or on fire risk indices defined over the pre-fire and fire seasons.

Carvalho et al. (2010): High Resolution Hamburg Model (HIRHAM).

Amatulli et al. (2013): Regional Climate Model (RCM) HIRHAM (*Christensen et al., 1996*), which is based on the limited area model HIRLAM and the general circulation model ECHAM (*Roeckner et al., 1996*). ERA-40 1961–1990 (meteorological baseline dataset used to correct the RCM-HIRHAM); ERA-40 1985–2004 (meteorological dataset used to build the empirical burned area model); ERA-40 2005–2006 (meteorological dataset used to validate the empirical burned area model); RCM-HIRHAM 1961–1990 (Control run); RCM-HIRHAM A2 2071–2100 (Scenario A2); RCM-HIRHAM B2 2071–2100 (Scenario B2).

3.1.1.3.2.3 The scale of analysis (scale and temporal resolution)

Spatial domains of MM5, using by *Carvalho et al. (2011)*:

Geographical extent	Grid cells	Resolution (km)	Area (km2)
Iberian Peninsula	52 × 52	30	1560 × 1560
Portugal and Galicia	85 × 55	10	850 × 550

3.1.1.3.2.4 Level of uncertainties in predicting changes (if possible)

The results from study *Carvalho et al. (2011)* not including the dynamics between climate / weather / vegetation / fire.

According to the authors of the study *Pereira et al. (2013)* the results of their simulations with the increase of burnt areas are likely overestimated, relating the following factors: (1) the use of GCMs or regional circulation models (RCMs), (2) the use of a linear BAM, and (3) not taking into account other important factors regarding fire occurrence and size. Other limitations come from the fact that the methodology does not account for the role of potential future changes and many other important factors regarding fire occurrence and size that are not yet fully understood nor properly modelled, such as those related to changes in fuel structure; climate−vegetation dynamics and conservation planning; patterns of lightning strikes and anthropogenic activities and drivers of fire, such as control over ignition, fire management, suppression activities, and land use/land cover changes.

Carvalho et al. (2010), used the HIRHAM model where temperature and humidity were taken into account, but the model did not correct the wind speed. The dew point temperature was corrected only for certain months, and not for the tested period as a whole. In addition, according to the authors, the corrections made to the regressions improved the accuracy of the results significantly, but the regressions are not completely accurate. Finally, as always with a RCM model, there is an uncertainty in the predictions of the future climate. Issues to approach in future studies includes determining if there is a difference between the HIRHAM 50 km resolution and the higher resolution (12 and 25 km) versions.

Amatulli et al. (2013) while estimating future burned areas used the three most common modelling techniques MARS (Multivariate Adaptive Regression Splines) outperformed RF (Random Forest) and MLR (Multiple Linear Regression). MARS builds linear functions in each hyper-region based on regression coefficients, which are able to project values outside the data cloud. On the other side, the algorithm tree of RF is often difficult to interpret, since the multi-dimensional complexity of the functions hinders an interpretable representation of the models. However, they believe that statistical techniques specifically designed for the analysis and modeling of extremes have proven to fit the wildfire environment quite well and are certainly worth exploring further to support climate change projections.

3.1.1.3.3 Spain and Catalonia

3.1.1.3.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

In *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)* talk about different scenarios but are not specified.

Finally, in the *Third report on climate change in Catalonia* it is manly used the RCP 4.5.

3.1.1.3.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

Not mentioned in the *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)*.

In the *Third report on climate change in Catalonia* the extreme scenarios have been studied through the extreme scenarios defined by Expert Team on Climate Change Detection and Indices (ETCCDI) of World Metheological Organization (WMO). When it has not been possible to have future scenarios, the method used have been through statistical downscaling (MOS) to the regional climatic models (RCM).

3.1.1.3.3.3 The scale of analysis (scale and temporal resolution)

Not mentioned in the *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)*.

In the *Third report on climate change in Catalonia* the scale of analysis has been 20x20 km.

3.1.1.3.3.4 Level of uncertainties in predicting changes (if possible)

Not mentioned in the *Law 16/2017 on Climate Change (Catalonia)* and *Project of Law on Climate Change and Energy Transition (Spain).*

In the case of the *Third report on climate change in Catalonia*, it is mentioned that there are high uncertainties regarding the possible development of new wildfires episodes (wildfires in mountain areas, or in winter or spring). The uncertainty is also related to the number of extreme episodes, that could be increased linked to expected summer critical conditions. Regarding avalanches, there is also a high level of uncertainty to predict the future avalanche activity.

3.1.1.3.4 Italy

3.1.1.3.4.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

CMCC (2017) and *CMCC (2020)*: A1B, RCP4.5 and RCP8.5.

Faggian (2018): RCP 4.5, A1B (Eq. RCP 6.0), RCP 8.5 and Fire Weather Index.

Michetti and Pinar (2019): A1B of the IPCC Special Report on Emissions Scenarios (SRES) (Morita et al. 2001).

3.1.1.3.4.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

CMCC (2017) and *CMCC (2020):* The regional climate models of the EURO-CORDEX program, with spatial resolution at 12 km, and the COSMO-CLM model in the configuration developed by the CMCC Foundation for Italy, with spatial resolution at 8 km, were used in this analysis with three climate scenarios (RCP2.6, RCP4.5 and RCP8.5) of the Intergovernmental Panel on Climate Change (IPCC).

Faggian (2018): One RCM for MED-CORDEX (ICTP-RegCM4) (for fire danger analysis).

Michetti and Pinar (2019): Climate change projections for Italy are derived from European-scale projections resulting from the ENSEMBLES project (http://ensembles-eu.metoffice.com/), which uses regional climate models (RCMs) driven by global climate models (GCMs). The underlying socioeconomic scenario, governing the future amount of greenhouse gas concentration in the atmosphere leading to the assumed values of precipitation and temperature, is the A1B of the IPCC Special Report on Emissions Scenarios (SRES) (Morita et al. 2001).

3.1.1.3.4.3 The scale of analysis (scale and temporal resolution)

CMCC (2017) and *CMCC (2020)*: Provide an estimation of the impact of projected changes in temperature and precipitation on forest fire frequency for two future periods (2021-2050 and 2071-2100)

Faggian (2018): Provide an estimation of the impact of projected changes in a grid cell (12 or 25 km)

Michetti and Pinar (2019): Provide an estimation of the impact of projected changes in temperature and precipitation on forest fire frequency and total area burnt for different geographical clusters in Italy during 2016–2035.

3.1.2 Floods

3.1.2.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

3.1.2.1.1 Europe

The *European Floods Directive* (2007/60/EC) generalizes: “the scale and frequency of floods are likely to increase in the future as a result of climate change, inappropriate river management and construction in flood risk areas.”

Atmospheric warming and associated hydrological changes have significant implications for regional flood intensity and frequency. To investigate climate change impacts on the hydrological cycle, research employed a combination of climate and hydrological models that have the ability to integrate various contributing factors and assess potential changes to hydrology at global to local scales through the century *(Andersen and Marshall Shepherd, 2013).*

The European Environmental Agency (EEA) in *Climate change adaptation and disaster risk reduction in Europe* (2017) systematizes the different studies developed in the European context and returns an overall picture of the possible impacts on floods resulting from climate change.

According to the *EEA (2017)*, extreme weather and climate-related events, that result in hazards such as floods and droughts, will become more frequent and intense in many regions and impacts related to changes in precipitation, notably heavy precipitation events leading to floods and landslides, are projected to increase further in the future. Pluvial floods and flash floods, which are triggered by intense local precipitation events, are likely to become more frequent throughout Europe, while in regions with projected reduced snow accumulation during winter, the risk of early spring flooding could decrease.

EEA referred to future changes in the risk of river floods in Europe, by summarising some studies (*Rojas et al., 2012; Alfieri et al., 2015 and Kundzewicz et al., 2017)* that use a hydrological model driven by an ensemble of climate simulations.

An interested result of these analyses is related to the frequency analysis of flood peaks above the 100-year flood level, which is the average protection level of the European river network (Rojas et al.,2013; Jongman et al., 2014) in the RCP8.5 scenario (high-level greenhouse gas concentrations in the atmosphere). In particular it is possible to argue that using three different future periods based on the hydrological model LISFLOOD and an ensemble of seven climate models, the level of change in 100-year (Q100) floods shows large regional differences in Europe (*Alfieri et al., 2015*).

For the end of the 21st century, the greatest increase in Q100 floods is projected for the British Isles, north-west and south-east France, northern Italy and some regions in south-east Spain, the Balkans and the Carpathians. Mild increases are projected for central Europe, the upper section of the Danube and its main tributaries. In contrast, decreased Q100 floods are projected in large parts of north-eastern Europe owing to a reduction in snow accumulation, and hence melt-associated floods, under milder winter temperatures *(Madsen, 2014).* These results are consistent with earlier studies *(Dankers and Feyen, 2008; Ciscar et al., 2011; Rojas et al., 2012)*.

For example, in northern Europe, rainfall-dominated floods in smaller rivers may increase because of projected increases in precipitation amounts, even where snowmelt-dominated floods in large rivers are projected to decrease *(Vormoor et al., 2016)*.

In particular in *Global warming increases the frequency of river floods, Alfieri et al (2015)* investigated projected changes in the magnitude and frequency of different hydrometeorological variables to assess future changes in flood hazard in Europe. The results indicate that the change in frequency of discharge extremes is likely to have a larger impact on the overall flood hazard as compared to the change in their magnitude. On average, in Europe, flood peaks with return periods above 100 years are projected to double in frequency within 3 decades.

The authors found that by the end of the century, both mean annual precipitation and average discharge are projected to decrease in southern Europe and to increase in north-eastern Europe, while in central Europe the ensemble of projections does not agree on a specific trend. Projected changes in extreme values are on average less significant and show different spatial patterns for precipitation and discharge. On the one hand, a positive trend for the maximum daily precipitation is found in most of the study region, with both magnitude and statistical significance becoming stronger moving towards eastern and northern Europe. On the other hand, the trend of future discharge extremes has a rather different pattern, as a consequence of the interplay among various hydrological processes, which includes the effects of a warming climate on the reduced snow accumulation cycle and the growth of evapotranspiration rates. As a result, the authors found a reduction of peak discharges in southern Spain, Scandinavia and Baltic countries, while a large portion of central Europe including the British Isles are likely to experience a progressive increase in the magnitude and frequency of discharge peaks.

Finally, a frequency analysis on simulated peaks over a threshold revealed further insight on the distribution of future extreme peak flows in Europe. Interestingly, the expected annual frequency of events with peak discharge above the 100-year return period is projected to rise significantly in most of the considered European countries, including some where the overall number of severe events is likely to decrease. The projected figures are unsettling, showing significant increase in the frequency of extreme events larger than 100% in 21 out of 37 European countries since the first time slice (2006–2035), and a further deterioration in the subsequent future. These findings relate to a range of event magnitude mostly above the average protection level of European rivers, hence they have serious implications on the associated flood risk and the potential impact on business and society.

Another interested study has been conducted by:

- *Sassi et al. (2019)* in *Impact of climate change on European winter and summer flood losses* that investigated the impact of precipitation change on European average winter and summer financial losses due to flooding. The results show that for both raw and bias-corrected statistics the average flood loss in Europe generally tend to increase in winter and decrease in summer for the future scenario, and - consistent with that change - they also show that the average flood losses have increased (decreased) for winter (summer) from pre-industrial conditions to the current day. The magnitude of the change varies among scenarios and statistics chosen.

- *Madsen et al. (2014)* in *Review of trend analysis and climate change projections of extreme precipitation and floods in Europe* that reviewed many trend analysis and climate change projections of extreme precipitation and floods in Europe. The review of likely future changes based on climate projections indicates a general increase in extreme precipitation under a future climate - which is consistent with the observed trends - and hydrological projections of peak flows show large impacts in many areas with both positive and negative changes. Despite expected increases in extreme precipitation throughout Europe, many areas dominated by peak flows during the spring to early summer snowmelt season are projected to have decreased flood magnitudes under a future climate, reflecting a decline in snow storage during winter periods. In addition, peak flows are expected to occur earlier. These projections are consistent with the observed trend towards earlier snowmelt peaks and decreases in spring peak flows.

- *Dankers and Feyen (2008)* in *Climate Change Impact on Flood Hazard in Europe: An Assessment Based on High-Resolution Climate Simulations*, that reported a likely decrease in the 100-year return level – Q100 is the average protection level of the European river network - in northeastern Europe, as well as in some rivers in central and southern Europe, and increases in many parts of western and eastern Europe. Increases are also projected for the British Isles and northern Italy, while decreases are indicated in some rivers in eastern Germany, Poland, southern Sweden and the Baltic countries. The decreases projected for southern Sweden, as well as some of the increases projected for inland rivers in Norway, are somewhat at odds with the projections reported based on national studies *(e.g., Lawrence and Hisdal, 2011; Bergstrom et al., 2012; Lawrence et al., 2012*).

Reviewing many studies on future floods projection, *Kundzewicz et al. (2017)* in *Differences in flood hazard projections in Europe – their causes and consequences for decision making* stressed that projections from most European scale studies (except Lehner et al. 2006, reporting largely different results) show some robustness and similarity, in general. However, there is much less agreement on projections of flood hazard in Europe (i) between the European-scale and global-scale studies, as well as (ii) between different global-scale studies. There is a systematic difference between projections of changes in flood hazard in southeastern Europe (Italy, Greece, Iberian Peninsula) in most European and most global studies. The main causes of differences identified in their review analysis are related to different emissions scenarios, driving climate models and downscaling techniques, as well as bias correction methods. Further, there are differences in simulation of hydrological processes by global hydrological models and regional hydrological models and their performance, especially for extremes, as well as general problems related to extreme value techniques applied for time series that are not long enough. Differences can also be found in the time horizons of future projections, as well as resolution of impact models, and return period. Also, the control (reference) intervals often differ between studies. Moreover, they stressed that flood hazard may be specifically connected, regionally or locally, to particular flood types and temporal/spatial scales that are not adequately covered by the conceptualization of the processes in the large-scale models. Hence, the results of the projections could more appropriately be seen as indicators of changes in flood hazard. Flood typology relies on meteorological inputs and also on catchment controls and flood time scales (elevation, catchment scale, river scale etc.).

3.1.2.1.2 Portugal

In Portugal, during 1865-2010 1.621 disastrous floods and 281 disastrous landslides were recorded that led to casualties or injuries, and missing, evacuated or homeless people (Azores and Madeira were not considered). These occurrences were responsible for 1,251 casualties. More than half of this number of casualties was due to a single flash flood event in the Lisbon region in November 25–26, 1967. During 1865-2010 no increase in the number of events in time can be observed *(Zêzere et al., 2014).*

The majority of cases (85.2 %) were floods that caused 81 % of total casualties. Clusters with high density of flood cases are observed in the Lisbon region and the Tagus valley, in the Oporto region and the Douro valley, in the Coimbra region and the Mondego valley and along the Vouga river Valley. Most floods occurred in November to February (75.6 % of total flood cases), while landslides tend to concentrate from December to March (73 % of total landslide cases) *(Zêzere et al., 2014).*

The climatic scenarios put forward by the global and the regional models show a clear trend towards a concentration of precipitation in winter and a drastic decrease in summer. This evidence is particularly clear for northern Portugal. Central and southern Portugal may register an increase of the number of winter´s days with precipitation above 50 mm, by 2100 *(Veiga de Cunha et al., 2000).*

A decrease in summer and autumn runoff will be observed in different regions of Portugal. By 2060, runoff is projected to decrease by 13% for the northwest of the Iberian Peninsula, 22% for the Douro river basin, 17% for the Tejo river basin and 23% for the Guadiana river basin. Also by 2100, the annual mean runoff in the Vouga and Mondego basins may be reduced from 15% to 30% *(Ayala-Carcedo, 2000).*

The HadCM3 and HadRM2 models predict a reduction in the summer and autumn runoff between 10% and 80% at the national level. The concentration of precipitation in winter and the estimated general increase in the frequency of heavy precipitation events is likely to increase the flood magnitude and frequency, particularly in the northern part of the country *(Veiga de Cunha et al., 2000).*

3.1.2.1.3 Italy

At Italian level according to the *Italian National climate change adaptation plan* (CMCC, 2017), the frequency of river floods will be more impacted in basins with reduced permeability that respond more quickly to meteoric stresses and have reduced mitigating effect against short-term and high intensity precipitation. Urbanization and land use can have a negative impact, contributing to the aggravation of hydro-geological phenomena.

As confirmed also in *Risk analysis: climate change in Italy (CMCC, 2020)*, many anthropogenic factors have contributed significantly over the years to the initiation or exacerbation of the geo-hydrological risk in Italy. Climate change induces an increase in the frequency and intensity of some atmospheric events that regulate the occurrence of the hydrogeological phenomena. From the combined analysis of these factors and of the climatic scenarios, it is clear that the worsening of a very complex situation is expected. The rise in temperature and the increase in precipitation phenomena localized in space play an important role in exacerbating the risk. In the first case, the melting of snow, ice and permafrost indicates that the areas most affected by variations in magnitude and seasonality of the instability phenomena are the Alpine and Apennine areas. In the second case, heavy rainfall contributes to a further increase in the hydraulic risk for small basins and the risk associated with surface landslides in areas with more permeable soils.

3.1.2.2 The cascade effects or feedback effects triggered

3.1.2.2.1 Europe

Not all climate change impacts, will emerge in the same way or at the same time: some emerge abruptly, others slowly and are ongoing, and there can be multiple impacts which occur concurrently and in different combinations. The interactions between these impacts therefore will have spatial and temporal implications, propagating across different settings and contexts (*Lawrence et al., 2020*).

Cascades result from interdependencies between systems and sub-systems of coupled natural and socio-economic systems in response to changes and feedback loops. The combined effects of interacting stressors may affect the ability of individuals, governments, and the private sector to adapt in time, before widespread damage occurs (*Lawrence et al., 2020*).

According to *Cradock-Henry et al.*, there is little practical guidance for those interested in characterising, identifying or assessing cascades, and few empirical examples. They elaborate a systems-based methodology to identify and evaluate cascading climate change impacts and implications.

3.1.2.2.2 Portugal

Precipitation events will likely be concentrated in wintertime leading to a strong decrease in water availability during the remaining seasons of the year. The runoff reduction appears to be small in the northern region of Portugal, but increases progressively towards the south. If confirmed, this trend will increase the current spatial asymmetry of water availability in Portugal.

Moreover, a 5% to 10% increase in crop water demand is expected by 2060, when assuming the continuation of current crops. It is also expected that water quality will he degraded by higher water temperatures and by river flow re-duction in the summer, particularly in the southern region.

3.1.2.2.3 Italy

According to the *Risk analysis: climate change in Italy* (*CMCC, 2020*), the scientific community ascribes an important role in exacerbating the geo-hydrological risk to the increase in temperature, with a consequent effect on the melting of snow, ice and permafrost. The data available on Italy regarding rainfall suggest that the conditions of geological, hydrological risk and plumbing are exacerbated as a result of (i) an increase in the number of precipitation extreme events (expected from climate change studies) and (ii) an increasing urbanization of the territory which led, on the one hand, to an increase in outflows and a reduction in disposal capacity from part of the river beds (tombstones, reduction of the extension of floodplain areas, etc.), on the other hand, to an increase risk exposure.

Moreover, climate change is expected to further exacerbate specific components of fire risk, resulting in impacts on exposed people, assets and ecosystems in the most vulnerable areas. Increases in the danger of fire, altitude shift of vulnerable areas, extension of the fire season and an increase in extremely dangerous days are expected which, in turn, could translate into an increase in the surfaces traveled with a consequent increase in gas emissions. greenhouse and particulate matter, therefore with impacts on human health and the carbon cycle.

In this regard, according to *Esposito et al. (2019)* in *Characterizing Consecutive Flooding Events after the 2017 Mt. Salto Wildfires (Southern Italy): Hazard and Emergency Management Implications,* the effects of wildfire (partial or complete destruction of vegetation and changes in soil hydraulic properties) alter the hydrologic response of watersheds, increasing post-fire debris and sediment-laden flow hazard.

3.1.2.3 Climate change modelling chain

3.1.2.3.1 Europe

3.1.2.3.1.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

Dankers and Feyen (2008): A2, B2 at 50 km and A2 at 12 km SRES scenarios.

Rojas et al. (2012): A1B scenario.

Sassi et al. (2019): RCP2.6 1.5 °C warming scenario.

Alfieri et al. (2015): RCP 8.5.

EEA (2017): RCP8.5 scenario.

3.1.2.3.1.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

Dankers and Feyen (2008): HadAM3H/ HIRHAM4 RCM.

Rojas et al. (2012): Larger ensemble of GCM/RCM combinations ENSEMBLES representing 5 GCMs and 8 RCMs and the LISFLOOD hydrological model.

Sassi et al. (2019): Community Atmospheric Model (CAM) version 5 and RMS European Flood Model (probabilistic, high resolution flood catastrophe model that is widely used in the insurance industry to estimate flood risk for a given portfolio of insured exposures).

Alfieri et al. (2015), also cited by EEA (2017): Seven EURO-CORDEX climate projections fed into a distributed hydrological model LISFLOOD.

Arnell and Gosling (2014): The simple climate model MAGICC (Osborn 2009). CMIP5 and Mac-PDM.09 (a daily water balance model).

3.1.2.3.1.3 The scale of analysis (scale and temporal resolution)

Dankers and Feyen (2008): HadAM3H/ HIRHAM4 RCM.

Rojas et al. (2012): Climate simulations with a lateral resolution of ca.25 km, covering the period 1961–2100. A re-gridding process (nearestneighbor) was required to project this information onto the 5 km grid of LISFLOOD (hydrological model).

Sassi et al. (2019): Approximately quarter degree spatial resolution (reflecting a projected climate in the year 2115).

Alfieri et al. (2015): 0.11 horizontal resolution (˜12 km) and meteorological variables of the seven climate scenarios regridded at 5 km x 5 km (from 2006 to 2100).

Arnell and Gosling (2014): Based on the estimation of flood frequency relationships at a grid resolution of 0.5×0.5°, using a global hydrological model with climate scenarios derived from 21 climate models, Together with projections of future population.

3.1.2.3.1.4 Level of uncertainties in predicting changes (if possible)

At the regional and local scale, the projections provided by different studies are not always in agreement and quantitative projections of changes in flood frequency and magnitude remain highly uncertain (*EEA, 2017*).

As reported by *Sassi et al. (2019)* in *Impact of climate change on European* winter and summer flood losses, assessments of climate change on flood risk can be very uncertain for many reasons, such as climate model choice (*Deser et al., 2012*), downscaling and bias-correction procedures, hydrological model choice and parameter estimation (*Donnely et al., 2017*).

As stressed by *Kundzewicz et al (2017)*, other sources of uncertainty arise when:

- only a small number of years of flooding are simulated: many studies of future flood risk based on climate models output have been limited to simulations of no more than 100 years;
- ground data have not an adequate quality and quantity and so the material for calibration and validation is not satisfactory.

Rojas et al. (2012) in *Assessment of future flood hazard in Europe* using a large ensemble of bias-corrected regional climate simulations obtained the future projections using a 12-member ensemble of high-resolution climate simulations; correcting (large) biases in the precipitation and temperature fields employing a QM method (*Piani et al., 2010;Dosio and Paruolo, 2011*) using the high-resolution E-OBS data set as target; and implementing a robust approach to quantify climate (inter-model) and extreme value fitting (intra-model) uncertainties; hydrological results were validated against 30 years of observational data at 554 gauging stations located across Europe, hereby representing a wide range of climatic and hydro-morphological conditions.

Results show that large uncertainties are tied to the projected changes of future extreme discharges. Uncertainties originate mainly from the climate projections, where both GCM and RCM might provide similar levels of uncertainty translated to the impact model (LISFLOOD). Fitting results at individual stations confirm the danger in relying on single climate projections, as few outlier simulations can considerably deviate from the other members of the ensemble. Therefore, a multi-model approach is essential to provide a reliable assessment of future flood hazard. The uncertainty analysis also revealed that in the majority of river cells that show a considerable change in the ensemble-average flood magnitude, climate and fitting uncertainty tend to follow the change in flood magnitude. This suggests that in these cells mostly the high-end tail extreme values will be affected by climate change. In addition, for flood hazard assessment, climate (or inter-model) uncertainty takes a significant share out of the total uncertainty, which will continue to be relevant by the end of the century.

In *Global warming increases the frequency of river floods in Europe* by *Alfieri et al (2015)*, changes in the frequency of future extreme peak flows were evaluated by the authors on the sample of simulated peaks over threshold, rather than on values taken from the analytical curves fitted on the sample of selected maxima. This enables a more consistent evaluation (1) of the frequency of extreme events and (2) of relative changes between the baseline and the future scenarios, thanks to the use of the same frequency distribution (i.e., of the baseline) as reference for the comparison. An improved evaluation and visualization of the uncertainty has been proposed by the authors, based on the coefficient of variation computed on the ensemble of relative changes of the model projections. The proposed method is similar to that used in previous studies, though it is more suitable to detect variations of an ensemble of projections, each with a relative baseline simulation.

3.1.2.3.2 Portugal

3.1.2.3.2.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

Ayala-Carcedo, F. (2000): Impactos del Cambio Climático Sobre los Recursos Hídricos en España y Viabilidad del Plan Hidrológico Nacional 2000. Madrid.

IPCC, 1996. Climate Change (1995): The science of Climate change, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge.

IPCC, 2001. Climate Change (2001): The science of Climate change, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge.

IPCC-TGGIA 1999. Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version I. Prepared by Carter, T. R. et al., IPCC. Task Group on Scenarios for Climate Impact Assessment.

3.1.2.3.2.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

HadCM2, HadRM2 and HadCM3 - IPCC, 2001. Climate Change 2001. The science of Climate change, Contribution of Working Group II to the Second Assessment Report of the Intergovernamental Panel on Climate Change. Cambrige University Press. Cambridge.

3.1.2.3.2.3 The scale of analysis (scale and temporal resolution)

Acronym	***Source***	***Scale***	***Resolution***
HadRM2	Hadley Centre for Climate Prediction and Research	Regional	40 x 50 km
HadCM2	Hadley Centre for Climate Prediction and Research	Global	220 x 420 km
HadCM3	Hadley Centre for Climate Prediction and Research	Global	220 x 420 km

3.1.2.3.3 Italy

3.1.2.3.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

CMCC (2017) and *CMCC (2020)*: RCP4.5 and RCP8.5.

3.1.2.3.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

CMCC (2017) and *CMCC (2020):* RCM COSMO-CLM in the configuration optimized by the CMCC on Italy (*Bucchignani et al., 2016; Zollo et al., 2016*) and eleven EURO-CORDEX models.

3.1.2.3.3.3 The scale of analysis (scale and temporal resolution)

CMCC (2017) and *CMCC (2020):* spatial resolution of 8 km, covering the periods 2021-2050 and 2071-2100 for COSMO-CLM and spatial resolution of 12 km from 1971 to 2100 for EURO-CORDEX models.

3.1.2.3.3.4 Level of uncertainties in predicting changes (if possible)

In the *Italian National climate change adaptation plan* (CMCC, 2017): the future climate projections were obtained considering two different IPCC scenarios: RCP4.5 and RCP8.5. in order to evaluate the uncertainty of the climate projections with respect to the two scenarios considered. Currently, considerable and different sources of uncertainty (among others, the quantity and quality of historical series of observations, shortcomings of the current modelling chains of climate simulation, contemporary variations in land use and cover and levels of anthropization) make complex and the estimate of the variation of occurrence and magnitude of the instability phenomena is uncertain.

Moreover, according to the *Risk analysis: climate change in Italy* (CMCC, 2020), there are currently several factors that make the estimate of the occurrence and magnitude variation of the hydrogeological phenomena complex and uncertain, such as for example the quantity and quality of the historical series of observations, limits from the point of view of spatial resolution and of the climate models that represent the input for hydrological, hydraulic and slope stability models, adequate spatial and temporal knowledge of the variations in the use and cover of the land and levels of anthropization. However, given the relevance and diffusion, the problem of geo-hydrological instability on the whole national territory, the definition of adaptation actions and the priority contexts on which to operate to mitigate the effects of these phenomena are currently essential and can no longer be postponable.

3.1.3 Storms

3.1.3.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

Storms can have several reasons. In RECIPE we focus predominantly on the type "winter storm" resulting from extratropical low pressure systems at midlatitude level. This type of storm appears almost exclusively during the winter half-year (October – March) due to high temperature gradients between the subtropics and polar regions. In the area where both, warm and cold air masses collide a so-called polar front emerges and more or less extreme low pressure systems form that are moved by westwards currents over the North Atlantic onto Central Europe. Under certain circumstances (e.g., very large horizontal differences of air temperature and water vapour content) intensive cyclones can form resulting in hurricane like wind speeds. Characteristically, winter storms have a vast geographic spread (diameter of 1000 km or more), which allows to distinguish them from other storm events with smaller scale.

The most influential climate variable determining wind disturbance remains the frequency and intensity of strong winds, for which current and future trends remain inconclusive (*Seidl et al., 2017*). There are indications that climate change influences the occurrence and duration of winter storms and very likely increases frequency and severity (i.e., peak wind speeds) across Europe (*Donat et al., 2011*). Projected changes in extreme wind speeds are indicated to rise in Central and Northern Europe, while slightly declining over the Mediterranean region. Likely, there is a poleward shift of midlatitude storm tracks. Consequently, areas that were previously untouched by severe windstorms will have to face a new hazard situation. Additionally, new and unknown weather phenomena may arise.

Climate-mediated changes in forest structure and composition were particularly relevant in the context of wind disturbance. Wind disturbance, for instance, which is currently the most important disturbance agent in Europe, is expected to respond more strongly to changes in precipitation (and the corresponding changes in tree soil anchorage and tree growth) than to warming temperatures. Indirect effects, mediated by climate-related changes in vegetation structure and composition, were most frequently reported for wind disturbance,

Indirect effects of climate change are changes in tree anchorage (e.g., less soil frost), wind exposure (e.g., tree growth) and overall wind resistance of stands (e.g., tree species composition).

3.1.3.2 The cascade effects or feedback effects triggered

In combination with other weather phenomena, winter storms can lead to cascading effects or lead to feedback events. A phenomenon observed in recent years is relatively sudden temperature changes during winter in conjunction with high wind speeds resulting in flooding and landslides. An approaching storm front often leads to quick temperature rise and brings along high levels of precipitation. The resulting rapid snowmelt fills streams that may be blocked with fallen trees (fallen due to lower root anchoring capacities) and provoking landslides on steep slopes. In proximity to human dwellings this can lead to overwhelming situations for local emergency bodies and case severe damage.

Storm damage in forest areas in combination with drier and hotter summer months lead to increased biotic threats for trees and forests (e.g., bark beetle infestation, pathogens spread). That way, even small and per se non-severe storm damage in forests provide ideal conditions for pest and pathogen populations to build up and spread to other unaffected parts of a forest. In the years 2018 and 2019 the described combination of hazards has led to unprecedented situations in the German forestry sector: dead trees need to be left standing in the forest, as forest managers and private forest owners are lacking transportation capacities or economically it is not viable. This leads to an additional threat to people, as dead trunks can fall.

Simultaneously, the proliferation of pests and diseases has an impact on wind exposure (e.g., insect disturbances increases canopy roughness), soil anchorage (e.g. pathogens decrease rooting stability) and resistance to stem breakage (e.g. pathogens decrease stability).

Meanwhile, there is an increase in the occurrence of local extreme weather events with smaller geographical extension, such as heavy precipitation, hail storms, and tornados. However, compared to the impact of winter storms, the potential threat of these events on forests is substantially smaller. Nevertheless, the local devastation of these types of new weather events makes them worth to be considered. In the following, we concentrate on heavy winter storms as these are most relevant for the forestry sector.

3.1.3.3 Climate change modelling chain

3.1.3.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

Donat et al. (2011): SRES A1B scenario (A1B).

Peltola et al. (2010): A2.

3.1.3.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

Donat et al. (2011): Nine GCM simulations from five different GCMs were examined (ENSEMBLES project setup, see Table 1a).

3.1.3.3.3 The scale of analysis (scale and temporal resolution)

From *Donat et al. (2011)*: Daily maximum calculated for 6-hourly instantaneous values of wind speed, resulting in four instantaneous wind speeds stored at 00:00, 06:00,12:00 and 18:00 UTC.

All scenario simulations followed the SRES A1B scenario and were integrated until at least the year 2050. A smaller set of simulations continued until the year 2100.

All RCM simulations were carried out for a common domain including the whole continental European area (from approximately 10 W to 40 E and 30 N to 65 N). Overall, a set of 14 RCM simulations was considered (see Table 1b for a list and description of labelling nomenclature), downscaling seven different GCM runs. Most RCM simulations were carried out at a resolution of 0.22 (approximately 25 km), but two (KNMI-RACMO2 E5 1/2) were performed at a coarser resolution of 0.44 (approximately 50 km).

Peltola et al. (2010): Nation-wide (Finland).

3.1.3.3.4 Level of uncertainties in predicting changes (if possible)

From *Donat et al. (2011)*: Numerical climate model simulations are affected by various uncertainties, the most important ones being model uncertainties, uncertainty due to internal variability, and sensitivity to the initial conditions and to boundary conditions (*Murphy et al., 2004; Stainforth et al., 2005; Giorgi, 2006*). Wind storm occurrence has particularly high variability (*Bärring and von Storch, 2004; Wang et al., 2009*). Hence, a reliable estimation of long-term changes requires large samples, which can also be obtained from ensemble simulations (see, for example, *Della-Marta et al., 2010; Donat et al., 2010a*).

3.1.4 Avalanches

3.1.4.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

Research related to risk of avalanches and climate change is diverse. Clearly, we can define five groups. In total, more than 50 research have been analysed (see references): documents, tools, projects, guidelines, etc. related to **snow avalanches** (natural hazard), **multi-risk or cascade effect**, **hazard factors** (snowpack, terrain, weather, overloading), **exposure categories** (population, infrastructure, buildings, critical facilities, economic activities, environmental services) and **risk management**. However, we can find research that encompasses more than one group.

Specially, we found a greater number of research on natural risk (snow avalanches) and hazard factors (basically the snowpack). Instead, we found some studies related to the elements exposed to risk, such as economic activities (ski resorts), and research in relation to multi-hazards, cascade effects or risk management in a context of climate change. More research seems to be needed, in relation to the implementation of climate change knowledge concerning snow avalanche risk management.

The impact of climate change on snow avalanche risk is uneven across territories. Each territory has its own particularities (snow cover, terrain, meteorology and climatology, population, infrastructures, critical facilities, economic activities, environment services, etc.) and therefore, climate change affects them differently.

Depending on the territory there are different future projections. In some places the forecasted the number of snow avalanches will increase (*Ballesteros-Canovas et al., 2018*), while in other mountain areas it is expected to be the same or even decrease (*Naaim et al., 2016*).

In contrast, a large majority of research agrees that the number of wet snow avalanches is expected to increase in the coming decades as a result of rising global temperatures (*Garcia, 2016*). Some studies indicate that wet snow avalanches, in addition to being more frequent, will advance in the calendar (*Lazar et al., 2007*). Other research analyzes the climatology of snow avalanches and predicts lower activity in winter and an increase during spring, with a higher number of wet snow avalanches (Martin, et al., 2001). Snow avalanche activity is also expected to decrease in low-mid mountain areas and increase in high areas, but research, in relation to the effects of climate change, is limited and conclusions vary depending on the place and time (*Wilbur et al., 2018*).

Other aspects are also analyzed, such as the relationship between specific synoptic situations, weather conditions and avalanche episodes (*Jaedicke et al., 2008; Garcia, 2017*). The North Atlantic Oscillation (NAO) is also related to the danger of snow avalanches. The expected trend, in relation to climate change, with the NAO at a positive stage, whereby places such as Norway may see an increased risk of snow avalanches in relation to prolonged situations of positive phases of the NAO (*Laute et al., 2018*). This does not mean that inverse situations of negative phases cannot occur, given the typical variability of the climate at the interannual level.

Regarding the factors of hazard, much emphasis is placed on the analysis and future perspective of the snowpack in various mountain areas. Greater stability of the snowpack is expected (Wilbur et al., 2018), but at the same time greater internal instabilities are also expected, due to the increase in temperature and precipitation in the form of liquid water (*Bellaire et al., 2013*). This depends on the climatic characteristics of each mountain area.

A decrease in the thickness and duration of the snowpack is expected, especially on sunny slopes and at lower altitudes (*Garcia et al., 2017*). It is the lower altitude mountain areas that are most sensitive to the effects of climate change (Howat et al., 2005). A loss of snow cover is expected during spring, which is accentuated by temperature increases of 1ºC (*Casola et al., 2009*). Climate change scenarios suggest a decrease in snow cover and snow water equivalent (SWE) which could lead to new water resource management problems. (*Özdogan, 2011*).

We find projects such as the "European Network for a harmonized monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction" that highlight one of the needs that some risk managers pointed out in the interviews, which is the monitoring of snow and snow cover on sunny slopes, for a better understanding of how global warming affects it.

3.1.4.2 The cascade effects or feedback effects triggered

Research focused on the impact of climate change on economic mountain activities such ski resorts. For example, according to studies, a shorter duration of the ski season and a decrease in low-altitude skiers is projected (*Pons et al., 2012*). Therefore, climate change affects both ski resorts and people, with a higher concentration of skiers, snowboarders, etc. at higher altitudes (hazard factors).

There are guidelines that predict an increase in multi-risk or cascading effects. For example, a higher number of fires in forested and snow avalanches areas at the same time, favours greater snowpack instability and less protection if too much forest was lost due to these fires (*Guidelines for Snow Avalanche Risk Determination and Mapping in Canada, 2002*).

Some research predicts that the snowmelt period will be shortened from one to a month and a half in years that are very snowy. In contrast, in years of low snowfall the duration of the snow melting process is expected to be very similar to the current period (*Asaoka et al., 2013*).

3.1.4.3 Climate change modelling chain

The following are some examples of models used in climate change analysis toward snow avalanche risk.

SNOWPACK model. SNOWPACK is widely used for research purposes all around the world in more than 35 institutions. The model has been successfully applied to the Alps, Scandinavia, Northern America, Japan, Russia, even Antarctica. It has lead (together with Alpine3D, its spatially distributed derivative) to more than 60 ISI publications. It has been used for hydrological studies, **climate change impact studies**, snow stability questions, road weather applications, permafrost research, snow farming, etc. (SNOWPACK, 2020. In *WSL Institute for Snow and Avalanche Research SLF*).

HIRHAM Regional Climate Model. HIRHAM is a regional atmospheric climate model (RCM) based on a subset of the HIRLAM (*Undén et al., 2002*) and ECHAM models (*Roeckner et al., 2003*), combining the dynamics of the former model with the physical parameterization schemes of the latter. The HIRLAM model – High Resolution Limited Area Model - is a numerical short-range weather forecasting system developed by the international HIRLAM Programme (http://hirlam.org) and is used for routine weather forecasting at a number of meteorological institutes, i.e., DMI (Denmark), FMI (Finland), IMS (Iceland), KNMI (The Netherlands), met.no (Norway), INM (Spain), and SMHI (Sweden). The ECHAM global climate model (GCM) is a general atmospheric circulation model developed at the MaxPlanck Institute of Meteorology (MPI) in collaboration with external partners. The original HIRHAM model was collaboration between DMI, the Royal Netherlands Meteorological Institute (KNMI) and MPI. (*Danish Climate Centre, Ministry of Transport and Energy, 2007*).

Snowmelt Runoff Model. SRM can be used to simulate the daily streamflow of a snowmelt season, in a year, or in a sequence of years, to provide short-term and seasonal runoff forecasts, and to evaluate the potential effect of **climate change** on the seasonal snow cover and runoff (*Martinec J. et al., 2019*).

Snow Thermal Model – SNTHERM. Information on snowpack properties. Applications like water availability, reservoirs managing, flood forecasting, and **assessing climate change impacts** are just some few examples in which these data play a critical role. (SNTHERM – Snow Thermal Model, 2012).

WRF-HadCM3. HadCM3 is a coupled climate model that has been used extensively for climate prediction, detection and attribution, and other climate sensitivity studies. This particular model is used for climate change projections in relation to snowfall for example. (HadCM3: Met Office climate prediction model, 2020).

MAGICC-SCENGEN. This model is used to model **climate change projections**. **MAGICC** consists of a suite of coupled gas-cycle, climate and ice-melt models integrated into a single software package. The software allows the user to determine changes in greenhouse-gas concentrations, global-mean surface air temperature, and sea level resulting from anthropogenic emissions. **SCENGEN** constructs a range of geographically explicit climate change projections for the globe using the results from **MAGICC** together with AOGCM climate change information from the CMIP3/AR4 archive (MAGICC/SCENGEN, 2020).

Crocus-MEPRA-SAFRAN. Crocus is an unidimensional thermodynamic-based computer model able to simulate the energy and mass balance of the snowpack. Its main purpose is to accurately describe the time evolution of the physical properties of the inner snowpack (thermal conduction, radiative transfer) based on a semi-quantitative description of the time evolution of the morphological properties of the snow grains along with snow metamorphism. This approach allows to realistically simulate energy and water fluxes at the snowpack interfaces (ground and atmosphere). **MEPRA** is an expert system of avalanche risk forecasting. The main objective of this model is to analyze the mechanical stability of the Crocus snowpack and then estimate a spontaneous avalanche risk and an accidental avalanche risk. MEPRA is a helping tool for all the avalanche forecasters to analyze all the SAFRAN-Crocus-MEPRA simulated snowpack (2618 simulated points in the French Alps and 2786 for the whole Pyrenees). The merge of mechanical and expert approach for snowpack natural and accidental stability analysis is the MEPRA originality. The objective analysis module **SAFRAN** (*Durand et al., 1993*) originally developed at CNRM/CEN for operational needs estimate avalanche hazard in mountainous areas, is a simple application particularly suited for viewing or initializing 1D models. It is also used operationally for hydrological monitoring and estimating rates throughout the metropolitan France. Its main features are the use of a non- regular grid and flexibility in the areas of analysis and observations used and the ability to run on small computer configurations. SAFRAN is also a tool for research and development which is the basis of many studies on the impact of climate and climate change. (*Crocus-SAFRAN-MEPRA, 2020*).

3.1.4.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

After analyzing the literature in relation to snow avalanches towards climate change, we found that various climate change scenarios are generally used (various future projections). For example, the SRES scenarios (A2, B1, B2, A1B, A1FI) and the RCP scenarios (2.6 W/m^2, 4.5 W/m^2 and 8.5 W/m^2).

3.1.4.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

Generally, Global and Regional Climate Models (GCMs and RCMs) are used. In example, the Snowpack Model, HIRHAM Regional Climate Model, Snowmelt Runoff Model (snow quantity) and Snow Thermal Model-SNTHERM (snow quality) are used to analyze the snow cover. WRF-HadCM3 is used for snowfall analysis. The MAGICC-SCENGEN model is used to model climate change projections and SAFRAN-Crocus-MEPRA chain is used to analyze the snow avalanche hazard.

3.1.4.3.3 The scale of analysis (scale and temporal resolution)

In general, the scale of analysis is regional, since each zone has its own particularities that generates a specific type of snow cover according to the characteristics of the terrain and the predominant snow-meteorological conditions. However, we also found some studies that have a more global approach. At the temporal level, long time series of data are usually analyzed in order to have an overview of possible trends.

3.1.4.3.4 Level of uncertainties in predicting changes (if possible)

The uncertainty of climate change in relation to the risk of snow avalanches has been reflected in the latest IPCC report *Special Report on the Ocean and Cryosphere in a Changing Climate: Chapter 2. High Mountain Areas*. It seems clear that more wet snow avalanches are expected, due to rising temperatures, but the level of confidence in the future prediction is medium, for example, regarding to the increase or decrease in the number of snow avalanches in the coming decades.

3.1.5 Landslides

3.1.5.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

The main triggering factors of landslides (within the frame of RECIPE: spontaneous shallow landslides as described in the annex) are heavy precipitation events. Prediction of their development in the course of climate change is not that secure as the rise of temperature. Anyhow, most analyses show increasing heavy precipitation, even more pronounced in the winter half-year and Central Europe (*Coumou and Rahmstorf, 2012; Hoegh-Guldberg et al., 2018; Madsen et al., 2014*). In contrast, increasing temperature leads to increasing evapotranspiration in case of more or less stable rainfall sums (per year), resulting in decreasing soil moisture contents and "better" system conditions at the begin of precipitation-events (Hagen et al. 2020).

The change of conditions usually causes instabilities of systems. This will be also the case for landslides. However, the type, extent, magnitude and direction of the changes in the stability conditions, and on the location, abundance, activity and frequency of landslides in response to the projected climate changes is less clear. Since EU spans a large area with different landscapes climatical and geological conditions, it is unrealistic to represent uniform climate change impacts for the entire EU. One must rely on regional and local analysis according to the situation of the area (*Cloutier et al., 2012; Gariano and Guzzetti, 2016; Hagen and Andrecs, 2016; Huggel et al., 2012*):

- High altitudes: Increased prone of landslides because of thawing permafrost areas due to rising temperature.
- Medium to low altitude areas: more landslides activity and shift of events to the winter half-year due to increased precipitation events and reduced solid fraction (snow), especially in Central and North Europe.
- South Europe, low to medium altitudes: due to higher temperatures and constant or decreasing precipitation sums, the threat form landslides may decline.
- Generally: unexpected landslides events (time, situation), which differ from past observations or have not been observed so far.
- An increase in the number of people exposed to landslides risk is likely (*Gariano and Guzzetti, 2016*).

3.1.5.2 The cascade effects or feedback effects triggered

Literature, dealing with effects of wildfire, wind throws avalanches etc. on landslide susceptibility is rare. However, forests have a significant protection effect in mountainous terrains against hydrogeomorphic hazards like landslides. There are some studies dealing with these tasks.

As the processes listed before cause deforestation and a sudden or gradual decrease of root reinforcement, evapotranspiration, and interception, effects on landslides can be assumed (*Cislaghi et al., 2017, Kim et al., 2013*).

It is widely recognised that forests can stabilize steep slopes. However, there is considerable argument about to what extent trees reduce hydro-geomorphic hazards. Field studies and scenario modelling showed that landslide densities were lower in forested terrain than in open land and occurred on steeper slopes (*Kim et al., 2013, Malek et al., 2015, Rickli and Graf, 2009*). An approach to quantify the root reinforcement is provided by *Schwarz et al. (2012)*.

Wind throws lead to a sudden loss of root reinforcement and destabilisation of slopes due to loosing up the soil. Hence, increased landslides can be assumed in these areas. However, wind throws often affect exposed crests and ridges with thin soil layers and soil moisture below average which generally do not tend to landslides.

As wildfires may affect large areas, the overlapping with unstable slope areas is comparatively high. However, at least the root reinforcement at these areas is only gradual; a successive increase of landslides in case of inadequate reforestation can be assumed.

The area of deforestation in the course of avalanches is low, thus the effects of this process can be assumed as marginal.

3.1.5.3 Climate change modelling chain

3.1.5.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

IPCC do not provide information on the assumed development of precipitation broken down to the different RCP scenarios, even lees for heavy precipitation.

3.1.5.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

IPCC provides an overview basing on numerous modelling with different approaches.

3.1.5.3.3 The scale of analysis (scale and temporal resolution)

Beside the IPCC reports (large scale, European regions, models: GCMs) there are some modelling with higher spatial resolution (e.g. Alps with RCMs like Aladin and MM5*, Schöner et al., 2011*) offering also estimations on the development of heavy precipitation.

3.1.5.3.4 Level of uncertainties in predicting changes (if possible)

Uncertainties of prediction (events) increase according to *Schöner et al., 2011* with:

- Decreasing spatial scale (prediction of local developments are more insecure).
- Decreasing temporal scale (prediction of short precipitation periods are more insecure).
- Increasing of the thermic and hygric complexity (prediction of thermic induced precipitation events is more insecure).

3.1.6 Rockfalls

3.1.6.1 Main literature evidences from R+D+I projects, operational guidelines or other theorical tools

Triggering factors of rock fall are diverse. Earthquake, water, ice, storms, and vegetation growth are the final forces that cause unstable rocks to fall. Geomorphic responses to climate change are complex and highly variable spatially and temporally. In the course of climate change, permafrost degradation due to rising temperature will be relevant. Besides, the development of heavy precipitation, freeze-thaw change and storms have be taken into account as well. While the rise of temperature and thus the rise of the permafrost line is a fact, the development of the other climatic parameters and its influence on rock fall triggering is insecure. There is evidence of increasing heavy precipitation, even more pronounced in the winter half-year and Central Europe (*Coumou and Rahmstorf, 2012; Hoegh-Guldberg et al., 2018; Madsen et al., 2014*). There is no consensus on changes of near – surface wind speeds due to global climate change, analysis differ from regional increasing wind speeds (e.g., Smits, 2005) to no evidence of substantial changes, the latter is predominantly assumed at present.

The change of conditions usually leads to instabilities of systems. This will be also the case for rock fall.

In high altitude regions with permafrost degradation a clear increase of rock fall activity is very likely

In non permafrost regions, increasing heavy precipitation events may cause the rockfall frequency (*Krautblatter et al 2010*). However, analysis basing on a rockfall inventory for Austria (mainly non-permafrost areas), showed no increase of rockfall frequency during warmer periods (*APCC, 2014, Glade et al., 2019, Sass and Oberlechner, 2012*). Hence it can be concluded:

- High altitudes: Increased prone of rock fall frequency because of permafrost degradation areas due to rising temperature.
- Other areas: Regional differences in the impact of the CC may occur, but no significant increase of rock fall frequency overall.
- Generally: shift of rock fall active zones to higher altitudes and main activities earlier in the year.

3.1.6.2 The cascade effects or feedback effects triggered

Forests have a significant protection effect in mountainous terrains against hydrogeomorphic hazards as rock fall. There are some studies dealing with these tasks. Starting zones of rock fall are mostly not or only incompletely wooded, and thus less affected. In contrast, transportation zones are often covered with forests which can reduce the rock fall range. Vice versa, the range of rock fall will increase in areas deforested by wildfire, wind-throw and avalanches (*Bebi et al., 2015, Degraff and Gallegos, 2012, Melzner et al., 2019*):

- Interaction between rocks and vegetation is disrupted by wildfire. Not only trees are removed or diminished, but the organic material mantling hillslopes can be lost, enlarging the range of rock fall. Increased surface runoff (e.g., from upside areas) can trigger rock fall as well. There is scattered evidence that high temperatures occurring at nearly vertical rock walls have an impact on the rock mass structure and may cause rock fall events.
- Wind throws lead to a destabilization of rocks due to loosing up the soil and hence increase rock fall frequency. However, the fallen trees are also an obstacle for the rocks and may reduce the range.

- The area of deforestation in the course of avalanches is low, thus the effects on rock fall are assumed as marginal.

3.1.6.3 Climate change modelling chain

3.1.6.3.1 Type of IPCC scenarios (RCP 2.6 W/m2, RCP 4.5 W/m2, RCP 6.0 W/m2, RCP 8.5 W/m2)

IPCC do not provide information on the assumed development of precipitation for the different RCP scenarios, even lees for heavy precipitation.

3.1.6.3.2 Type of climate model used (GCMs, Regional or Empirical Statistical downscaling Models) and type of hydrological model

IPCC provides an overview basing on numerous modelling with different approaches.

3.1.6.3.3 The scale of analysis (scale and temporal resolution)

Beside the IPCC reports (large scale, European regions, l models: GCMs) there are some modelling with higher spatial resolution (e.g., Alps RCMs like Aladin und MM5, *Schöner et al., 2011*).

3.1.6.3.4 Level of uncertainties in predicting changes (if possible)

Uncertainties of prediction (events) increase according to *Schöner et al. (2011)* with:

- Decreasing spatial scale (prediction of local developments are more insecure).
- Decreasing temporal scale (prediction of short precipitation periods are more insecure).
- Increasing of the thermic and hygric complexity (prediction of thermic induced precipitation events is more insecure).

3.1.7 Comments

From the review carried out, it is possible to argue that climate change will have important and sometime different impacts on hazards.

In the Table 4 some main elements are reported.

Table 4. General synthetic framework of mapped climate change impacts on Hazard

Hazard	Impacts	Hazard Factors	Uncertainty
Wildfire	More wildfire occurrence and spread, thus expanding northward the areas prone to forest fires. Faster propagation rates. Longer flame lengths.	Heat waves Drought and Aridity Wind Changes in vegetation Forest health	High level of uncertainty

Hazard	Impacts	Hazard Factors	Uncertainty
	Severity of the fire season. Probability of large and extreme fires.		
Flood (flash flood)	More frequent throughout Europe and less frequent in regions with projected reduced snow accumulation during winter (EEA, 2017). More intense: on average, in Europe, flood peaks with return periods above 100 years are projected to double in frequency within 3 decades.	Heavy rain fall Vegetation Rising temperature	High level of uncertainty
Storm	More intense over the 21st century. More lengthy, more frequent and more severe i.e. peak wind speeds) across Europe (Donat et al., 2011). Likely, there is a poleward shift of midlatitude storm tracks. Consequently, areas that were previously untouched by severe windstorms will have to face a new hazard situation.	Wind Precipitation Trees	Medium to high level
Rockfall and Landslide	High altitudes: Increased prone of landslide and rockfall because of thawing permafrost areas due to rising temperature. Medium to low altitude areas: more landslides activity and shift of events to the winter half-year especially in Central and North Europe. No significant increase of rock fall frequency overall. South Europe, low to medium altitudes: the threat form LS may decline. No significant increase of rock fall frequency overall.	heavy precipitation sums and intensities permafrost (thawing) raising temperature	High level
Avalanche	GLOBAL: The impact of climate change on snow avalanche risk is uneven across territories. PYRENEES CATALONIA: 1. An increase in the number and magnitude of wet snow episodes 2. Most very large and extremely 3. Great interannual variability in duration and thickness	Snowpack Terrain Weather (raising temperature, heavy snowfalls, etc.)	Medium to high level

Some important final remarks are arisen from a comparative and overall analysis of the results of the review:

- It is projected that there will be new areas at risk and a different timing of the risk will be happen and this together with the change in frequency and intensity, could represent an important challenge that civil protection stakeholders and risk managers should deal with.
- Most of the climate change scenarios used for projected climate change impacts are the Representative Concentration Pathways (RCPs) IPCC's scenarios[5].
- Most of the climate change impacts are affected by high level of uncertainty. As climate change models are affected by high level of uncertainty due to among others the climate response to the greenhouse gas emission or the complex interactions among the physical processes of the system, this is propagated to the impact models, that use the climate model output as inputs

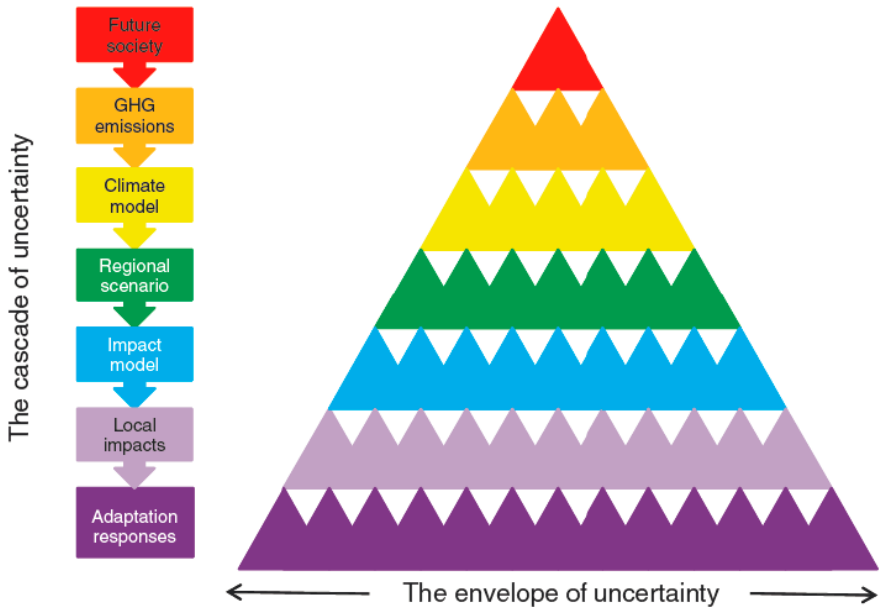


Figure 1. The cascade of uncertainty in climate change prediction (source: Wilby and Dessai, 2010[6])

The last remark is very import for better calibrating the actions or measure that should be implemented for coping with the climate change.

[5] This set of scenarios are a new set of scenarios that were developed for, but independently of the IPCC AR5 (2014). They describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use (Moss et al., 2008). The RCPs have been developed using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to project their consequences for the climate system. These climate projections, in turn, are used for impacts and adaptation assessment (IPCC AR5, 2014). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. These are referred to as pathways in order to emphasize that they are not definitive scenarios, but rather internally consistent sets of (time-dependent) forcing projections that could potentially be realized with more than one underlying socioeconomic scenario. The number after the acronym RCP identifies the approximate value of radiative forcing (in W m–2) expected to be reached at 2100 (IPCC AR5, 2013). Four RCPs were selected and used as a basis for the climate predictions and projections in the IPCC AR5: RCP2.6 (stringent mitigation); RCP4.5 and RCP6.0 (intermediate stabilization scenarios); and RCP8.5 (very high GHG emissions) (https://climate-adapt.eea.europa.eu/knowledge/tools/uncertainty-guidance/topic2).

[6] Wilby and Dessai, 2010. Robust Adaptation to Climate Change. Weather. 65. 180 - 185. 10.1002/wea.543.

According to *Street and Nilsson (2014)*[7]:

- Consideration of uncertainty is an essential element of decision-making as it is inherent in all evidence and in all decisions. It is an integral part of supportive data and information, especially but not only in that related to the future. Appropriately integrating the associated uncertainties as part of the evidence provides a better understanding of that evidence and can enhance its utility within decision-making processes.
- Recognizing the nature and characteristics of uncertainty and reflecting these in how the associated evidence is used are crucial to making better informed, more relevant and more robust decisions. By acknowledging and considering uncertainties, rather than expecting readily identifiable and deterministic outcomes, the uncertainties become more manageable. As a result, it becomes possible to formulate coherent decisions and policies.
- Not 'sufficiently' including uncertainties increases the likelihood that the action taken will be inadequate, inappropriate or increase vulnerability. There is an increased likelihood of maladaptation when neglecting uncertainties in the knowledge base.
- Ignoring uncertainty can undermine effective risk management as the risks that would result from including uncertainty are simply ignored and not considered in actions to be taken.

3.2 Documentary review on Climate Change Impacts on Risk Management

For better understanding the impacts and the challenges of the climate change on risk management, an analysis from the literature review of the following elements has been carried out:

- major climate change impacts on each phase of the risk management cycle;
- the influence of uncertainties associated to climate models;
- major challenges for ensuring coping capacity;
- major challenges for assessing and reducing exposure and vulnerability;
- major challenges for improving resilience.

The elements analyzed make it possible to study and to bring out the impacts of climate change on the different elements of the risk management cycle, also focusing on the different drivers of risk, with a particular attention on coping capacity and resilience and vulnerability as separate elements. The underlying idea is that, for better investigating how the climate change influences the risk management and so for better defining the most suitable actions for coping with the climate change, it is important to understand how the climate change affects each risk drivers and what it is possible to put in place for "reinforcing" them.

[7] Street and Nilsson (2014) Introduction to the Use of Uncertainties to Inform Adaptation Decisions. In: Capela Lourenço T. et al. (eds) Adapting to an Uncertain Climate. Springer, Cham. https://doi.org/10.1007/978-3-319-04876-5_1

This is essential in order to allow communities to adapt the most suitable structural and non-structural measures in the attempt to mitigate and, where possible, prevent the impacts of a natural hazard.

Moreover, it is worth of notice that analyzing vulnerability as complex driver that encloses the coping capacity and the resilience would mean losing or underestimate, among others, important information about the non-structural measures to be implemented on the territory.

Thus, it is fundamental to take into account and describe separately vulnerability and coping capacity and resilience in order to better define risk scenarios impacts.

A final remark is needed: the civil protection system is very interested in identifying the actions to be implemented to strengthen its ability to react to an event and risk managers have the urgency to identify the actions that allow a system not only to reduce its vulnerability but also to strengthen its resilience.

3.2.1 Wildfires

3.2.1.1 Major Climate Change Impacts on each phase of the risk management cycle

3.2.1.1.1 Europe

Recent studies

A study carried out by *Otero et al. (2020)* analysed future fire risk management in Montseny Biosphere (north east Spain) under climate change by proposing several mitigation measures. The study stated that the massif will have drier vegetation and higher temperatures and that annual burned area during next decades can be doubled and cause victims and damages. To manage these new risks, the authors identified strategic management areas to change fire behaviour to better conditions and to give opportunities to fire services, prescribed burns, forest management through local companies and extensive grazing.
The report of the European Environment Agency lead by *Kurnik (2017)* also assess the future challenges of fire management in Europe. Extreme fire weather conditions (Drier vegetation, higher temperatures, heat waves, low relative humidity, strong winds) are expected., as well as changes in fire regimes, more severe fire weather conditions, expansion of the fire-prone areas, and longer fire seasons are likely to occur in Europe, even if relevant spatial variations are projected. Moreover, the impacts of forest fires are expected to be more significant in southern European countries and fire-prone ecosystems. However, forest fires may become problematic in other European regions as well. More smoke pollutants are expected. Risk treatment is focused on better managed insurances, definition of natural hazard hotspots across Europe (including wildfires). More and better cooperation and exchanges across authorities, bodies and services (e.g., fire service, meteorological services, rural agents, etc). Legislation competence of provinces (in planning, building affairs and disaster measures execution) and municipalities (land-use planning, local disaster management). Implementation of training programs to improve community resilience.
PCF (2020) developed a wildfire management plan under current and future climate change scenarios in a blanket bog ecosystem in the border between Northern Ireland and Republic of Ireland. The impact of climate change in the area will cause deeper water table horizon due to increasing temperatures and persistent drought periods, drier aerial vegetation and dry winds from central Europe. In regard to wildfires, this climate change will cause longer fire seasons, more intense fires able to generate spotting phenomena and jump from the surface to crowns, faster wind driven fires (possibility to observe plume driven fires). Management efforts focus on to foster a mosaic landscape through different management practices (mechanical cutting of grasses and shrubs, re-wetting drained peatlands, proper management of grazing

and prescribed burns control), improving fire units' response to fire (fire analysis, monitoring) community-based response plan through stakeholders and landowner's participation.

A report done by *Bailey et al. (2019)* discusses future fire management scenarios posed by climate change. The document states that climate change will cause higher temperatures, more heatwaves, drier fuel, droughts, early snowmelt and increased lightning activity. In response to that, more fire ignition probability, increased annual burned area and increased wildfire risk is expected. The authors start from the approach that in ecosystems where fires are a natural disturbance, fire suppression can lead a fuel accumulation that generates megafires in the future. In this sense, more prescribed burns and less fire suppression under safe conditions is needed. Restore original forest adapted to the local fire regime. Forestry practices. Charge or fee for homeowners in fire risk areas. Budgetary contributions for companies with facilities in fire risk areas. Identification of key areas for fire prevention and protection to be more cost-efficient with prevention budget. Build resilient communities (fuel breaks at WUI, fire drills, emergency plans, smart gardening, urban planning).

Finally, *Muller et al. (2020)* wrote a document after a workshop about forest fire management in the Alps. In this area, climate change is likely to cause drought periods and heat waves and rural abandonment, especially in the southern side. Dry lightning strikes are also expected. In regard to wildfires, new scenarios posed by climate change may increase danger at WUI, more frequent and intense fires. More fire risk days and longer fire seasons (early autumn and late spring. Increasing tree mortality, air pollution and soil erosion. Authors suggest the following fire management guidelines: prevention measures (early warning systems, increase resilience of forests, improve forest management planning, forest awareness raising, anticipate effects of fires), suppression measures (knowledge of forest infrastructure, deployment of specialized units, adapted firefighting techniques, efficient air support, technical fires), post-fire management (restore forest cover, minimize risk of fire effects, monitoring of burnt sites, investigate fire behaviour, establish case studies), knowledge transfer and exchange (multi stakeholder approach, trainings of fire brigades, forest fire research, workshops, joint terminology).

EU Strategies

The different EU Strategies analysed recognize that climate change will affect the different elements of the risk and thus risk management will need to adapt. However, it is commented only on a general level without specific measures explained or actions detailed.

In *Sparking firesmart policies in the EU* more specific details and measures are shared.

The review *Climate change impact on wildfire danger* do not mention climate change impacts on risk management.

In the existing literature, there are hundreds of recent studies and projects or initiatives analysing the impact of climate change on wildfire risk management.

Not mentioned in the *UN 2030 Agenda for Sustainable Development* neither in the *EU Forest Strategy*.

The *EU Strategy on Green Infrastructure* (GI) argue for applying GI solutions for disaster reduction. Such as functional flood plains, riparian woodland, protection forests in mountainous areas, barrier beaches and coastal wetlands that can be made in combination with infrastructure for disaster reduction.

In the *European Green Deal*, from economic point of view, claim to incorporate climate and environmental risk into the financial system. This means better integrating such risks into the EU prudential framework and assessing the suitability of the existing capital requirements for green assets. It will be important to ensure that across the EU, investors, insurers, businesses, cities and citizens are able to access data and to develop instruments to integrate climate change into their risk management practices.

More specifically related to:

Prevention: the Commission will work on building capacity to facilitate grassroots initiatives on climate change and environmental protection.

Preparedness: the Commission will adopt a new, more ambitious EU strategy on adaptation to climate change. This is essential, as climate change will continue to create significant stress in Europe in spite of the mitigation efforts. Strengthening the efforts on climate-proofing, resilience building, prevention and preparedness is crucial for the future.

In *Sparking firesmart policies in the EU* there are some general considerations: New megafires and climate change context calls for more effective science-based forest fire management and risk-informed-decision-making. This also means shifting the focus from suppression to prevention and increase awareness and preparedness of populations at risk. Furthermore, specifically at each risk phase stage highlighted some measures or challenges:

Response: Cutting edge early-warning systems.

Recovery: Species selection and regeneration cuttings as part of adaptive management.

Prevention: Must integrate the long-term adaptation of forests to climate change, adopting both short- and long-term preventive measures.

Preparedness: According to this document both agencies and communities are not well prepared to deal with extreme fire events. The preparedness of agencies and communities to deal with megafires events requires adequate evaluation and timely communication through the development of early-warning systems, as well as training personnel for efficient emergency operations, including evacuation or confinement plans. This also entails developing public awareness and education and addressing the misconceptions that fire protection is the sole responsibility of the fire department.

According to *Global fire challenges in a warming world*, investments in international cooperation, integrated management, local community involvement, cutting-edge technologies, and long-term data collection are critically needed to ensure the future of fire disaster risk mitigation. Future sustainable fire risk mitigation demands integrated region-specific approaches based on a clear understanding of fires in context, population awareness and preparedness, fire surveillance and early-warning systems, adaptive suppression strategies, fire-regime restoration, landscape-scale fuel management, changes of many land use practices, and active restoration of landscapes. More specifically related to:

Prevention/Preparedness: Future land development policies must prioritize the protection and the restoration of natural and cultural landscapes that have been degraded by the inappropriate use of fire or, conversely, by historical fire exclusion; keeping a place for fire in forest resource management and landscape restoration has been shown to be a cost-effective and efficient solution to reduce fire hazard. Most important will be providing appropriate institutional support to encourage local capacity building to support activities that can effectively mitigate the local fire risk. In some areas this could mean a focus on building fire resistant infrastructure and structures and support of appropriate land management activities (e.g., removing flammable invasive vegetation, use of prescribed fire or thinning dense vegetation).

Response: Early warning systems provide key information to support international suppression resource-sharing agreements, which is an important fire management strategy recognized by the global fire community for combatting the increasing severity of fire seasons under climate change.

Recovery: Although Forest Landscape Restoration favours historic fidelity, native species, and strongly advises against ecosystem conversion, the challenges imposed by climate change will require adaptation to novel conditions including novel fire regimes that may arise spontaneously or as a result of intentional adaptation.

In the *Global assessment report on Disaster Risk Reduction* there are some general considerations about risk management. The document recognizes that the very nature and scale of risk has changed, to such a degree that it surpasses established risk management institutions and approaches. To prevent the creation of new risk through development a more integrated approach is required to adapt to and reduce risk from climate change, together with broader development efforts. Emergent climate-related risks will alter most of our current risk metrics: growth in death, loss and damage will surpass already inadequate risk mitigation, response and transfer mechanisms. An essential step in ensuring effective risk reduction is to engage women so that their experience of risk is a default input to global, regional, national and local strategies for risk reduction, sustainable development and climate change. It is needed to advocate strongly for a systems approach that combines infrastructure investment and risk reduction as a much more cost-effective means to manage risk. There have been suggestions made towards an increasingly adaptive risk management framework with a focus on solutions with multiple benefits. Policy changes and a greater focus on risk reduction also help to decrease risk, but in places where economic growth outstrips investment in risk management and governance structures, risk will continue to grow. The focus of national and international attention must shift from protecting social and economic development against perceived external shocks, to transforming growth and development to manage risks, in a holistic manner, in a way that promotes sustainable economic growth, social well-being and a healthy environment that strengthens resilience and stability. National planning bodies with representation from all sectors must develop risk reduction strategies. As the risk context is constantly changing, flexibility and agility is required of national- and local level processes, to be able to accommodate new and emerging risks. Integrated risk governance, or policy coherence, is the key to effective risk reduction at national and local levels. Addis Ababa Action Agenda supports national and local capacities in the development of integrated strategies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, and resilience to disasters. Additionally, related to:

Response: Monitoring risk and disasters helps to prevent, prepare and reduce impact. The FAO Early Warning Early Action (EWEA) system translates warnings into anticipatory actions to reduce the impact of specific disaster events. The systemic nature of risk requires systems-based approaches; climate risk needs to be a part of all development and risk reduction planning.

3.2.1.1.2 Spain

One of the general aims of the *Law 16/2017 on Climate Change (Catalonia)* is encourage education, research, development and technology transfer as well as disseminate knowledge on climate change adaptation and mitigation. Several of their subsections are referred to the **prevention** phase: Recover and preserve the underground water reservoirs to act as water reserve in drought episodes. In forested areas evaluate and manage risks associated to climate change and facilitate forest management to reduce wildfires risk.

Project of Law on Climate Change and Energy Transition (Spain). Here there is a specific instrument that will be developed: Climate Change Adaptation National Plan (PNACC, in Spanish). Their goals will be among others: gather, analyse and disclose climate change information related to exposure and vulnerability; identify and evaluate foreseeable impacts as well as their risks in the different climate change scenarios.

In general terms, the *Third report on climate change in Catalonia* mention that the new needs posed by climate change will be to reinforce preparedness through risk awareness and the transference of knowledge to better cover the risk management; prevention through new and more knowledge about climate effects and compilation of information about risk episodes and, finally adapting prevention and response measures to new scenarios expected.

3.2.1.1.3 Portugal

The achieved results point to dramatic consequences of climate change on future forest fire activity over Portugal. *Carvalho et al. (2011)* believe that the predicted increases in fire weather risk will have environmental, social, and economic impacts and may dramatically impact the organizational structures that deal with wildfire and society in general. Policy makers, together with fire management authorities have to develop two-folded strategies that include both mitigation and adaptation. The early starting of the fire season, in relation to the historical fire season limits, indicated by fire risk increase in early summer, together with higher severity will impose greater demand on forest fire fighting management and means, including the expansion of the current fire suppression capacity.

Moreira et al. (2020) shows that current wildfire management policies in Mediterranean region are destined to fail. Focused on fire suppression, these policies largely ignore ongoing climate warming and landscape-scale build-up of fuels. The result is a 'firefighting trap' that contributes to ongoing fuel accumulation precluding suppression under extreme fire weather and resulting in more severe and larger fires. They believe that a 'business as usual' approach to wildfire in Mediterranean will not solve the fire problem and recommend that policy and expenditures be rebalanced between suppression and mitigation of the negative impacts of fire. This requires a paradigm shift: policy effectiveness should not be primarily measured as a function of area burned, but rather as a function of avoided socio-ecological damage and loss.

Oliveira et al. (2020) refers that the sharp demographic decline and the aging of population, together with the reduction of farming activities and the subsequent land abandonment, make it imperative to find a suitable territorial vocation, perhaps different from before, but capable of creating more economic value and promoting the management of the land in a more effective and sustainable way, thus also reducing the risk of wildfires. In response to the decrease of silvo-agricultural activities and rural exodus *(Skulska et al., 2018*) points to the need to use accumulated fuel in forest areas for the production of green energy and the creation of mosaic landscapes, especially in central and northern Portugal.

3.2.1.2 The influence of uncertainties associated to climate models

3.2.1.2.1 Europe

Recent studies

According to *Kurnik et al. (2017)* models have significant limitations which lead to uncertainties in the magnitude and timing, as well as regional details, of predicted climate change. For this reason, fire danger estimates are affected by uncertainties in future climate projections, and this can be particularly relevant when assessing extreme events. Human factor is also an uncertainty, as 90-95% of ignitions are human induced. In the same sense, *PCF (2020)* discuss that monthly anomalies for maximum and minimum temperature as well as rainfall under RCP8.5 scenario projection is very uncertain, but clearly, it will have a great impact on SPEI index and fuel availability. The report of *Bailey et al. (2019)* also recognizes uncertainties concerning the projections of future fire regimes, which will have a direct impact on fire management needs. Lastly, according to *Muller et al. (2020)*, while climate projections are quite clear for southern Alps, future context in the northern part is still uncertain. Many indirect effects and tipping points may be relevant worldwide but also in the Alpine region.

EU strategies

Not mentioned in the *UN 2030 Agenda for Sustainable Development*, the *UE Green Infrastructure Strategy*, the *European Green Deal*, the *EU Forest Strategy*, *Climate change impact on future wildfire danger* and neither in *Global fire challenges in a warming world*.

Nevertheless, in *Sparking firesmart policies in the EU* two limitations are recognized: the applicability of fire models is limited due to uncertainties in climate projections and spatial and temporal resolution issues. And the limited scientific knowledge to address fuel management under future climate/land-use scenarios.

The *Global assessment report on Disaster Risk Reduction* specifically says that countries are struggling some types of climate risk information due to the high level of uncertainty of global climate projections and a lack of standardized guidelines for incorporating the information into planning and implementation processes. From a policy and governance perspective, climate and disaster risks present a significant degree of uncertainty in estimating potential impacts. This is due to the complex nature of the phenomena, as well as limitations in science and technology to understand projected events and how exposed people and assets will react, due to varied sources and types of vulnerability. Converting uncertainty into acceptable risk quantities that essentially emanate from complex system behaviour is currently very difficult, even impossible.

3.2.1.2.2 Spain

Not mentioned in *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)*.

The *Third report on climate change in Catalonia* exposes that there is a high level of uncertainty regarding the specific future episodes, and thus, the specific risk management measures to apply to be effective front new risk situations.

3.2.1.2.3 Portugal

Since in Portugal 97% of forest fires are human-induced (one of the most complex and therefore difficult factors to include in prediction models), policy makers should be aware that without major changes in the patterns of human activities, the number of fires due to human causes is likely to increase. Therefore, a better land using planning is needed if not to counteract, at least not to strengthen the effects of a dryer and warmer climate *(Carvalho et al., 2011)*.

A study made by *Costa et al. (2011)* in Portugal also pointed to a strong role of socio-economic and landscape factors, sometimes even stronger than climate, in shaping fire occurrence and burned area patterns. These factors alone (i.e., without considering climate) were shown to explain a wide range of variability and contribute significantly to uncertainty.

3.2.1.3 Major challenges for ensuring coping capacity

3.2.1.3.1 Europe

Recent studies

The study done by *Otero et al. (2020)* states that the identification of strategic areas is not an automatic process, it mainly depends on human expertise. Apart from that, these areas are based on the analysis of historic fires that could be different in the future. There is a lack of human and economic resources to carry out forest management in the strategic areas (mechanical clearings, grazing, agriculture, prescribed burns).

Hazard interactions and their 'secondary effects' could not be assessed in the study of *Kurnik et al. (2017)* because of a lack of 'knowledge of the inter-hazard physical interactions' and a lack of hazards metrics with finer time resolution, where monthly data would be needed across hazards. Exchange of data between agencies and services requires an standardized protocol and homogeneous data (software's, files, etc). Giving more decision power to provinces and municipalities facilitate local management of disasters, however, it requires a high level of communication between regions and national authorities, particularly when facing large fires across boundaries.

In regard to the fire management plan done by *PCF (2020)* in Ireland, fire services of the area are not specialized in fire events because of the lack of forest fires, but the area has experienced strong fire seasons recently (2010, 2011, 2017, 2020) due to increasing drought periods and temperatures. Lack of fire monitoring and post fire reports to better understand the event in a technical way was also identified. Deployment of units, engines and water is a constraint as access to the area is difficult.

Bailey et al. (2019) suggest that identification of key areas to help fire suppression can change with new fire regimes driven by climate change. Thus, the coping capacity of fire services can be compromised and a review of strategic areas may be needed.

In terms of fire prevention, *Muller et al. (2020)* identified as coping capacity challenges the identification of critical and key areas through fire risk maps under climate change context, access to steep and high altitude areas, difficulties to have a proper fire danger assessment considering the large spatial resolution of the assessment and the narrow and small areas that need an specific assessment, current risk assessments do not consider ignition causes, risk assessment during winter must be improved. On the other hand, in terms of fire suppression, the authors discuss the need to improve forest road network, water availability, firefighting training, equipment for forest firefighting and that the use of helicopters to deploy units increase suppression costs.

EU strategies

Not mentioned in the *UE Green Infrastructure Strategy and* the *EU Forest Strategy*.

The target 11.5 of the *UN 2030 Agenda for Sustainable Development* exactly establish that by 2030, it is needed to significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a special focus on protecting the poor and people in vulnerable situations.

In the *European Green Deal* the Commission will support businesses and other stakeholders in developing standardised natural capital accounting practices within the EU and internationally to ensure appropriate management of environmental risks and mitigation opportunities and reduce related transaction costs.

In *Sparking firesmart policies in the EU* several challenges are highlighted. It is needed to improve coherence between EU policies' objectives with respect to wildfire risk management. Is also needed the improvement of the coordination among EU policies and national policies on disasters prevention, preparedness and response to different risks. There is a need test the recently developed climate-adaptation plan to enhance forests' resilience to climate change; MOTIVE project generated an adaptive forest management toolbox that has contributed to equipping forest managers with methods for strategic forest management planning, for example forest thinning, reintroductions of grazing, fire breaks (short-term), introducing more climate-resilient species, turning artificial plantations and simplified forest ecosystems into more natural and diversified forests (long-term).

According to *Global fire challenges in a warming world*, climate change, with longer, hotter, and drier fire seasons, in combination with other environmental changes linked to population growth and unsustainable land-use practices, is contributing to extreme wildfire events that exceed existing fire management capacities. These ongoing changes in global fire activity in terms of location, intensity, severity, and frequency will likely have immense costs to biodiversity, ecosystem services, human well-being and livelihoods, and national economies. The likelihood of catastrophic fires impacting upon communities already exists, with or without alteration to fire regimes due to climate change. However, unless civil society is fully engaged in a call to action, adaptation to future conditions is unlikely. Adaptation requires a change of social mindset from feeling helpless to one of living with fire and being personally prepared.

In the *Global assessment report on Disaster Risk Reduction* there are several concerns about coping capacities. Rapidly growing urban environments and fragile or complex situations can create new risks as well as compound risks arising from natural hazards, armed conflict, poverty, malnutrition and disease outbreaks, thereby increasing the vulnerability of affected populations and reducing their coping capacity. Repetitive historical observations have been used to characterize risk by statements about the probability of certain interactions of hazards, vulnerability, exposure and capacity. However, the essential feature of the extreme, catastrophic, risk events actually witnessed in recent history, is the lack, or complete absence, of the patterns expected based on historical observations. One major challenge is establishing causal attribution of systemic losses as the basis for assigning accountabilities and responsibilities so essential for risk governance. Other challenges that require direct attention and action: awareness, risk governance, legal infrastructure, produce and communicate good risk communication, risk assessment, data collection, open and available data with higher resolution imagery, cooperation and partnerships. Ageing infrastructure and weak institutional and infrastructural capacities pose a challenge to risk management in many regions of the world. While strategies are a central element of a wider disaster risk governance system, to effectively implement policy, these strategies need to be supported by a well-coordinated institutional architecture, legislative mandates, political buy-in of decision makers, and human and financial capacities at all levels of society. Having in place subnational and local Disaster Risk Reduction strategies or plans that complement the national policy framework has been increasingly recognized over the past two decades as an important requirement of a functioning risk governance system.

EU projects

The Horizon 20250 project Anywhere (EnhANcing emergencY management and response to extreme WeatHER and climate Events[8]) aims to develop an operational prototype of the ANYWHERE distributed platform for Emergency Management Operation Services (A4DEMOS). It is enabled integration of forecast between the MH-EWS service platform, risks, and vulnerabilities analyses, open and commercial data, local sensor data, crowdsourced data and social media information, for monitoring and decision support during emergency management. It interfaces with legacy systems through standardized interface layers and offer specific ""plugs-in"" and toolkits to support integration and sharing of data as new sources of information become accessible. Additionally, A4DEMOS includes a set of built-in tools to be used operationally to support W&C-induced emergencies and crises management and to collect data from the field.

The ongoing Horizon project HEIMDALL (Multi-Hazard Cooperative Management Tool for Data Exchange, Response Planning and Scenario Building[9]) applies available data fusion techniques and modelling algorithms to improve situation and risk assessment and identify the relevant scenarios available and the corresponding response plans to be applied, based on decision support techniques.

HEIMDALL will provide services and products scenario planning and scenario building for first responders (FR), command and control centres (C&C) and incident managers of different actors involved in natural and man-made hazard responding. The identified functionalities are: simulation and integration of different data sources, situation assessment, scenario matching, decision support and communication and information sharing among different actors and authorities. HEIMDALL can efficiently support the training for those scenarios and allow collaboration between the actors and at the same time offers the possibility to include tools supporting the actors in their job.

The ongoing INTERREG Marittime project MED STAR (Strategie e misure per la mitigazione del rischio di incendio nell'area Mediterranea[10]) has the objective of optimizing the fighting interventions both in the case of cross-border fires and in the case of large events that are difficult to control, developed within the territories, for the extinguishing of which the collaboration of neighbouring regions and the use of optimal land and air resources. the project also aims to identify the chains of command and operational protocols to be followed for effective communication, during emergencies, between the various operational

[8] http://gebrada.upc.es/anywhere/the-project/
[9] http://heimdall-h2020.eu/
[10] http://interreg-maritime.eu/web/med-star

institutions responsible for managing fires (Fire Brigade, Civil Protection, Volunteers, Forest Agencies, etc.) in the various areas of program.

3.2.1.3.2 Spain

Not mentioned in *Law 16/2017 on Climate Change (Catalonia)*, *Project of Law on Climate Change and Energy Transition (Spain)*.

The *Third report on climate change in Catalonia* mention that there is a need to develop a holistic vision and consider the change with a global perspective to ensure a proper risk management. Specifically, is recommended to integrate the climate change adaptation, the risk reduction in land and sectoral planning processes and, to stablish interdepartmental commissions for risk reduction to ensure the intersectoral coordination (multi-stakeholder model).

3.2.1.3.3 Portugal

Coping capacity represents the ability to react to a wildfire event. It can be viewed as an additional factor of vulnerability, considering that a lower ability to respond will increase the potential for loss of exposed elements. Lack of coping capacity derives from structural shortcomings (whether institutional or infrastructural) that limit a country's ability to effectively respond to, and prepare for, disasters.

According to the E*U (2019)* report, the general ability of Portugal to coping capacity was estimated on average 2 points, on a scale of 1 to 10, where 1 means very low capacity and 10 - very low capacity. The worst scores were obtained when assessing infrastructures and access to health care. According to the criteria defined, half the villages within the parish did not have a building that might be transformed into a shelter, but a new structure could be built specifically for that purpose, to ensure each human settlement has a safe zone within its boundaries and to reduce evacuation times.

Oliveira et al. (2020), in turn, considers that the vulnerable circumstances of residents cannot be changed with fuel treatments nor with forest management strategies, but protective measures can be implemented to increase people's coping capacity and the resistance of built-up structures. Also, in Portugal, the evacuation system is poorly developed. Its effectiveness depends on the wishes of the residents and the capabilities of the authorities. In severe wildfire conditions, which are expected to increase due to climate change, institutional and suppression capacities will likely be overridden. For these reasons, fire management approaches must integrate strategies to improve community preparedness and people's coping capacity, tailored to their needs and abilities, to enable a suitable adaptation to fire-prone environments.

3.2.1.4 Major challenges for assessing and reducing exposure and vulnerability

3.2.1.4.1 Europe

Recent studies

Socioeconomic activities and urban areas were considered in the analysis of the study of Otero et al. 2020. To reduce vulnerability an facilitate the management of a fire in terms of civil protection, some strategic areas were exclusively identified near towns, urbanizations, and industries just to avoid an eventual direct impact from the fire to urban areas.

Identification of disaster hotspots in Europe under climate change depends on temporal and spatial projections that have uncertainties. All disaster risk reduction actions in these hotspots are a challenge. *(Kurnik et al., 2017*).

In northern Europe (*PCF, 2020*) difficulties to define strategic areas because of the lack of historic data and the lack of fuel models for peatlands were found. Information for the visitors needs to be improved, as well as emergency communication to society.

Different challenges described by *Bailey et al. (2019)* are the following: Prescribed burns may be more difficult to execute (finding the appropriate prescribed window and vegetation) under climate change context. Letting burn small and low intensity forest fires is not well seen among society, a better addressed message should be sent from fire community to society with the aim to make citizens understand that fire is a natural disturbance. Forest management reduce forest fire vulnerability, but there are constraints in terms of economic incomes. Establishing fees for people and companies in high fire risk areas are unpopular policies, despite they could help to avoid building in these areas and increase the budget allocated for fire prevention and extinction.

In mountain areas (*Muller et al., 2020*), i.e., the Alps, dead wood due to climate change can facilitate fire propagation, low awareness of fire risk within alpine community and difficulties to create fuel breaks in mountain areas. In terms of fire suppression, changes in forest composition can make fire behaviour more aggressive and the abrupt and diverse terrain can create unexpected wind changes. Post-fire management was also discussed, particularly, the function of protection forest may be lost and lead to an increase risk of natural hazards.

EU Strategies

Not mentioned in the *EU Forest Strategy*.

According to Target 1.5 of the *UN 2030 Agenda for Sustainable Development,* "By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters".

The *UE Strategy on Green Infrastructure* claim that GI can also help reduce vulnerability to risks by supporting local livelihoods and economies. Investments in ecosystem-based disaster risk reduction and GI can thus provide many benefits for innovative risk management approaches, adapting to climate change-related risks, maintaining sustainable livelihoods and fostering green growth.

Following the *European Green Deal*, the Commission will pay particular attention to the role of outermost regions, taking into account their vulnerability to climate change and natural disasters.

Sparking firesmart policies in the EU is more focused at ecosystem/biodiversity level. It recognizes the challenge to: (1) understand ecosystem's vulnerability and potential to adapt to changes in climate and fire regime; (2) improve the understanding of ecosystem's vulnerability to various fire recurrences and intensities; (3) improve knowledge on species' acclimation capacity to new fires regimes and, increased drought and climate change. In addition, recognize the need to improve knowledge on wildfire occurrence and behaviour in WUI areas, in particular with respect to land-use fragmentation and climate change and the need for context-specific analyses of the weather/climate influence on future fire regimes.

In *Global fire challenges in a warming world* only recognizes that climate-change driven shifts in forest composition may lead to increased exposure to fires and may change the capacity of forests to offer ecosystem services, as well as further tax already overburdened emergency services.

In *Global assessment report on Disaster Risk Reduction* there are several considerations to new vulnerabilities. Increased urban development pressure can cause settlement growth in hazard-prone areas, such as the informal settlements on the natural flood drainage areas, or the landslide-prone gullies and ridges combined with poor infrastructure and services. Such settlements can also destroy natural protective ecosystems that have historically mitigated the risks of landslides, flooding and storms, such as absorbent wetlands and binding vegetation cover on steep land. Often, these informal settlements occupied by populations with the lowest adaptive capacity, including residents without land tenure, and recent migrants. In addition, in an increasingly interconnected and interdependent world, displacement may exacerbate vulnerabilities by exposing people to new risks and challenges. Vulnerabilities accumulate and cascade, and so interventions that protect those groups whose vulnerability profiles make them more susceptible to disaster are imperative. Vulnerability reduction measures – captured in national adaptation plans for action and Disaster Risk Reduction plans – must be closely linked to the simultaneous systemic changes that must be engineered in energy, industrial, land, ecological and urban systems if we are to remain below the 1.5°C threshold. For exposure estimation, there are also major challenges related to the availability of topographic data sets with sufficient resolution.

EU projects

The ongoing INTERREG Marittime project MED STAR (Strategie e misure per la mitigazione del rischio di incendio nell'area Mediterranea[11]) will address the issue of adaptation strategies and plans to counter the possible negative impacts of climate change on fire risk. MED STAr will focus on the definition of territorial planning aimed at reducing the fire risk in natural and interface areas, at different scales of application (regional and local) to be proposed as a common approach for spatial planning in all program areas.

[11] http://interreg-maritime.eu/web/med-star

3.2.1.4.2 Spain

One of the aims of the *Law 16/2017 on Climate Change (Catalonia)* is to reduce the vulnerability of the population, socio-economic sectors and terrestrial and marine ecosystems to the adverse impacts of climate change, and also create and strengthen national capacities to respond to these impacts. The Government urge the municipalities to incorporate specific measures in their own particular planning to reduce the vulnerability when facing extreme weather episodes and to be able to keep the basic supply working. Nevertheless, no specific measures are mentioned.

The *Project of Law on Climate Change and Energy Transition (Spain)* comment on applying effective management operations, aimed to reduce social, economic and environmental system's exposure and vulnerability when facing climate change impacts. Other extra considerations must be taken by the Central Government in insular areas due to their higher risk against climate change. Nevertheless, no specific measures are mentioned.

Related to the *Third report on climate change in Catalonia,* it is mentioned the need to move towards the knowledge about present and future effects of climate change in natural hazards, enhance the observations, complete the data bases, and analyse the synergies between risks, among other actions that can help to know better the risks effects. This demands a knowledge transfer to cover the current weakness in risk management for those sectors more sensible to climate variations. It is also necessary to enhance the risk awareness and the co-responsibility of population, using new ways as the "citizen' science". It will be very important to enhance the tools application that have shown their effectivity, as risk and vulnerability evaluation, early warning, etc.

3.2.1.4.3 Portugal

The wildfire risk management focuses on hazards mitigation measures and on segmented and very static vulnerability assessment rep-resents a fragmented view of risk and disaster as a social construction.

The holistic approach proposed by the *MOVE* (Methods for the Improvement of Vulnerability Assessment in Europe) (*Birkmann et al., 2013*) project offers support for wildfire vulnerability assessment. The proposed framework allows the development of a methodology that does not only focus on the calculation of a single value obtained by more or less impressive mathematic processes but focused on the comprehension of the nature of vulnerability and its components and drivers. The indicators and components weighting is still a challenge as is the best method to aggregate the indicators.

Despite the limitations of the assessments conducted to date, *Tedim (2012)* believe that it is necessary to bring significant inputs for cost-effective wildfire risk management. If the factors that influence vulnerability are understood, communities and civil protection agencies will be in a better position to make informed choices regarding risk and how the community can be mobilized to manage it. Also, *Tedim (2012)* considers that the objective of building a vulnerability map is very important because it can be integrated into risk assessment, and complement the hazard map, as well as an important tool for landscape planning. The indicators list provided by the *MOVE project* (components of exposure, susceptibility/fragility and components of lack of resilience), can also function as a checklist to build a vulnerability profile and which can be done at different spatial scales (e.g., household, community, parish, municipality, region and even country).

3.2.1.5 Major challenges for improving resilience

3.2.1.5.1 Europe

Recent studies

Habitats of Montseny (*Otero et al., 2020*) area located at high altitudes are very vulnerable to climate change, with some species, such as European Beech, that would be very difficult to recover if burned.

According to the study of *Kurnik et al., 2017*, Northern Europe has a fire regime with surface low intensity fires. If fires jump to tree crowns, mortality will increase and in consequence forest recovery will be compromised. Training society in how to respond against wildfires requires a minimum of initial awareness, but sometimes awareness is gained after passing through a severe event.

In the UK (*PCF, 2020*) management practices in a Special Area of Conservation are a challenge because of the wide range of different actors and points of view. According literature and past experience, there is not any management practice that will prevent wildfires alone, but the area needs a combination of different management practices that creates a mosaic landscape. The effects of fire on the habitat is still not well known. There are too many questions in regard to the acceptable fire return period.

Prescribed burns impacts on vegetation have to be studied to better know how regrowing vegetation will respond to climate change. Identification of better adapted species to new climatic conditions and fire regimes. More public risk awareness is needed to gain community resilience. Society is hardly ever keen to participate and to take action to protect their homes. (*Bailey et al., 2019*).

According to *Muller et al. (2020)*, in terms of fire prevention, to ensure resilience is important to take care of tree species composition to adapt forest to new scenario, but owner structure with small landowners make forest management unviable. Concerning post-fire management, reforestation measures will become more difficult due to climate change, some species suitable in a given location today may be unsuitable under climate change, monitoring of post-fire effects at short and long term.

EU Strategies

In the *UN 2030 Agenda for Sustainable Development* two targets explicitly mention resilience: target 2.4 says that by 2030, it is needed to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality; Target 13.1 says that it is needed to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

The *UE Strategy on Green Infrastructure* claim GI solutions to be a disaster resilience booster and also an integral part of EU policy on disaster risk management.

Following the *European Green Deal* the Commission will also examine how Europe financial system can help to increase resilience to climate and environmental risks, in particular when it comes to the physical risks and damage arising from natural catastrophes.

In the *EU Forest Strategy* the vulnerability of the forests to climate change is highlighted. Consequently, it is therefore important to maintain and enhance their resilience and adaptive capacity, including through fire prevention and other adaptive solutions (e.g., appropriate species, plant varieties, etc.).

Sparking firesmart policies in the EU do not explicitly mention challenges for improving resilience.

The only mention in *Global fire challenges in a warming world* is that mitigating disaster risks and increasing the resilience of socioecological systems to fire must be acted upon, using holistic approaches to landscape management as a base for action.

Global assessment report on Disaster Risk Reduction highlights two specific examples on resiliency management. In the FAO, resilience-relevant work is defined around three main groups of shocks: natural hazards, including climate change extreme events; food chain crises and transboundary threats, in alignment with the Sendai Framework. Through this holistic approach, FAO is able to address the compound nature of disasters and the interconnectedness of threats. The Global Assessment reinforces the message that it is needed to reduce vulnerability and build resilience. Building resilience is necessary to adequately respond to, and reduce, risks and prevent disasters. Resilience requires: planning and preparation based on assessments to avoid or minimize risk creation and reduce the existing stock of risk; the development of capacity to restore functions quickly and effectively in the face of disruptions; and the capacity to adapt and change after a shock. See Potenza (Italy) example.

EU projects

The INTERREG Marittime project PROTERINA-C[12] focuses on issues linked to climatic change and its impacts on natural and anthropized environment, with special attention to hazard conditions induced by these changes. Key elements of the projects are the formation/information campaigns for population at risk and for local authorities.

In the project PROTERINA-C one of the Ligurian pilot actions deals with integration of the emergency plans with the management plans of peri urban green areas at high risk from fires in the interface areas in Genoa. The underlying idea is that the improvement of the Civil protection plan, by more awareness of population and by its integration with other territorial plans can reduce the increasing territorial vulnerability and foster the local resilience.

The ongoing Horizon project HEIMDALL (Multi-Hazard Cooperative Management Tool for Data Exchange, Response Planning and Scenario Building[13]) allows information sharing and communication among the relevant stakeholders, including first responders deployed on the field and the population at risk, thus enhancing stakeholder and population awareness.

[12] http://www.mi.imati.cnr.it/~anto/Projects/PROTERINA/Proterina.html
[13] http://heimdall-h2020.eu/

3.2.1.5.2 Spain

The *Law 16/2017 on Climate Change (Catalonia)* drive to adapt the productive sectors and incorporate the analysis of the resilience to the climatic change in the planning of the territory, the activities, the infrastructures and the buildings. Nevertheless, no specific measures are mentioned.

For the case of the *Third report on climate change in Catalonia*, there is no specific mention to it.

The *Project of Law on Climate Change and Energy Transition (Spain)* recognize that it is necessary to increase resilience against climate change impacts and risks. Effective management operations can also enhance the recovery capacity after a weather associated perturbation. Nevertheless, no specific measures are mentioned.

3.2.1.5.3 Portugal

Some researchers believe that minor adjustments in knowledge, governance, institutions or behaviours will not suffice to meet the sustainability challenges posed by global change. New insights into how societies might learn to deal with wildfire risk are greatly needed. These studies essentially propose to rethink societies and produce alternatives, radically new, social-ecological orders (Otero and Nielsen, 2017). Thus, a priority for wildfire practitioners and researchers should be to explore the conditions, strategies and pathways that might accelerate these necessary transformations.

Tedim et al. (2018) shows that it is also important to agree on a common term and definition to label extraordinary fires, if the scientific community wants to effectively transfer knowledge to enhance wildfire management policies and practice. Extraordinary wildfire events (an increased frequency of which in the future will also contribute to the increase of burned area), are complex social-ecological phenomena requiring a transdisciplinary approach to understand what they really represent. From the fire management point of view an agreed-on definition can more quickly help to identify fires that will exceed the current capacity of control. From a disaster risk reduction perspective, defining the social and ecological contributions to EWEs is fundamental to developing realistic and comprehensive estimates of risk and how risk can be reduced.

3.2.2 Floods

3.2.2.1 Major Climate Change Impacts on each phase of the risk management cycle

3.2.2.1.1 Europe

Many projects[14] and research have been developed to address the needs related to possible impacts that climate change can have on flood risk. A brief summary of the challenges that these projects have faced to better address the impact of climate change on the different phases of the risk management cycle is reported below:

Preparedness

- PROTERINA-3Évolution: Participatory approach in civil protection planning.
- PROTERINA-3Évolution and ADAPT: Construction of civil protection plans able to integrate the possible impacts of climate change.
- PROTERINA-3Évolution and Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities: Improve the alert system by making it more understandable and local.
- Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities, Proterina-3Évolution: Improve risk communication systems.
- Strengthen in situ monitoring network with the availability of rainfall data on the sub-hourly scale (CMCC,2020).
- PROTERINA-3Évolution: Organize civil protection exercises (both table-top and full-scale) to strengthen the civil protection system.
- According to *Kundzewicz et al. (2017)* improving governance capacity and a transparent and comprehensive division of responsibilities (*Runhaar et al., 2016*). It is necessary to develop adaptive risk reduction strategies and associated governance arrangements (*Hegger et al., 2014*) in order to keep destructive water away from people and property, and keep people and property away from destructive water in the changing climate.

Prevention

- ARIMA, PROTERINA-3Évolution, Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities: Improve the risk assessment process:
    - taking into account also the socio-economic component;
    - using hydro weather models on a local scale;
    - involving stakeholders in risk assessment.
- PROTERINA-3Évolution, ARIMA: Definition of processes and tools to increase awareness and participation.
- EFLIP and Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities.

[14] INTERREG MARITIME IT-FR PROTERINA-3Évolution; INTERREG MARITIME IT-FR ADAPT; DG-ECHO Project ARIMA (Assessment and simulation of present and future multi-hazard risk in the Marrakesh-Safi region), EFLIP (EFLIP – Economic impacts of flood risk in Lombardy and innovative risk mitigation policy), Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities

- IMPREX: Increased data sharing by meteorological services would improve the accuracy of regional climate change assessments, including understanding of past and future climate and weather extremes.
- Diversify flood risk strategies, i.e., to provide a multitude of flood risk measures — complementing the “classic” flood defense measures with flood prevention, mitigation, preparation and recovery — as a backup in case one strategy fails (*Hegger et al., 2014* - STAR FLOOD).
- Hence, a long-term commitment is needed to iterative policy revision, flexibility and learning in the broader governance system. Finally, there is a need to develop and apply appropriate science – policy interfaces that stimulate interaction between processes of knowledge production and knowledge utilization (*Van Enst et al., 2016*).
- As an alternative, a bottom-up approach that starts with the vulnerability of the system has often been proposed and may be more appropriate for adaptation studies at the local scale.
- PROTERINA-3Évolution, ADAPT, EFLIP: Implement nature-based solutions to mitigate flood risk.
- EFLIP: analyse and improve the practice and policies on collecting data on vulnerability to, and economic impacts of flood risk (EFLIP) for better assessing actual and future risk.

Recovery

- EFLIP explores and promotes options for individual and collective flood risk mitigation and financing including insurance coverage and nature-based solution (NBS), starting from the analysis of the past events.
- According to *Smith et al. (2018)* in *Disaster recovery in an era of Climate Change: the unrealized promise of institutional resilience,* research and practice benefit from advances in the ability to measure disaster recovery. Indicators have the potential to assist disaster recovery researchers by making it possible to draw comparisons across disasters, places and times. Moreover, the authors stressed that indicators can help policymakers assess progress and inform future recovery action, which is particularly important because of the iterative and adaptive nature of disaster recovery planning. More recent research has shown that this information can be used to monitor, evaluate, and update plans over time and lead planners and policymakers to consider facets of recovery that have historically been overlooked but are nonetheless important.

3.2.2.1.2 Portugal

Veiga de Cunha et al. (2000) refers that the climate change will not impose profound changes in how water resources are managed, but it will be likely that the task of managing the Portuguese water resources will become even more challenging. Therefore, the challenge of climate change must be addressed increased attention on water resources management strategies and policies.

Sousa and Silva (2005) considers that reducing the risk of flooding requires re-evaluation of various types of structural strategies (e.g., construction of additional dams, dikes and other hydraulic works that aim to control the risk of flooding) and non-structural (those that act in the field of vulnerability reduction, e.g spatial planning measures, construction rules, etc.).

3.2.2.2 The influence of uncertainties associated to climate models

3.2.2.2.1 Europe

As reported by *Kundzewicz et al. (2017)* in *Differences in flood hazard projections in Europe – their causes and consequences for decision making*, because it is naïve to expect availability of trustworthy quantitative projections of future flood hazard (as some practitioners clearly do), in order to reduce flood risk, one should focus attention on identification of current and future risks and vulnerability hotspots and improve the situation in areas where such hotspots occur. For decision making, it is necessary to develop an approach based on mapping vulnerabilities, and then try to estimate the probability that these are being affected. Decision making under uncertainty requires identification and quantification of the uncertainty involved, and then improvement of a framework for decision making, including the risk of action vs the risk of inaction. Moreover, the authors in this regard reported that besides top-down approaches, which rely heavily on hazard projections, there are also **bottom-up approaches that start from the vulnerability of communities and that are very useful when uncertainties in projections is large** or surprises with high impact are possible (*Di Baldassarre et al., 2016*) and low-regret options lend themselves well to applications.

The *Italian national climate change adaptation strategy* (*CMCC, 2017*) reported that several approaches have been developed to address uncertainty in planning, regardless of the type of risk. These approaches offer an alternative in situations where there is not enough certainty to be able to uniquely identify the best solution. As examples, these solutions have been reported:

- “Adaptive management”. Based on selecting a strategy that can be continually modified to achieve better performance as knowledge improves and information about the future increases. In this case, the administrators should look for flexible strategies that can be retouched based on experience and research. Learning, experimenting and evaluating are fundamental activities in this approach and are actively involved in the decision-making process. Adaptive strategies work best in situations where decision time scales are such that "incremental adaptation" is possible and decisions can be updated as new information becomes available.
- “Planning based on scenario analysis”. Faced with profound uncertainty, decision makers can choose to consider a number of possible outcomes. This is the scenario analysis approach. The scenarios present a number of different plausible future conditions (or “world states”). The analysis is then made to compare the performance of alternative policy decisions in these different future conditions. In addition to providing a useful description of the uncertainty, the scenarios can also bring clarity regarding the trade – off or the compromise made within the decision-making process. This is particularly useful when stakeholders maintain different values and priorities.
- “Robust or resilient strategies”. This approach identifies the range of possible future situations that could arise, and then tries to identify strategies that work relatively well across that range. A “robust” strategy can be defined as one that performs well over a wide range of alternative futures.
- “Adaptation measures against uncertainty”. In addition to general approaches, there are a number of priority measures that an administrator can take in planning adaptation in the face of uncertainty. The most appropriate option will depend on the nature of the decision, the sensitivity of that decision to specific climate impacts and the level of risk that can be tolerated by society. Options include:

- "Low - regret" or "no - regret" measures that produce benefits even in the absence of climate change and with which the costs of adaptation are relatively low compared to the benefits of the action;
- "Win - win (--- win)" which achieve the desired result in terms of reducing climate risks or exploiting potential opportunities, but also bring other social, environmental or economic benefits;
- Reversible and flexible options that allow future changes;
- Adding "safety margins" to new investments to ensure that these responses are resistant to a range of future climate impacts;
- "Soft" or soft adaptation strategies, which could include building adaptive capacity to ensure that an Organization is better able to cope with a range of climate impacts (e.g., through more effective proactive planning);
- Reducing decision time horizons (e.g., forestry sector may choose to plant tree species with shorter rotation time);
- Delaying action (which should not be confused with ignoring the future). This can be seen as part of a long-term active adaptation strategy in which it has been established that there is no significant benefit to immediately taking a particular action.

More specifically, among the criteria for evaluating the various actions reported in *the Italian national climate change adaptation plan* (*CMCC, 2017*), there is one related to the "performance in presence of uncertainty". This criterion evaluates to what extent a specific action can be applicable in a plurality of possible climatic and socio-economic conditions. The criterion is in turn divided into the two specific characteristics of:

- Robustness, which implies the ability of the action to maintain an acceptable effectiveness in different contexts.
- Flexibility, which describes those actions that can easily adapt (at "low costs") to different contexts. The adaptation may consist either in transformations of the action or its integrations with complementary actions or, in extreme cases, the abandonment of the same share if this proves unsuitable (maladaptation).

3.2.2.2.2 Portugal

V*eiga de Cunha et al. (2000)* considers that the argument that the impacts of climate change on Portugal's water resources are not yet fully understood cannot be a reason to postpone action. The results of different studies have already identified some trends with a high probability of occurrence, which should be considered in water management strategies and policies. Furthermore, a sound water management policy has always required a capacity to decide under uncertainty. Policymakers and water managers routinely forecast both the hydrological regime and act upon these forecasts. They try to plan in advance the response to future scenarios, usually selecting flexible and adaptable policies to be able to quickly react to specific situations. In this perspective, climate change, does not require any drastic change in water management it only constitutes an additional source of uncertainty that will influence flume values of water demand and availability.

This stresses the need for further water resources assessment studies and climatic change research in order to include the climate change information in water management practices. According to *IPCC (2001),* such knowledge must include an explicit consideration of all the potential supply-side and demand-side actions.

Furthermore, reactive or proactive adaptation measures have to be taken on a basin scale, accounting all the local users that directly or indirectly interact.

In addition to the issues discussed above, which are particularly relevant for water managers, other more general issues related to economic and social planning, development, land use, wealth enhancement or hazard insurance must be considered, in order to reduce, as much as possible, the vulnerability of the water sector to climate change.

3.2.2.3 Major challenges for ensuring coping capacity

3.2.2.3.1 Europe

As reported by *Kundzewicz et al. (2010*) in *Assessing river flood risk and adaptation in Europe—review of projections for the future*, there have been three basic adaptation strategies of coping with floods (cf. *Kundzewicz and Schellnhuber, 2004*):

(i) protection (as far as technically possible and financially feasible, bearing in mind that the absolute protection cannot be achieved);

(ii) accommodation (living with floods); and

(iii) retreat (relocation from flood-risky to flood-safe areas). This latter option aims to rectify maladaptation (inappropriate adaptation of flood-prone areas) and floodplain development.

Strategies for flood protection and management may modify flood waters and/or susceptibility to flood damage and impact of flooding. Site-specific adaptation may include some of the following components of holistic flood management (cf. *Kundzewicz, Takeuchi 1999*).

The pre-flood preparedness may comprise:

- flood risk management under consideration of all possible causes of flooding;
- construction of physical flood defense infrastructure;
- legislation;
- investment on research and development on floods;
- development control within the flood plains;
- increasing source control, infiltration and storage/retardation facilities in urban basins;
- land-use planning and management;
- building codes, flood proofing; implementation of flood forecasting and warning arrangements;
- public communication and education of the extent of flood risk and actions to take in a flood emergency;
- disaster contingency planning; maintenance of preparedness of community self protection activities; and
- insurance schemes.

Operational flood management includes:

- detection of the likelihood of flood formation;
- forecasting of future river flow conditions from hydrometeorological observations;
- warning issued to the appropriate authorities and the public on the extent, severity and timing of the flood;

- emergency protection of levees from breach and overtopping;
- strengthening of defences; decision to operate reservoirs and retardation ponds;
- issuing prior warning on emergency spill to the people to be affected;
- emergency rescue of lives and property from the flooded areas.

According to the *Italian National Adaptation Strategy* (2017), it is possible to identify some challenges for coping capacity in face of climate change. The most important are:

- Strengthening of alert systems.
- Strengthening of monitoring activity.
- Strengthening of the territorial coverage during floods.
- Improvement of weather-climatic forcing predictive capabilities.
- Improvement of alert systems (homogenization of messages on the national territory, more effective and timely communication, preparation of administrators) and of the related civil protection plans (preparation, dissemination to the population, exercises at local level involving the population).
- Training of the "Flood preparedness" of the population.
- Ensure continuous effective risk communication actions, aimed at the population and administrators, to reduce the impact of hydro-meteorological events and spread awareness of the “residual risk”.

3.2.2.3.2 Portugal

The main conceptual change is the rejection of the traditional engineering assumption that considers the historical climate as reliable indicator of future conditions. Water management authorities must start considering the climate change as a decision variable.

The potential decrease of water availability and the increase of the hydrological seasonal asymmetries, together with more stressing conditions in terms of water quality and flood risk, underline just how important it is to have water management policies based on a solid and in-depth knowledge of the Portuguese water resources.

3.2.2.4 Major challenges for assessing and reducing exposure and vulnerability

3.2.2.4.1 Europe

The Floods Directive (EU, 2007) requires EU Member States to assess and manage flood risks, with the aim to reduce adverse consequences for human health, environment, cultural heritage and economic activity in Europe. It has to be coordinated with the implementation of the WFD.

The action lines provide a comprehensive mechanism for assessing and monitoring increased flood risk, also due to climate change, and for developing appropriate adaptation approaches. This EU instrument provides Member States with a general framework which has to be implemented by National Flood Risk Management programmes that take into consideration specific risks at regional and local levels. The key to success of this framework is closely related to efficient exchanges among the main actors, and this has to take place at European (EU), national, regional and local levels. At the EU level, the so-called Common Implementation Strategy (CIS) enables flood experts from Member States, including scientists, flood risk managers and stakeholders, to gather through the Flood Working Group (WGF of the CIS), meeting regularly to exchange views on technical/scientific challenges for the implementation of the Directive.

Alfieri et al. (2016) in *Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies*, reported that under the projected increase in frequency and magnitude of river floods, traditional approaches based only on rising indefinitely local flood protections are not sustainable in the long term. The combined effect of these two dynamics is likely to exacerbate the "levee effect" by reducing the frequency of moderate events and exposing the society to few catastrophic floods, followed by potentially long and painful post-event recovery. The authors recommend future adaptation strategies to be based on a combination of different measures working in synergy and optimized at the level of river basins, rather than through independent actions over selected river reaches. In agreement with previous research (*Zurich, 2014; Di Baldassarre et al., 2015*), they have showed that adaptation efforts should give priority to measures targeted at reducing the consequences of hazardous events, rather than trying to avoid their occurrence. In particular, relocation and vulnerability reduction measures should be further developed, due to their two key features of 1) reducing the impacts of all floods without reducing their frequency, thus strengthening the resilience of societies and ultimately the "adaptation effect"; and 2) reducing the effects of uncertainty in future climate on the consequent risk reduction due to adaptation measures. Further adaptation measures to reduce the peak flow should make use of natural retention capacity upstream, while rising flood protections should be seen as last resort, to compensate for the residual risk in areas where other options cannot be implemented. In the latter case, best practice in the realization of new structures include 1) the need for gradual and non-catastrophic failure in case of overload, and 2) building in redundancy, so that a single failure in the system would not compromise the overall flood risk protection capacity.

As reported by *Cardona et al. (2012)* in *Determinants of risk: exposure and vulnerability*, vulnerability and exposure are dynamic, varying across temporal and spatial scales, and depend on economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors. Individuals and communities are differentially exposed and vulnerable, and this is based on factors such as wealth, education, race/ethnicity/religion, gender, age, class/caste, disability, and health status. Lack of resilience and capacity to anticipate, cope with, and adapt to extremes and change are important causal factors of vulnerability. Moreover, taking into account the challenge posed by the assessment and reduction of the future vulnerability, the authors reported that it is embedded in the present conditions of the communities that may be exposed in the future (*Patt et al., 2005, 2009*); that is, new hazards in areas not previously subject to them will reveal, not necessarily create, underlying vulnerability factors (*Alwang et al., 2001; Cardona et al., 2003a; Lopez-Calva and Ortiz, 2008; UNISDR, 2009a*).

3.2.2.4.2 Portugal

Given the importance of the transboundary river basins for the Portuguese water resources it is of paramount importance to develop joint projects in cooperation between Portugal and Spain on this topic. This question should be considered with particular relevance in the general framework of bilateral scientific and technological cooperation.

According to *Rocha (2000),* the strategy to modify the vulnerability is to avoid dangerous, non-economic, undesirable or irrational uses in flooded areas. Among the measures, the regulation of flood zones should be one that should be given a special preference. This reinforces the need to develop robust and effective flood management rules.

3.2.2.5 Major challenges for improving resilience

3.2.2.5.1 Europe

As reported by *Lawrence et al. (2020)* in *Cascading climate change impacts and implications*, common implications emerged that affect risk assessments and adaptation decisions taken by decision makers, for example:

- The strategic significance of the dependencies between three waters infrastructure, flood risk management and utilities planning.
- The need for integrated multi-hazard approaches to address the coincidence of many hazards in some locations.
- Limits to the current, largely reactive mode of responding to climate events as they happen, highlighting the need for anticipatory approaches.
- How collaborative models of public engagement hold promise for increased public understanding of how climate change impacts propagate and their significance for actions at difference levels of government.
- Highlighting the dependencies between land use and infrastructure planning when managing risk and vulnerability so cascading impacts of climate change can be addressed as the impacts worsen over time.
- For informing adaptations that are designed and deployed to 'fit the problem space' of changing risk and uncertainty and to help identify opportunities while managing risk.

By examining the dependencies and feedback loops between different systems of concern when stressed with changing climate impacts, we are able to 'stress-test' our risk assumptions. This can facilitate the design of adaptation responses that are flexible, yet robust under different future conditions, and thus avoid reaching thresholds that are beyond the ability of communities and physical systems to cope. Illustrating dependencies between urban systems, the financial sector and human wellbeing outcomes, is one demonstration of the value of considering cascading impacts. By understanding these linkages and prioritising the critical nodes, adaptation responses can be made more transparent. This suggests the role that decision tools (network and systems tools) can play in decision making in complex systems to facilitate a deeper understanding of how systems stressed by climate change might behave. By so doing, this can motivate a shift from considering single impacts that conceal the reality of climate change impacts, to a more nuanced approach based on the generative effect of compounding stresses. This can inform adaptive planning and the institutional and governance arrangements for delivering more effective adaptation alongside mitigation policy and practice.

In the *EFLIP project* the authors proposed that flood insurance can and should play an increasingly important role in mitigating flood impacts, not only through risk sharing, but also through all aspects of the risk management cycle, including risk identification and modelling, risk awareness, damage prevention, risk transfer, and recovery. Insurance can incentivise and reward risk reduction through adjustments of premiums and policy terms (e.g., deductibles). They explore ways of harnessing insurance for better protection of environment, and ecosystem services also for the sake of disaster risk reduction.

The EEA (2017) in *Climate change adaptation and disaster risk reduction in Europe. Enhancing coherence of the knowledge base, policies and practices*, suggested as opportunities to enhance coherence between climate change adaptation and disaster risk reduction in policy and practice:

- Developing consistent and complementary knowledge and coordination platforms at EU, national and regional level.
- Improved monitoring and risk assessment (outcomes and processes).
- Enhancing coherence between climate change adaptation and disaster risk reduction climate services.
- Long-term national programmatic approaches.
- Nature-based solutions (NBSs) to maximise co-benefits.
- Monitoring and evaluation to improve policy implementation and adaptive Management.

According to *Driessen et al. (2018)* in *Governance Strategies for Improving Flood Resilience in the Face of Climate Change*, to be "flood resilient", countries should have sufficient capacity to resist, the capacity to absorb and recover, and the capacity to transform and adapt.

In particular, in the framework of the STAR-FLOOD project, six key governance strategies have been identified thanks to systematic and detailed analyses and evaluations of flood risk governance and associated legal frameworks in Belgium, England, France, The Netherlands, Poland and Sweden between October 2013 and September 2015. These are:

1. **Diversification of Flood Risk Management approaches**: it is increasingly argued that optimizing the capacity to resist floods, absorb and recover from floods, and to adapt and transform requires a diversified portfolio of flood risk management approaches. The authors specified that the extent to which approaches can be diversified depends on physical and institutional features, as well as general levels of development, flood risk management legacies, culture and politics.
2. **Alignment of flood risk management approaches to overcome fragmentation.** This requires to enhance the connectivity between policy sectors and administrative levels to overcome fragmentation that a diversification of flood risk management approaches may create. Hence, the employment of bridging mechanisms or processes that broadly entail information exchange, coordination of policies and cooperation mechanisms are needed. Regarding this, top-down and bottom-up policy processes should be combined and coordinated.
3. **Increased involvement of private actors, including business, NGOs, and citizens in addition to strong public involvement**: the input of a diverse set of resources and capacities that are embodied in the expertise and knowledge of stakeholders is needed to implement a diverse set of flood risk management approaches and strengthen all the three capacities. Moreover, from a normative perspective, participation in decision-making is considered by the authors important because participation enhances the legitimacy of measures that are taken to decrease flood risks and contributes to representative deliberation, procedural and distributive justice, and socio-political acceptability.
4. **Adequate formal rules that balance legal certainty and flexibility.** Flood risk governance requires a delicate balancing act between legal certainty—that is the assurance that one's rights are clear and will be respected—and flexibility which might be necessary for adaptive governance. To establish the different resilience capacities, both are needed to some extent: legal certainty is required to achieve clarity about responsibilities amongst public authorities and communities and provides much needed structure and guidance, which is necessary to be used for flood risk management; on the other hand, to achieve a high capacity to adapt and transform, formal rules should also provide enough flexibility to enable tailored approaches and adaptive pathways whereby a change in course is possible if dynamics require it (e.g. due to urbanization or climate change patterns).
   Flexibility and the possibility to adapt because of changing circumstances is generally provided by multiple year planning cycles: a new planning period should take new circumstances into account.

Long-term strategic planning combined with short-term operational planning provides citizens with clarity on what can be expected in the near future.

5. **The assurance of sufficient resources**: diversification of flood risk management strategies requires resources, including finances, knowledge, and capacities. In this regard, the authors see two important developments that, from a resilience perspective, provide opportunities and risks: private investments and decentralization.
   Increasing appeal is being made to local governments as well as private actors to take up more responsibility in flood risk management. From a resilience perspective, this has, in principle, the advantage that the resource base is broadened and that locally tailored approaches are enabled, strengthening the capacity to adapt and transform and the capacity to absorb and recover. However, decentralization as well as reliance on private investments is not without risks. For example, a lack of funds and expertise at the level of local communities can limit the development of approaches.
6. **Appropriate normative principles for dealing with distributional effects**: resilient flood risk governance requires mechanisms to ensure social equity and to address "unfair" distributional effects.

3.2.2.5.2 Portugal

APA (2019) reports that the program of measures is one of the most important elements of the Flood Risk Management Plan, considering that it outlines the technically and economically feasible actions that allow achieving a reduction of the risk of flooding by decreasing its potential detrimental consequences. It is important to provide a framework for the origin of the different sources of funding to be mobilized for implementing the program of measures. In this respect, ensuring an alignment between the relative financial effort, i.e., the financial effort of each of the sources of funding, of the programs of measures in Portugal and other Member States, namely Spain, is considered to be particularly relevant.

Non-structural measures might complement flood risk attenuation in some zones, easing the financial issue. Because the construction of non-sustainable (engineered) dams is extremely costly, the only possible way to mitigate flood risk in these critical zones would be to couple flood attenuation with hydroelectric use, or through the implementation of an extensive reforestation program in the catchment with the purpose to increase evapotranspiration and reduce runoff (*Terêncio et al., 2020*).

3.2.3 Storms

3.2.3.1 Major Climate Change Impacts on each phase of the risk management cycle

Prevention: Weakened trees (e.g., from water stress and/or pest and pathogen infestation) require closer monitoring of tree health to ensure safety along roads, which implies more effort for forest owners or forest managers.
Multi-hazard interactions can lead to new hazard scenarios for which little to no experience exists.

Preparedness: Novel hazard scenarios spurred by climate change, make it challenging for emergency bodies to prepare for every possible scenario. Instead general preparedness and adaptability for new situations should be encouraged.

Response: Winter storms are often accompanied with heavy precipitation events and rapid temperature changes. Climate change increases the variability. This leads to challenges during the response phase, which may impede emergency management.

Recovery: Increased winter temperatures lead to less frost days and more precipitation in form of rainfall instead of snow. Frozen ground facilitates harvesting operations and minimizes soil disturbance. Following a winter storm event, timely processing of fallen trees helps to recuperate timber, thus reducing economic losses and more importantly reduces breeding material for secondary pests (e.g., bark beetles), thus reducing their spread.
Changing environmental conditions (drier / hotter & more extreme precipitation events) can make it harder to regenerate forests following a natural hazard. E.g., usual tree planting techniques have lower success rates and require more expensive planting material (i.e., container plants with better roots) or watering of seedling. This means higher costs.

3.2.3.2 The influence of uncertainties associated to climate models

N/A

3.2.3.3 Major challenges for ensuring coping capacity

The main challenge for emergency authorities is to increase overall adaptability to an increasing number of possible and new scenarios. Uncertainty needs to be addressed and incorporated in the emergency planning. A functioning horizontal and vertical communication across institutions is crucial to ensure coping capacity during a crisis. It can be trained and should be part of the preparation phase prior to a natural disaster.

3.2.3.4 Major challenges for assessing and reducing exposure and vulnerability

Assessing exposure and vulnerability is part of a comprehensive risk analysis. While the tools and procedures are clear and available, often responsible authorities have other priorities in their day to day work or are not mandated to do so. Reducing exposure and vulnerability means that activities identified in the risk assessment need to be implemented. This goes even further than conducting a risk analysis and requires political will and determination.

3.2.3.5 Major challenges for improving resilience

Climate-mediated increase in disturbances and natural hazards could exceed the ecological resilience of forests, resulting in lastingly altered ecosystems or shifts to non-forest ecosystems as tipping points are crossed. Consequently, disturbance change is expected to be among the most profound impacts that climate change will have on forest ecosystems in the coming decades.

3.2.4 Avalanches

ICGC reported that the did not find many publications and projects that implement knowledge on climate change in snow avalanche risk management. Therefore, further study is needed. The following are some studies that have been done in relation to climate change and how it affects risk management.

The Austrian Alps are experiencing winters with higher rainfall and higher than normal snow accumulations. However, during the summer we find a decrease in precipitation. This large amount of snow in winter has resulted in unprecedented large avalanche episodes. These changes affect the management of risk and future emergencies and pose a challenge (*Salzer et al., 2010*).

ICGC find research that seeks to implement climate change trends in critical equipment management and decision-making in future risk management (*Zeidler et al., 2013*) and studies that highlight the need to update and incorporate knowledge on climate change in risk planning and management (*Hestnes et al., 2016*).

Finally, there is research that suggests some recommendations for improving knowledge and developing procedures for dealing with risk in a climate change context (*Garcia, 2016*).

3.2.5 Landslides

3.2.5.1 Major Climate Change Impacts on each phase of the risk management cycle

Intensity (magnitude) and frequency of a damaging landslides can be directly influenced by climate change in the coming decades. Damage events experienced so far can be significantly exceeded. To overcome such events, structural measures alone are often not sufficient, since the spatial occurrence of landslides is difficult to predict. Therefore, a combination of structural, organizational and spatial planning measures must increasingly be used in the preparation phase of the risk cycle. The approach of risk governance by involving all actors in the interaction and decision-making process is also necessary.

Suitable scenarios that represent the possible effects of climate change (overload concepts) are recommended as a basis for coping with the damaging events.

3.2.5.2 The influence of uncertainties associated to climate models

Uncertainties in the assessment of the impact of climate change in the area of landslides require a closer look at the “Residual Risk” (undetected risk, unknown risk and accepted risk). For this risk, which remains despite protective and precautionary measures have been taken, the planning of contingency measures and recovery capacities is needed (*Bebi, et al., 2016*). For such planning, appropriate scenarios are required that provide information about the type and extent of the hazard.

3.2.5.3 Major challenges for ensuring coping capacity

The following questions need to be answered when dealing with damage events caused by landslides: What are the potential dangers? What risks are you willing to take? What measures are required? How can you proceed according to the "better rebuild" principle in the event of a damaging event? (*Bundesamt für Umwelt Bern, 2017)*.

In Austria, one of the essential features of disaster management is the separation of responsibilities for prevention/preparedness and recover. While preparedness such as the setting up of emergency organizations, exercises, training, planning, infrastructural precautions, etc. is mainly the responsibility of the municipalities, district administrative authorities, state governments and the blue-light organizations, the avoidance of natural hazards is largely the responsibility of other actors such as the torrent and avalanche control division, the protective water management and regional spatial planning. The cross-competence cooperation of all actors in the entire risk cycle is therefore an essential objective and challenge.
Accordingly, it is very important to know the relevant actors and stakeholders and their roles, responsibilities and capacities to contribution to the management of natural hazard risks.

3.2.5.4 Major challenges for assessing and reducing exposure and vulnerability

There are still considerable gaps in terms of standardized functional relationships between forces acting through landslides processes and the structural damage caused by these events (*Papathoma-Köhle et al., 2017*).

These gaps are primarily due to the general lack of available data (e.g., inventories), particularly with regard to the extent of damage and the actual causal damage that has occurred *(Fuchs et al., 2018*). Another challenge in vulnerability research is that a multitude of systems interacting with each other (social systems, physical systems, etc.) behave dynamically.

In Austria, for example, the stock and infrastructure have experienced an exponential increase of the damage potential since 1950. Therefore, risk management have to base on holistic perspectives and measures. For example, technical (structural) measures for planning as well as financing, implementation and maintenance require an institutional background.

This also applies to the most effective restrictions that generally avoid the effects of hazards e.g., by keeping endangered areas free. Although this only works as long as there are no vulnerable uses in dangerous matters. Potential hazard index maps are also the basis for managing vulnerability. These are not used for detailed planning, but the higher-level (regional) planning. These maps are not appropriate to set building restrictions, but show potential endangered areas, where further surveys "on the spot" are necessary/recommended.

Comprehensive information is required that not only specifies the degree of landslide risk, but also gives meaningful recommendations for action.

3.2.5.5 Major challenges for improving resilience

Resilience should not only focus on the resilience of infrastructure and society but on the usability of protective structures ("robustness", "redundancy" and "ease of maintenance") as well.

To increase resilience of state and society, the cooperation of different actors and professions (including disaster control manages) implementing numerous measures in a coordinated manner is necessary. Deepening cooperation with critical infrastructure operators: A "public-private partnership" between the administration and critical infrastructure operators is important.

In the area of strengthening resilience, the so-called "risk governance" has become more and more important in recent years (*Alpenkonvention, Ständiges Sekretariat, 2019*). Risk governance aims to involve as many persons as possible who may be affected in the event of damaging events in the risk management planning processes. In addition, they should also be enabled to take responsibility (for themselves) and to find or implement solutions. The advantage of risk governance is that it can be implemented in existing risk management frameworks.

3.2.6 Rockfalls

3.2.6.1 Major Climate Change Impacts on each phase of the risk management cycle

Prevention: In this context, spatial planning is of great importance, since restrictions on land use keeping endangered areas free or requirements for targeted land use can reduce risks significant. However, this requires standardized protection goals, harmonized design events and uniform safety levels as well as construction engineering rules in building codes and technical standards.

For spatial planning usually static planning information is preferred. Thus, it is not the intention of most of the tools (hazard maps) to consider changes (climate change, land use changes) or draw scenarios so far. Anyhow, additional modules to extend the hazard focused maps by information on risks scenarios as climate change will be necessary to meet future challenges.

Rockfall events are site-specific and predominantly lead to local impacts. Some Austrian federal states offer regional hazard index maps (e.g., the NÖ Atlas, Land Niederösterreich (2018), with scales of M=1:25,000-50,000). However, these maps do not contain information on energy intensities or probabilities. The current hazard zone plan of the Austrian torrent and avalanche control only provide the designation of "brown reference areas", which "could possibly be affected" by rockfall (or other gravitational processes as landslides).

Also, early warning systems are of great importance with regard to the management of future extreme natural hazard events. In the case of rockfall, however, these systems have so far only been taken in relation to known hotspots respectively after damaging events. Large-scale early warning systems are currently not feasible from a technical and economic point of view. Sentinel2 data, photogrammetric or laser scanning methods using drones and GPS-based monitoring could offer new opportunities.

Preparedness: At the moment, rockfall is incompletely considered in disaster control plans or local alarm plans, which is a major problem with regard to the possible effects of climate change.

Response: Several well-structured institutions are involved in the management of rock fall impacts (fire brigades, road maintenance departments, geological services of the federal states, torrent and avalanche control, federal armed forces).

Recovery: Risk-oriented spatial planning should help to reduce the required resources for technical protections or recovery measures after events. Thereby, the focus is on planning and non-structural measures. However, this is challenging, since the protective effects can be achieved much faster by technical measures.

Nevertheless, a residual risk remains despite of technical measures. However, this is often economically and socially much more accepted than a total avoidance of usage in endangerd areas, e.g., by relocating residential buildings. Unclearly regulated framework conditions (e.g., where should / can / may rockfall material be deposited?) and insufficient insurance coverage for homeowners are further weak points in the recovery process.

3.2.6.2 The influence of uncertainties associated to climate models

Sass and Oberlechner (2012) have compared and examined the rockfall records available in Austria in order to identify a comprehensive trend due to climate change. No microclimatic conditions (such as freeze-thaw changes or pore water pressure) were considered. The analysis of 252 events in Austria between the years 1900 and 2010 with a release volume between 10^2 and 10^6 m^3 showed that only 9% of the recorded events occurred at altitudes above 2.100 m (where permafrost would be possible). It must be mentioned here that release volumes below 10^2 m^3 were not taken into account, which means that the focus was more on rock-avalanches than on single block rockfalls. The small percentage of events above 2.100 m could also be due to incomplete documentation because of the lack of potential risk for humans and infrastructure in this high altitude areas.

Due to the warmer conditions events in receding permafrost regions may occur more frequently. Below permafrost regions there is (currently) no indication that events will increase due to climate change (*Gruner, 2008; Sass and Oberlechner, 2012*). In an annual comparison with precipitation and temperature, no correlation between warming and rock fall events was found. At best, a tendency towards more events in cold years, especially after cold winters (possibly due to frost blowing), was observed. Most events were observed in spring, presumably due to increased water supply by meltwater and rain (pore water pressure) and by freeze-thaw changes.

Protective structures are usually planned according to a "design event", which have a defined return period. This is a retrospective approach, (events from the past are considered → block deposits / silent witnesses) with limited suitability for addressing significant changes in the magnitude and frequency of damaging events. The consequences are considerable uncertainties with regard to the design of technical measures in response to a possible change in frequency and magnitude due to climate change. Therefore, a reconsideration of the "design event" may be necessary in order to maintain the currently existing safety level in the medium to long term.

3.2.6.3 Major challenges for ensuring coping capacity

In the context of coping strategies, the equipment and training of emergency forces and disaster response services, the preparation of disaster plans and practicing are essential factors. Other important measures include infrastructural precautions (crisis centres, securing telecommunications, etc.) and risk communication (education, motivation for strengthen self-responsibility, (*Jachs, 2011*)). The establishment of well connected structures as well as the connection to key persons to other organisations is crucial (*BMI, 2007*).

In Austria, municipalities are responsible for local hazard. Beyond that, the emergency services are also available nationwide and are organised at district and provincial level as well. Generally, rescue services in Austria belong mainly to the voluntary sector. In the federal state of Tyrol, for example, more than 32.000 voluntary members in fire brigades are regularly involved in the management of natural hazards (https://www.feuerwehr.tirol/). Other major actors in this context are the road maintenance authorities of the federal states and the operator of the "ASFINAG" motorways, who are often responsible for documenting the damage events and initiating/implementing necessary emergency measures.

The greater the damaging effect of an event, the greater the number of public actors. Unclear responsibilities may cause delays in (necessary) actions (*Reindl-Krauskopf et al., 2016*). Hence, a coordinated management of interdisciplinary and cross-sectoral cooperation (spatial planning, forestry, geology, torrent and avalanche control, community) is required. Hence, it is important to maintain existing structures, to close structural gaps, and also to ensure the involvement of private companies (e.g., earthworks contractors) for the damage management.

If these civil resources are not sufficient, the Federal Armed Forces can also provide assistance. It is important to maintain the number of volunteer militiamen in particular in order to secure capacities. In 2010, for example, the Austrian Armed Forces not only had 26,000 basic military personnel but also 27.000 volunteer militia soldiers[15] on call for deployment.

Recently, spontaneous volunteer civil forces have also become additional operational resources. However, appropriate structures are needed to accommodate such spontaneous volunteers, to ensure the positive effects of support.

There is also further potential for strengthening coping capacities in cross-border cooperation, both between local / Austrian authorities and at European and international level.

3.2.6.4 Major challenges for assessing and reducing exposure and vulnerability

Rockfall events have their starting point mainly at very steep slopes (>45°) in alpine regions. Accordingly, the greatest challenges in terms of vulnerability are the increasing land use on mountain slopes (few building sites in flat areas), the general land consumption and the still continuing expansion of tourism in Alpine valleys. The associated increase of damage potential (increase in value of the building stock) and the

[15] https://www.diepresse.com/595185/das-osterreichische-bundesheer-zahlen-und-fakten

decoupling of living and economic areas (and thus increased mobility) increase vulnerability all the more if spatial delimitation of classified rockfall hazard areas is not available (as in Austria). The seasonal shift of the personal risk from residential and work places to leisure and holiday areas (*Örok, 2016*) also plays a significant role.

The quantification of vulnerability requires the estimation of the relationship between frequency and magnitude of damaging events and the damage patterns of exposed values. However, as the intensities and occurrence probabilities of rockfall events in Austria are not at all spatially differentiated (with the exception of expert opinions for individual slopes), no reliable statements can be made about the particular vulnerability of critical infrastructures in the Alpine region. Therefore, only the following general hypotheses can be formulated:

- The technical sub-systems of critical infrastructures in the Alpine region are more vulnerable to natural hazards than those outside the Alpine region. Increased precautionary measures are therefore required to ensure that the Alps as an economic and living space are secured sustainably.
- Due to the specific geographical conditions, it is more difficult and expensive to build up (technical) redundancies of critical infrastructure in the Alpine region. Accordingly, the costs for their operation increase.
- This may lead to business management considerations to move critical infrastructure to less vulnerable regions.

According to *Atkisson et al. (1984),* financial expenditures to reduce vulnerability consists mainly of investments in technical measures (dams, reservoirs, etc.), while others include mainly recurrent expenses on personnel (e. g. avalanche warning services). Due to the hardly temporal prediction of rockfalls, such a warning service does not exist so far. In Austria, rockfall events are mostly treated reactively, after they have occurred.

An active reduction of vulnerability through non-structural measures is possible by controlling the spatial distribution of uses and construction activities. This would require clear guidelines for decisions (based on improved data) in the construction process. The possible reconstruction of buildings after catastrophic events at the same location must also be critically examined (like in Huben (Tyrol) after a rock avalanche in 1999).

In Austria, the handling of natural hazards is largely delegated to political decision-makers (*Rudolf-Miklau et al., 2015*). For this reason, individual precautions to reduce vulnerability are partly neglected (*Kanonier, 2006*) and financial support through governmental aid programmes (disaster funds) or donations is relied on. However, there are considerations to transfer this currently practised system of risk transfer to a system with mandatory building insurance also for private households.

3.2.6.5 Major challenges for improving resilience

The attempt to ensure comprehensive protection of all relevant systems of state and society is replaced by the concept of resilience. The aim is to strengthen the resistance and regeneration capacity of these systems. However, since the state institution alone cannot ensure the increase of resilience, the participation of all relevant stakeholders together is important. Anyhow, it is the response of government to create the political, strategic, and legal framework for such public-private partnerships.

Programs to increase resilience include measures in the categories of capacities, capabilities and culture. Building capacities means building reserves and building in redundancies. Capabilities can be developed by practising emergency situations and drawing up crisis and disaster management plans. Rockfall is inadequately considered in such management plans (see point a).

Resilience cannot be increased by a single, generally effective measure. For this reason, a large number of measures and integrated protection concepts were developed (*Fekete & Hufschmidt, 2016*). Thus, the national security research programme KIRAS or the EU programme HORIZON 2020 aimed on the increase of the knowledge base. Research institutions are still working together with public administration to develop practical technological solutions for the protection of critical infrastructures (Hager, 2020). The expansion of research (including data acquisition and documentation), the intensification of cooperation with the operators of critical infrastructures and the strengthening of coordination between the programs for the protection of critical infrastructures and civil protection are important components.

3.2.7 Comments

From the review carried out, it is possible to argue that there are many European and national projects and studies that concern with dealing with climate change impacts.

Many are the solutions, actions and measures analysed, implemented and proposed in these projects. In the Table 5 some main elements are reported.

Table 5. Main elements of the climate change impacts on Risk Management

DISASTER RISK	SOME EXAMPLES OF CHALLENGES FOR COPING CAPACITY	SOME EXAMPLES OF CHALLENGES FOR EXPOSURE AND VULNERABILITY	SOME EXAMPLES OF CHALLENGES FOR RESILIENCE
Wildfire	Cooperation and coordination and communication between stakeholders and actors of DRR actions. Legal framework and chain of responsibility.	Fuel management at landscape level. Community awareness and preparedness. Smart urban planning.	Holistic and transdisciplinary approaches to landscape management as a base for action. Development of capacity to restore functions quickly and effectively in the face of disruptions and to adapt and change after a shock.

DISASTER RISK	SOME EXAMPLES OF CHALLENGES FOR COPING CAPACITY	SOME EXAMPLES OF CHALLENGES FOR EXPOSURE AND VULNERABILITY	SOME EXAMPLES OF CHALLENGES FOR RESILIENCE
Flood (flash flood)	CP planning with new risk scenarios. Improving Early warning system.	Risk assessment. Risk transfer.	More nuanced and integrated approach based on the generative effect of compounding stresses. Nature-based solutions (NBSs) to maximise co-benefits. Increased involvement of private actors, including business, NGOs, and citizens in addition to strong public involvement.
Avalanche	Uncertainty of CC and New extreme scenarios in CP planning.	Knowledge, forecasting and assessment.	Integrated land management.
Storm	Uncertainty of CC and New extreme scenarios in CP planning. Horizontal and vertical communication across institutions.	More political will. Changing vegetation and land use management.	Holistic and transdisciplinary approaches to landscape management as a base for action.
Landslide & Rockfall	Chain of responsibility and involvement of private companies. More equipment and training.	Risk transfer. Risk assessment (More available data and early warning system). Integrated approach (Cross-sectoral cooperation).	Cooperation of different actors and professionals (both public and private) Risk governance aimed to involve as many persons as possible who may be affected in the event of damaging events in the risk management planning processes.

3.3 Needs and priorities for civil protection and risk managers posed by climate change

3.3.1 Methodology

Each partner enriched the review analysis on climate change through a qualitative survey which involved civil protection stakeholders and risk managers with the objective to better understand the main challenges and needs for facing climate change from their perspective, also as end users of the project results.

The methodology proposed is based on the conduction by each partner of a series of interviews to the different organisms involved in:

- Civil Protection and emergency management;
- risk management.

In this regard, it is important to mention two exceptions: as reported by FVA, in Germany the profession “risk manager” does not exist. Risk management is in fact predominantly carried out in landscape and urban planning, even though it would be highly beneficial to have a separate discipline for risk assessment of natural hazards. Also, BFW reported that in Austria, especially in the field of landslides and rockfall, many actors who are normally strongly involved in prevention and spatial planning are mainly executing (immediate measures in case of an event, set up protective structures). This indicates unclear distributions of competences in Austria for the assessment of damage disposition and the provision of preventive planning bases.

All the interviews were carried out following the same questions and template (see Annex I) and beyond the two exceptions mentioned, each partner was the responsible for the interviews in its region or country. Afterwards, each partner prepared a sum-up of the interviews to highlight the main points emerged from the interviews they performed.

Each partner has some preference risk of expertise (as can be seen in Table 6 and Table 7) so their contributions are benchmarked in each of these fields. However, as many reported, questions are related to different risks and many answers from interviewees are referred to different risks also. Moreover, some of the partners also have expertise in other risks and interviewed actors of a wider field of knowledge.

The questions to civil protection stakeholders are organized in two different parts:

- Extreme event experienced:
    - biggest natural hazard experienced (situation, tools used, data, resources, etc.);
    - main weakness points of the emergency management during this event;
    - best practices used during this event.
- Climate Change related scenarios:
    - main changes and challenges of the civil protection system;
    - new needs in this scenario in terms of operational management;
    - new needs in this scenario in terms of operational tools;
    - new needs in this scenario in terms of data integration;

- improvement and interactions in the balance between prevention-preparedness-response efforts/actions to have a more effective and efficient emergency management and response system;
- role of the population preparedness for facing CC.

The questions to risk managers are related to Climate change scenarios and in particular are focused on:

- biggest natural hazard experienced;
- territorial vulnerabilities that have increased the impacts and damages and that have affected the emergency management;
- best practices developed in the territory (in terms of risk assessment, mapping and planning tools, risk governance and policy, risk culture and communication, technical measures) that have mitigated the impacts and damages and that have favoured the emergency management;
- main changes and challenges for risk managers in order to face CC scenarios;
- new needs in terms of risk assessment tools;
- improvement necessary in the prevention phase by risk managers and other stakeholders in order to integrate this CC scenario in the disaster risk reduction measures;
- efforts/actions by risk managers to have a more effective and efficient emergency management and response system;
- improvement and interactions in the balance between prevention-preparedness-response efforts/actions to have a more effective and efficient emergency management and response system.

Starting from these questions, each partner summarized their interviews to finalize the gap analysis about climate change scenarios integration into disaster risk management (DRM).

For civil protection and emergency management stakeholders, the sum-up focused on:

- General description of the extreme events considered as proxy for climate change.
- Main concerns highlighted in terms of Civil Protection regarding the extreme events considering CC.
- Possible integrated actions/efforts among the different phases of the disaster risk management cycle, if any, for better coping with these new hypothetical scenarios.

For risk management stakeholders, the sum-up focused on:

- General description of the extreme events - considered as proxy for climate change with special attention on territorial vulnerabilities and best practices implemented for facing it.
- Main concerns highlighted in terms of risk management regarding the extreme events considering climate change.
- Possible integrated actions/efforts among the different phases of the disaster risk management cycle for better being prepared in the context of these new scenarios.

In order to reach the objectives of understanding the main challenges and needs for facing Climate Change from the perspective of civil protection and risk managers stakeholders, all the summarized information coming from each partner (from different countries, regions, territorial level and natural hazards expertise) has been gathered together in the next sections, sorted by issues (following the structure of the described sum-up review) and highlighting the most relevant assertions.

Finally, the needs collected have been prioritized by each partner and then read and mapped through the lens of the risk management cycle - identifying the phase concerned (prevention, preparedness, response and recovery) - and the lens of the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR) – identifying the priorities addressed - in order to contextualize them and to better understand where to focus efforts. [16]

3.3.2 Civil protection / Emergency management stakeholders

3.3.2.1 Overview of the interviewed profiles

The overall number of the civil protection / emergency management stakeholders interviewed is 54. These experts, who are the same interviewed in the context of the Deliverable 2.2., have different profiles and come from different authorities among countries involved operating at different administrative levels – local, regional and national level - as showed in Table 6.

Table 6. Administrative level and authorities interviewed (Civil Protection and emergency management stakeholders)

Country (Partner): risk analysed	#	ADMINISTRATIVE LEVELS	AUTHORITY / PROFILE
Germany (FVA): Storms	4	Local, regional and national	• German Committee for Disaster Reduction (DKKV) • Federal Office of Civil Protection and Disaster Assistance (BBK) • Regional council Freiburg • City and Rural District Karlsruhe
Austria (BWF): Rockfalls & Landslides	11	Local, regional and national	• Political decision-makers • representatives of public authorities, • support organizations of the federal states • fire brigades and CP and disaster management
Italy (CIMA): Wildfires	16	Local, regional and national	• Mayors and technicians of the Municipalities of 5 Terre • Regional Civil Protection sector (Liguria) • Regional Department of agriculture, firefighting (Liguria) • National Civil Protection Department

[16] The Sendai Framework for Disaster Risk Reduction outlines 4 priorities: (1) understanding disaster risk; (2) strengthening disaster risk governance to manage disaster risk; (3) investing in disaster risk reduction for resilience; (4) enhancing disaster preparedness for effective response, and to Building Back Better in recovery, rehabilitation and reconstruction.

Country (Partner): risk analysed	#	ADMINISTRATIVE LEVELS	AUTHORITY / PROFILE
Italy (CIMA): Floods	15	Local, regional and national	• Mayors and technicians of the Municipalities of 5 Terre • Regional Civil Protection sector (Liguria) • National Civil Protection Department
Spain (PCF, DGPC CAT, ICGC, CTFC): Wildfires & Avalanches	8	Regional	• Catalan Fire and Rescue Service • Catalan Civil Protection body
Portugal (ISA): Wildfires	5	Local, regional	• Municipal and inter-municipal civil protection offices

FVA conducted 4 interviews at different administrative and geographic levels, covering different stakeholder groups and levels of management (from Section President to Technical Advisor). The institutions are the following:

- The DKKV is the national platform for disaster prevention in Germany. It is an intermediary to international organisations and initiatives active in the field of disaster prevention and serves as competence centre for all questions of national and international disaster risk management.
- The BBK is the Federal Agency for Civil Protection and disaster risk reduction. As a subsidiary of the Federal Ministry of House Affairs it has a central organisational element working to ensure the safety of the population, combining and providing all relevant tasks and information in a single place.
- The Regional council Freiburg constitutes the higher emergency authority. It oversees the work of emergency authorities at district level and coordinates and advices during cross-district extreme events. It has operational competences for nuclear safety only.
- The City and Rural District Karlsruhe are two typical districts within the Federal State of Baden-Württemberg, Germany. The District Fire Service oversees and coordinates the operational Civil Protection of the firefighting service in the municipalities.

Consequently, there is a high degree of geographical representativeness and a wide range of responsibility.

BFW conducted 11 interviews to relevant actors in natural hazards and disaster management with regard to the processes of landslides and rockfall, the issue in which BFW has its expertise. They cover different levels of the managing process, from representative of fire brigades and Civil Protection to political decisions-makes. In Austria planning and executive activities are managed together. This indicates unclear distributions of competences for the assessment of damage disposition and the provision of preventive planning bases. The stakeholders interviewed were most frequently involved in flood events. Anyhow, rockfall and landslides also play a major role in their area of responsibility. In addition, large slope movements, surface water runoff, high winds, fire, snow load and ice smoothness are also mentioned as areas of application.

CIMA conducted 17 interviews at different administrative and geographic levels, covering different stakeholder groups and levels of management (some mayors but mainly technicians). They include Civil

Protection technicians from the National Department of Civil Protection with expertise in floods and fire, Civil Protection technicians from the (Liguria) Regional Sector of Civil Protection with expertise in floods and forest fires, experts from the Regional Department of agriculture, tourism, training and work policies in the internal areas, forest fire fighting, foresting, parks and biodiversity, and Municipal mayors and technicians of local Civil Protection. They are involved in all the risk management phases.

It has to be mentioned that in Italy, each region has a high degree of autonomy in this issue. They regulate the organization of Civil Protection systems, ensuring the implementation of the procedures for the preparation and implementation of activities aimed at forecasting and preventing risks, managing the regional operating room (also aimed at information exchange with the Department of Civil Protection, Prefectures and Municipalities), managing the regional mobile deployment resources including also the volunteer organizations, organizing training activities in the field of forecasting, prevention and management of emergency situations and in general aimed at raising awareness on Civil Protection matters.

The degree of representativeness in these series of interviews is very high because the amount and the coverage of all the administrative levels.

In the case of Spain, local partners coordinated to conduct the interviews, tackling main emergency bodies in the target region of analysis of Catalonia.

PCF conducted 2 interviews from the Catalan Fire and Rescue Service (CFRS), so with expertise in wildfires. They hold different levels of responsibility but with a high degree of technical expertise. One mainly deals with the management of the command and control central room and communication and use of technological tools to communicate and monitor operations in the field. The other interviewed is more wildfire oriented, being a wildfire analysis and assessment specialist.

CTFC conducted 1 interview from the Catalan Civil Protection (DGPC CAT) body. The representative works, with a mid-level responsibility, coordinating the global strategy from a local perspective, giving support to the territorial coordination of the different operational corps and local stakeholders, programming the operative resources and their dimension for the Civil Protection actions and coordinating the logistic actions in case of emergency.

Finally, **DGPC CAT** conducted 5 interviews, all within the Catalan Civil Protection body and all with mid-level or high responsibilities. Their role is related to planning, operational emergency management, development of technology and communication, so they cover a wide range of fields.

In relation to the interviews performed by the Spanish partners, it has to be highlighted that all are from Catalonia and covers different bodies related to the Civil Protection and emergency services from the regional government. It needs to be mentioned that in Spain each region has a high degree of autonomy in relation to the emergency management, although there is a basic regulation at the country level that all regions must follow. In the particular case of Catalonia, it has its own emergency management bodies for fire and rescue services, police, health emergency service, forest officers, Civil Protection and institutions for risk management in some natural risk (hydrology, meteorology and geology).

On the other hand, municipalities play a very important role although only Barcelona holds its own fire department, many of them holds local police and all have a high degree of autonomy in emergency planning. However, regarding natural emergencies, the management is performed at a regional level because the Catalan administration holds the resources and only in case of an emergency affecting other autonomic regions or in case of non-manageable dimensions there would a coordination from the Spanish administration.

Finally, **ISA** collected information through 5 interviews with: 2 Municipal Civil Protection Operational Commanders (Seia and Portimão); 2 Coordinators of the forestry technician's municipal offices (Monchique and Viana de Castelo) and 1 Planning consultant, wildfire protection and control technician in the inter-municipal community Alto Minho.

As a conclusion, the number of interviews is high and can help drawing a picture of the needs, improvements and weaknesses in relation to Civil Protection and the emergency management facing climate change. Obviously, it has to be pointed out that each country has different organizational schemes implying different responsibilities and activities among the bodies at national, regional and local levels.

3.3.2.2 General description of the extreme events considered as proxy for climate change

FVA reported that the most common natural hazard events in Germany are winter storms, flooding and torrential rain events. Multi-hazard events occur mostly as a combination of the latter (e.g., wind storm and subsequent flooding). In recent years, severe drought and heat waves have increased, which trigger additional hazards, such as forest fire resulting in air pollution and insect and pathogen infestations of forests.

For extreme storm events, there is a tendency for an increase in severity (i.e., maximum wind speeds) and in frequency (i.e., recurrence interval). However, the spatial occurrence remains highly unpredictable. Predominantly small patches of wind throw with damaged trees provide ideal propagation conditions for bark beetles, which can result in mass gradation, which affects even healthy trees. Increasingly drier conditions, caused by climate change lead to stressed trees with reduced protection mechanism. In recent years, this led to the die-off of forest stands at landscape level in some areas of Germany.

The described multi-hazard situation (windstorm – bark beetle – drought – more bark beetle) creates (next to massive damages for the forestry enterprises) unprecedented challenges that reach beyond the forest sector and also affects civil protection and society (e.g., increased soil erosion, reduced traffic safety). The described scenario is a typical cascade of events, with the initial storm event being the trigger. Depending on the size and type of wind damage and the human reaction, it is possible to steer the direction of the cascade and limit the extent of damage. E.g., when the damaged wood is cleared in time, the following bark beetle infestation will remain at a manageable level. Climate change comes on top of this and adds challenges.

The effects of climate change on forests become clearly visible with the recent drought periods of 2018 and 2019. The lack of precipitation led to weakened tree, particularly those that are less site-adapted. In the long term, climate change may change site conditions. Additionally, new types of pest and pathogen species appear or migrate from warmer climates, to which native species may not be adapted.

During winter months, storm periods bring abrupt changes in weather conditions and temperatures, which can lead to increased and sudden snowmelt in combination with heavy precipitation. These trigger flooding and soaked grounds, which can lead to landslides in steep terrain. In combination with a storm event, blown trees can block streams, increasing the risk of flooding and limit access to affected areas. An increase in soil erosion due to the die-off of forests becomes also problematic.

In summer months, it is mostly local storm cells that can cause extreme wind speeds and heavy rainfall leading to flash floods. This is the most common emergency scenario caused by natural hazard event. The drought and heatwaves of 2018 and 2019 lead to generally drier conditions in forests and lead to increased forest fire danger. In case of forest fires, it is mostly the resulting air pollution that causes problems for the general population.

In general, during the interviews civil protection agencies seemed to be confident about their abilities to respond to the new hazard situation.

BFW reported that in the course of climate change, intensive, convective, small scale precipitation-events in combination with hail events and resulting discharges are assumed to increase triggering multi-hazard scenarios as well as cascade effects. While the - at least in the subjective perception - heavier precipitation leads to rapid flood discharges in torrents. in their catchments. These landslides often develop to canalized debris flows and dam up the receiving water in the valley floor (Schnann, 2018; Sellrain, 2015; Gasen, 2005), causing multi-hazards and cascade effects.

The vulnerability is (mostly) particularly high at the valley bottom, where settlements and industrial areas are located close to the hazards as tributaries (Schnann), while the triggering events takes place high upstream in the catchment areas. According to the interviewed actors (especially at the district authority Landeck) it is currently still very difficult to predict such meteorological events. For example, the event in Schnann 2018 was only recognized from the population when the debris masses passed the village. The meteorological extreme-event high up on the mountain was not really noticed. Thus, the hazard occurred largely unexpected.

The best-practice example is not the anticipatory preparation/prevention at those places where high damages could be expected, but the rapid reaction and mobilization of equipment and forces at those places where the damage or process has already occurred.

The partly climate change-related impairment of the protection forest was mentioned as well. In the future, forest damage caused by e.g., windthrow events and the following bark beetle calamities (cascade effect!) in combination with a lack of reforestation will result in increased energy inputs in the transit and deposition zones of rockfall.

The following procedure can be seen as a best-practice example of the WLV (torrent and avalanche control): For dimensioning for example a rockfall protection dam, a design event is used which does not take the effects of existing protection forest into account. It is assumed that the forest may suffer from climate change and cannot maintain its protective effects after the implementation of the technical measure. Hence, for slopes with rockfall hazards, the energy inputs for the dimensioning of the protection measures are treated as if there were no protection forest between the release areas and the objects to be protected. In this way, possible negative changes caused by climate change and its effects (fire, bark beetle, windthrow) are anticipated to a certain extent. Potential cascade effects are reacted to early and foresightedly. However, from several representativeness of the WLV at the same time the important protective role of forests for different natural hazard processes was stressed. Up to now, it seems, that there is no one hundred per cent agreement on how to deal with climate change and the role of effected forests.

CIMA – regarding floods - reported different extreme events considered as proxy for climate change by the interviewed at different levels:

The actor at national level mentioned the event of Messina on the 1st of October 2009. This event can be considered paradigmatic of the dynamics and effects of climate change and, at the same time, it can be - even if partially - considered multi-risk, as the impacts of the event were accentuated by the fires which occurred two years earlier in the territory. The Ionian coast of Messina was affected by a very intense rainfall event (250 mm / 6 h) with an estimated return time of 300-500 years in a territory of around 50 km^2. The predictability of the event was very low, in relation to the limited area and the very small spatial scale: the weather models had not reported anything significant.

Specifically, the Municipalities of Messina and the neighbouring Municipalities of Scaletta Zanclea and Itala were particularly affected. Numerous mud and debris flows, landslides and floods led to the loss of 37 human lives and enormous damage to buildings, settlements and infrastructures. The main direct damages were related to buildings, settlements and infrastructures; indirectly, the whole economy of the area, based on the service sector, agriculture and tourism, was affected.

The territorial levels involved were both central, regional, provincial and municipal. During the event, standard tools (for consulting hydro-rainfall data, e-mail, fax, spreadsheets, etc.) were used, while means and resources by land, air and even naval vehicles were activated. The post-event residual risk was the subject of numerous field inspections aimed at identifying and delimiting the areas that could have been affected by any further events and in which adopt measures to safeguard the population, including the evacuation of a few thousand people. Moreover, the 2009 Messina event can be considered as multi-risk: in fact, on the basis of the field inspections, it has been ascertained that the interface fires that occurred in 2007 had at least contribute to the triggering of mud and debris flows.

The Liguria region actors reported the flood events of October / November 2019 in Liguria. During the period considered, a series of weather-hydrogeological events took place. Those that recorded the greatest effects on the ground were 14-15 October, 19-22 October and 2-3 November, in a disturbed context characterized by further episodes that - although less impactful - contributed to increasing the hydrogeological stress of the area. The events affected the whole region and in particular the territory of the Metropolitan City of Genoa and the provinces of Savona and La Spezia, causing floods, landslides, roads subsidence and disruption, tree crashes, etc.

The local actors of 5 Terre reported the flash floods and landslides event in Vernazza and Monterosso, 25 October 2011 that affected their territory. The storm structure, persistent and highly organized, produced very intense rainfall (153 mm/h in Brugnato, 129 mm/h in Calice al Cornoviglio, 111mm/h in Levanto) with cumulated, for the overall duration of the event, very high (539 mm/24h in Brugnato, 454 mm/24h in Calice al Cornoviglio, 382 mm/24h in Monterosso. The return period of the maximum values recorded vary, depending on the cumulative period, between 100 and 350 years. The event was such that all the territorial levels were activated: municipal, provincial, regional and national, given the declaration of the national state of emergency. The important effects of floods and landslides, which have spread widely in the Ligurian east, have led to significant damage to infrastructures (collapse of bridges and embankments, interruption of roads); the landslides have caused, in addition to damaging most of the provincial and municipal roads, also the interruption of the highway and railway roads. The networks of essential services (water, gas, electricity) and the sewage collectors were destroyed in the most affected population centers. Telephony services have had ongoing interruptions. Moreover, many footpaths have been inaccessible for over a year. The Municipalities were isolated for 48h and 800 people were evacuated, while 13 people lost their lives, the damage is calculated in hundreds of millions of euros.

CIMA – regarding wildfires - reported different extreme events considered as proxy for climate change by the interviewed at different levels:

At national level, two situations were discussed: the forest fires of the 2007 and the forest fires of 2017. The main causes of these events were:

- Scarce water availability in the periods before the summer season.
- Persistence of favorable conditions for triggering and propagating forest fires.
- High number of contemporary events with persistence even for several days.

The events of 2007 were mainly the consequence of conditions particularly favourable to the ignition and spread of fires with regional AIB response systems not calibrated for those conditions. All the regions of central and southern Italy were busy dealing with a large number of events, the forecasting tools were able to predict the particularity of the conditions, but the situation was so widespread and the contemporary events were so numerous that the resources available were unable to cover them all at the same time. The situation was complicated by the fact that some events used resources continuously over several days.

2017 was characterized by the simultaneous presence of climatic weather factors particularly favourable to the triggering and propagation of forest fires, and by organizational factors as it was the first summer campaign conducted in the absence of State Forestry Corps (CFS) suppressed due to the reform introduced by Legislative Decree 167/2016. Following the reform, the CFS staff was merged partly within the Carabinieri Corps and partly into the National Fire Brigade, this caused a dispersion of know-how and the need to create new balances in many of the regional AIB systems that boasted ten-year collaborations with the CFS. The weather and climatic conditions, although not comparable to those of 2007, were in any case particularly favourable and favoured the ignition and spread of fires with problems related to the massive use of resources and the persistence of events even for several days.
Before and during these events different tools are used, such as forecast models for the assessment of susceptibility to triggering and the spread of forest fires, tools for monitoring weather conditions, satellite information aimed at evaluating the pre-event and post-event scenario for assessing damage and defining the area covered by the fire. One of the biggest difficulties is having a clear idea of all the events in the area.
The damages are mainly borne by the forest heritage and vegetation in general. In the event of interface fires, the greatest damages are borne by tourist structures and farms, also with problems related to the management of livestock.
In the post event, local authorities were urged to reassess the conditions for landslide risk in the areas at greatest risk that were affected by fires.

Even at regional level, a 2017 event was discussed: a forest fire and WUI occurred between the 25 September and 14 of October 2017 in the territory of two provinces of the Ligurian Region (Imperia and Savona). During this event 125 hectares were burned. The main cause was the high drought of forest biomass.

PCF reported that one of the most important wildfires have been Solsonès 1998, Horta de Sant Joan 2009 and Sant Llorenç Savall 2003. However, floodings cause the same or more deaths than wildfires in Catalonia.

Sant Llorenç Savall 2003 fire affected a portion of a natural parc. Since it was a natural parc, people thought that it should be preserved, but parc regulation did not allow forest management. Therefore, the fire got an extreme behaviour.

The fire propagated through massive spotting, not in a linear front. The strategy was mainly to protect citizens and limit as much as possible the propagation of the front using several combinated maneuvers. 5 civilians were killed because the fire catched them in the middle of a road, trying to escape from their homes. However, their homes were a save place and did not burn. It was an early August fire; Catalonia experienced a very difficult week under a heat wave and simultaneity of wildfires. Almost 5000 hectares burned for 9 days. Despite the strong blaze was only during the first days.

Another severe wildfire was Torre de l'Espanyol 2019. It burned 5.000 hectares between 26-27th June 2019. Fire service suggested to activate the maximum alert for these days.

It burned a very abrupt terrain. The fire had the capacity to generate massive spotting at the front. Despite there was a low load of fuel, the fire had the capacity to burn in a very fast propagation rate. Weather was very complex, under a heat-wave situation. The suppression capacity was overcame by the fire. Both fires crossed municipality and county limits, therefore, it was a provincial emergency. Plenty of authorities attended the event (county, mayors, head of the interior department and province authorities).

At operational level, the fire mobilized resources from all parts of Catalonia, GRAF teams and aircrafts and helicopters. Nowadays, the deployment of units would have been almost the same. Maybe EPAF units would have played a role in using manual tools. Coordination between units and command posts would have been better, thus, the improvement potential is in the coordination and internal communication part rather than human resources and operations.

In the case of Torre de l'Espanyol, FS used all the tools available like GPS, radio, phones, cameras to collect information, etc. We used ArcGis, so every time someone saw a hotspot or anyone was making a manoeuvre it was documented and accessible for everybody. There was satellite data, multiple information from different weather stations. Also, fire service chat to share fire updates. Regional authorities and mayors of the area were present in the command post.

The fire burned farms and affected some houses. Of course, that has a socioeconomic impact on the area. There were road brakes, evacuations and some people in the area needed a rescue. Fortunately, any civilian or firefighter was killed. There was a nuclear plant near the area. The main concern was to protect electric power lines in order to avoid possible negative consequences on the nuclear plant. The fire had a lot of reignitions. Actually, it was not fully extinguished after 1 month.

CTFC reported that along the interview two important extreme events where mentioned: Gloria storm (January 2020) with an important flood events associated, and the fresh snowfall in March 2010, with high impact in the communication and electric network in a huge territory with thousands of citizens affected.

DGPC CAT reported floods, flash-floods, snowfalls and wildfires. Floods and flash-floods cause the main of the personal damages, whereas fires cause the main damage to the environment. It is mentioned also heavy winds and heat weaves. It seems that fires are less frequent in the last years than in the past and, besides, heavy winds are more intense and frequent. All these phenomena are related to climate change.

Regarding the trigger effect pattern, wildfires and heavy winds increase the severity of floods. Besides, wildfires may threaten chemical factories, which is known as NATECH (technological accidents triggered by a natural hazard or disaster which result in consequences involving hazardous substances).

ISA reported that along the interviews, four different wildfire events were discussed that occurred in Portugal between 2016 and 2018 in Seia, Viana do Castelo, Monchique and Pedrogão Grande, as well as a 2010 flashflood in Vila Nova de Cerveira.

These were wildfires with different damages in terms of burnt area, as well as different levels of other losses (human lives and property). A common feature of the analysed wildfires was the lack of measures to prevent this type of risk in terms of planning at the district levels, as well as better cooperation between local actors. Also, in relation to the Climate Change, was underlined the need to focus on fuel management:

- creating mosaic landscape;
- rethink protection and prevention plans in the presence of a new rural reality with a strong depopulation;
- promote landownership cadaster to increase the activity of private owners in the management of their territories;
- increase working and social conditions for shepherds;
- to solve the problem of lack of human resources, especially forest workers.

In addition, it is necessary to analyze the amount of water used to extinguish fires (due to the expected drought), and an increase in the number of wildfires in winter.

It is also important to reduce the time and barriers to up-to-date information (eg. geo-referenced information on the level of risks and their impacts and municipal emergency plans). Risk assessment and monitoring should be carried out on an ongoing basis, and municipal contingency plans should be updated more frequently. The installation of meteorological stations and high-resolution cameras by municipalities will help keep up to date information.

Some of the interviewed indicated that the lack of effective tools is felt in the control of many risks. New tools and a more dynamic and more assertive emergency response plan are urgently needed. Tables and other information guides should provide more solid and useful information.

In the case of flash floods, the question was raised of the needs of skilled professionals with knowledge and trained for this new type of risks. It could be a team of experts that could give support to these and other extreme events.

3.3.2.3 Main concerns highlighted in terms of Civil Protection regarding the extreme events considering CC

FVA reported that the extreme events of the past years showed that not all hazard situations can be predicted. Therefore, it is necessary to learn from these extreme and unprecedented cases and integrate the insights they offer into the planning and preparation of future events.

For example, the increase in the number and severity of small-scale extreme precipitation events is currently not covered by large-scale resolution of weather forecasting applications. Additionally, small creeks are usually not included in the mandatory EU water directive, thus, no flood simulations are undertaken. In case a local storm cell hits an area, the amount of precipitation can quickly exceed the capacity of the river bed and lead to partial flooding, which overwhelms existing civil protection capacities. Such highly severe and hard-to-predict events have a very long return period. It is important to realize that not all risk can be excluded or limited. Therefore, risk assessment needs to identify different risk and decide which ones are acceptable and which ones should be treated. Improved forecasting technology with real time predictions of local effects and hazard impacts can support better coordination of emergency response, such as special equipment distribution.

Certainly an advantage in Germany is the existence of a well-established network of forest roads, which allow access to even remote forest areas. Originally designed to enable sustainable forest management and the provision of timber resources, it proofs also beneficial for emergency management in natural disaster situations. However, the orientation and finding of the precise operation sites needs improvement. So far it is often the local knowledge of civil protection staff that ensures finding the right location. Currently, not all emergency vehicles are equipped with GPS receivers. It should be ensured that at least the heads of operation carry GPS devices.

Novel hazard situations may require different approaches and specialized equipment. This is particularly the case for the hazard “forest fire” in Germany. So far, there is only limited experience and equipment available. E.g., not every municipality needs and can afford a water tank carrying off-road truck, which then would be used in comparably rare occasions. Here, new approaches of regional cooperation, such as equipment and cost sharing may turn out fruitful.

BFW reported that from the perspective of civil protection and related risk management, one of the most important challenges to mitigate hypothetical climate change scenarios in disaster control is the ensuring sufficient personal resources. For example, the thousands of volunteer members of the statewide volunteer fire departments in the municipalities are an indispensable resource in natural hazard and disaster management. At present 32.741 members are active according to the fire-brigade federation of Tyrol[17]. It is important to maintain or (depending on requirements) expand these capacities in the future. For fire departments, the maintenance of annual disaster control exercises (also cross-border) is important.

Personnel bottlenecks also occur (at peak times) in state internal support organizations such as the State Geological Survey, which requires a flexible and rapid mobilization of (external) experts. However, this cause additional expenses and higher financial burdens (except for volunteer personnel in the fire departments).

Substantial financial expenses are required for the monitoring of instable slopes due to the long runtime (e.g., as now since May 2020 in the rear Ötztal, where the permanent monitoring of a slope became necessary. The snow melt in spring led to multiple slope movements with landslides and rockfall processes).

[17] https://www.feuerwehr.tirol/

Although the cooperation is generally described as proper, considering hypothetical climate change scenarios, increased cooperation is of great importance.

The elaboration of the adapted legal basis is considered as important in the future.

A challenge arises in the handling of the landfill of accumulating bed load / and rockfall deposits which may gain further importance by climate change. The affected "waste owners" have to face the question under which conditions and especially where surplus material can / may be disposed of. According to the law, accumulating bed load must be chemically sampled for possible contamination. Thus, responsible persons are already now challenged (financial and coordinative) and in future even more (especially at the community level).

Operational management, better coordination of tools and equipment are mentioned as well to overcome challenges ahead. In the case of an increased occurrence of major events such as 2018 (Schnann), the exchange of equipment between acting organizations (e.g., Armed Forces ↔ fire departments) should be possible more easily.

New requirements in terms of operational tools are just as important in view of the discussed climate change scenarios as the provision of new information and data. For example, the interviewed fire department leader mentioned that, taking into account the event trend, a higher number of large pumps and emergency power generators should be available.

In general, the equipment of public actors to prevent and recover damaged infrastructure should be improved to reduce the dependence of private companies (e.g., earthmovers and their excavators).

The consensus was that a rapidly changing climate requires new tools anyway.

For example, the hazard maps in Austria only represent the actual state – there are no scenarios (e.g., change of endangerment caused by climate change or land use) included. However, the willing to switch to scenario-based risk maps is currently limited.

Regarding the information and data needs to be covered in the future, the digital information is crucial. There is an increasing demand for improved high-resolution weather data. The small structured topographical conditions (small catchments) still cause weaknesses in the location of discharge events.

Geology experts ask for the establishment of InSAR proceedings for the monitoring / evaluation of rock faces as well as more frequent, more up-to-date laser scanning flights.

The river level measurement systems for the larger valley rivers, which has already been installed in the province of Tyrol for years, should be incorporated into the software of the fire departments for easier handling.

In addition to the digital requirements mentioned above, more consistent and continuous event registers - based on standardized event documentation - are desired as well.

CIMA – regarding floods - reported that the concerns and needs highlighted in terms of civil protection by the actors at different levels in some cases resulted different, as each one has different responsibilities and capacities within the civil protection system.

At national level, given the extreme event considered, the main difficulty reported was to understand and evaluate the event and risk scenario in real time, due to the remarkable speed of the event and the rapid evolution of the scenarios. Moreover, some other critical issues have been reported: the weakness of civil protection planning, the lack of operational procedures, the lack of a structured information activity for the population, the inadequate knowledge of the event and risk scenarios, the failure to prepare non-structural measures, etc.

The main challenges identified by the national level for the civil protection system in order to face a hypothetical CC scenario are:

- The increased frequency of spatially and temporally concentrated meteorological events, against which there are significant critical points from an operational point of view and significant conditions of forecast opacity.
- The contribution to the increase in risk conditions, resulting from the significant changes in land use that have taken place in recent decades, and in particular from the widespread soils sealing and extensive urbanization.
- Increase in the frequency of water crises, due to the progressive increase in temperatures and the accentuated variability and reduction of meteoric contributions: the above, together with anthropogenic factors (water network losses, obsolescence of the infrastructures, reduced interconnection of the water schemes, etc.) will result in a significant increase in the frequency and impacts of water crises.

In general, in this scenario their need in terms of *operational management* would be the strengthening of the governance, as an element of strategic importance in consolidating the civil protection system. The Italian civil protection system is in fact multilevel, polycentric and widespread, and complexity must certainly be combined with the necessary speed of intervention and effectiveness. In this context, there is the need to identify robust and flexible operating protocols and management approaches shared between the different institutional levels and for the different phases of the emergency cycle.

Their new needs in this scenario in terms of *operational tools* would be:

- Improvement of the forecasting and monitoring systems, which allow to predict with the widest possible time interval, the approaching of meteorological phenomena spatially and temporally concentrated and to be able to determine risk scenarios for the population.
- The possibility of having advanced nowcasting tools and other tools for managing territorial and geographic data, as well as advanced DSS tools are undoubtedly important aspects to improve the supply of operational tools.

Their need in this scenario in terms of *data integration* would be:

- to have platforms that allow the integration of the instrumental data transmitted by the measuring instruments (pluviometric, hydrometric, thermometric, radar, etc.) with information, also non-instrumental, from the territory (e.g., from territorial offices).

At regional level, taking into account the event described above, they reported that - given the complexity and duration of the extreme event considered - in the regional control room it was difficult to collect and organize information in a structured way, to continuously check and validate incoming information, to keep track of updates and to have immediate information on the territory by the operational staff.

One of the main concerns in terms of civil protection is then related to the timing of these events, which would be more frequent and sudden.

Their new needs in this scenario in terms of *operational management* would be:

- Being able to organize the information flow to send and record information from the territory directly, in order to get a real-time overall situation to be provided to the entire civil protection system to effectively manage the emergency
- More effective civil protection planning
- More collaboration between institutions or offices of the same agency
- More financial resources to program in ordinary time and more human resources
- Greater training and preparedness within the Municipalities, also on CC

Their new needs in this scenario in terms of *operational tools* would be IT tools that facilitate the construction and visualization of the real-time overall situation to limit response times and territorial structured reports from mayors and operational staff.

Their new needs in this scenario in terms of *data integration* would be to have an information flow already organized to send, record and integrate information from the territory directly, for example through a written and structured report.

At local level, the interviewed reported some weaknesses of the civil protection system during the extreme event described before:

- Poor coordination of actions implemented by the different municipalities and with other national or local agencies that were involved in the emergency management;
- Low level of infrastructure of the communication system;
- The Civil Protection plan did not take into account the risk related to the tourism crowding and its management. Microwave radio crashing, no electricity.

However, a good coordination between volunteers and the Operations Rooms were reported.

To face this CC scenario, requiring a faster responsiveness, they expressed as main changes and challenges for the civil protection system:

- Improvement of the civil protection plans, also for the management of tourist flows
- Greater coordination between local authorities
- Rising territory awareness
- Have a more stable road or radio infrastructure (or backup)
- Have people prepared and trained to manage these types of events.

Their new needs in this scenario in terms of *operational management* would be:

- Having more resources (volunteers and technicians dedicated to the emergency management) and more training
- Gaining greater coordination between the Region and the Municipalities in the post-emergency and damage collection phase.

Their new needs in this scenario in terms of *operational tool* would be:

- Improving the monitoring system and alerting procedures.
- Reassessing the emergency areas.
- Having a more stable (or back-up) infrastructure.

Their new needs in this scenario in terms of *data integration* would be gaining a greater coordination between the Municipalities and other local institutions.

CIMA – regarding wildfires – reported that one of the concerns at national level, given that the evolution of forest fire scenarios in Italy is usually of rapid development and the event closes in a few hours, is to quickly evaluate the scenario and its evolution so as to be able to undertake in a short time the most effective actions both for extinguishing and for civil protection. Moreover, it is necessary to focus on the participation of the population in understanding the risk and in the self-protection measures.

Regarding climate change related scenarios, the most probable is that of an increase in the frequency of water crises, due to the progressive increase in temperatures and the accentuated variability and reduction of meteoric inputs. This climatic scenario is plausible that will strongly influence the trend of fires and will have repercussions on several terms:

- Extreme conditions will be more frequent when fires start and spread.
- There will be impacts on vegetation at a physiological level, water scarcity will negatively influence the health of the species present, making them well predisposed to the passage of fire, pioneer species also more predisposed to the passage of fire will be favored.
- New pathogens will attack the vegetation making it predisposed to the passage of fire.
- Vegetation more inclined to the passage of fire will lead to a greater number of fires that will also affect landslide risk areas which, upon the occurrence of extreme rain events that will become increasingly frequent, will trigger landslides with probable repercussions on the anthropized environment.
- water scarcity and desertification will lower agricultural production until it is economically viable, there will be a further gradual abandonment of agricultural and rural areas, the lack of maintenance of these areas will favour their colonization by pioneer species more inclined to the passage of fire. Furthermore, their expansion will bring them closer to the populated areas by increasing the urban-rural interface areas.

In this scenario, the interviewed reported that reinforcing the AIB response systems alone cannot be a sustainable strategy, but in terms of operational management there is the necessity to have a long-term planning based on strategies coordinated at the different territorial levels, also supranational, with the aim of carrying out multi-scope interventions.

Their new needs in this scenario in terms of *operational tool* would be operational tools able to collect information in real time from the territory and, by combining static and dynamic information, to provide an evolution of the scenarios. These tools - if integrated with modules capable of simulating the effectiveness of possible preventive interventions - could be the basis for implementing the necessary structural and non-structural actions, increasingly finalizing them to the strategic objective proposed.

In terms of data integration, it was highlighted that the more data can be obtained, the more data can be processed and integrated, the more information can be obtained, the better it is possible to implement targeted actions.

At regional level, regarding the extreme event considered, an important constraint mentioned was the operational capacity due to the change of the entity that would have faced the fire event as a responder. In 2017, there was in fact a change of competence between the fire department and the forest rangers who previously dealt with the extinguishing and reconnaissance of fire damage. This made the system work slower and hinder the organization of civil protection.

Giving this kind of events, and considering it as a proxy of a hypothetical CC scenario, the main challenges and needs mentioned are:

- ensuring the availability of vehicles;
- gaining a greater competence and knowledge of new scenarios by the emergency management personnel;
- rising the knowledge and awareness of the population;
- improving the integration of procedures.

One of the main new need reported in this scenario in terms of *operational management* is the development of operating procedures that best identify roles and actions, while regarding operational tools, the need is more related to new or better forecasting and monitoring tools.

The new need expressed in this scenario in terms of *data integration* is to have and exchange information from other institutions such as municipalities or national or local agencies.

PCF reported that Fire Service (FS) always faces uncertainty, unknown scenarios. It is easier to gather knowledge in well-known topics, but the challenge is to gather knowledge in unknown contexts, because they are the scenarios that more damage can cause. As long as we are more aware of uncertainties and its impacts FS gain new methods and decision-making processes based on a wider framework. Every year new tools and new ways to obtain data are developed. However, too much data increases uncertainty. In the era of bigdata, they are focusing on what we know instead of paying attention on things that they do not know. The ideal would be to put efforts on scenarios that can cause severe impacts.

Weaknesses were at technological level. Signal is key to assure communication between deployed teams and command posts. If the communication is lost, the efforts of the units may be useless.

Training is a very important part to improve the response. However, Catalan firefighters are deployed in many different emergencies such as forest fires, urban fires, floodings, traffic accidents, mountain rescue, oil spills, industry explosions, buildings collapsing, etc. That makes training very difficult and highlights the need to have specialized teams inside the service. That is the example of GRAF units, that specialized their activities in forest fires (analysis, operations, etc). GRAF units have more potential to train the staff only in forest fires to ensure a more qualified response system.

The main challenge under climate change is to get used to the new scale of wildfires. Catalonia larger fires have never burnt entire massifs or counties in the recent decades. But nowadays, with increasing temperatures and hydric stress that climate change may cause added to fuel accumulation, some Catalan regions can entirely burn. In such cases, fire service will not be able to handle the situation without an active forest management.

In addition, a society change will be needed. We live in a very forested area and society must understand that it needs to be managed to be protected. Community awareness and self-protection measures will strongly help the fire service. People must understand that under certain scenarios, fire service capacity can be overwhelmed.

Regarding operational tools, PPE (Personal Protective Equipment) must incorporate sensors (CO_2, Available O_2, heart rate, toxic smoke…). That would facilitate the physical performance of the firefighter and its exposure to pollutants. New tools or systems to communicate units with commanders are needed. Concerning data integration, artificial intelligence is a field of expertise that will be extremely useful and will allow us to make a step forward in fire and emergencies management. Nowadays, units could be gathering more data, and somehow, we need to make a step forward in that sense. Apart from that, data gathered needs to be integrated in simulators and DSS to detect scenario changes according to data flow.

CTFC reported that there is a need related to basic supply network since it is a basic resource/service for population and emergency management. Expecting more and new extreme events, new risk prone areas, and thus, new risk situations, it is necessary to work on reinforcing the basic supply network to raise alternatives (for instance, should be enough resources "in case of emergency" for the private operators by law, including this in the contracts) in case of its fall (as in 2010 snowfall).

On the other hand, it would be necessary to work in the forecasting tools to integrate the CC scenarios and the recurrence of extreme events.

DGPC CAT reported that general concerns found in Civil Protection in any emergency are:

- Raise public awareness will help to implement some measures, especially in prevention, like the prohibition to establish camping areas in flooding areas, but also in relation to self-protection.
- Stronger civil protection measures in urban planning during the prevention stage will avoid dangerous situations.
- Improve forest maintenance for fire prevention (cleaning up, prevention fires…)
- Improve the risk analysis (local characteristics and effects, specific scenarios, locate the most vulnerable and problematic spots).
- Start a continuous training system for all the operative groups (fire fighters, police, emergency health….) to improve the interaction (coordination). It should bring an improvement of the coordination, knowledge between operative groups, in order to avoid duplication of tasks and clarify responsibilities.
- Develop and implement more standards and protocols in relations to the improvement and quality assurance in the planning and operational process.
- Increase the involvement of the population and stakeholders creating new work forums (though a daily base and active mechanism) which allow to detect needs in each filed, getting their concerns, how they may be affected and offering them the opportunity to participate in the emergency management to create synergies.
- It is recommended to raise awareness within the general population about the risk they are exposed to, the planning tools they may access.
- Municipalities should also give more information regarding the risk in their areas and give real public access to their plans.
- Local information should be transferred to the regional level to be integrated in the regional plans, because it is very difficult to know the local characteristics of each risk and municipalities may hold this knowledge. It is important that municipalities to detect possible situations difficult to be managed and to be transferred to the regional level for further analysis and planning.
- Start a georeferenced data base fed by local administrations, especially with the vulnerable spots, in order to better protect them in an emergency.
- Need to develop indexes to assess our performance and whether our taskforce and resources are enough.
- Need to implement standards for organizing and managing, especially for the operative service.

- Need local leaders to raise awareness.
- The obligation to hold a position of technician specialized in civil protection for each group of municipalities (the so called "comarca" which gathers different municipalities under the regional scale) which may give support to small municipalities.
- Improve the implementation of local plans.
- Support the interaction between local and regional actors to increase reliability between each other.
- Increase practical training to better know what to do in case of an emergency.

In a Climate Change scenario, all the above improvements will be necessary but also they will need to face new challenges:

- Faster events will be a main challenge.
- Understand that climate change is real and extreme events can happen and affect us.
- Identify the spots where in case of these events it may be difficult to manage the emergency.
- More staff.
- More resilient population.
- More use of self-protection (self-help).
- More prevention.
- More responsibility from the citizens.
- New impacts in management of urbanism and infrastructures (e.g., better management of second hose urbanizations which are normally in the middle of the forest).
- Increase in flooding areas, so new impacts in urban planning and infrastructures again.

In terms of *operational management*, they need:

- Include psico-social help, as population is more dependent on basic resources (water, electricity,). Population may feel insecure and easily lose confidence in the public management.
- More staff for psico-social to support needs from the population (e.g., after a flooding some people may have lost their homes and businesses and may feel devastated and confused, so they would need psychological support to overcome the situation and social support to help them in the way back to normality).
- Training and drills (all the emergency bodies together) to enhance make team building.
- Knowledge on the CC impact on the Civil Protection, in order to make the necessary changes
- New systems which help in the decision-making process, suggesting solutions to the experts and authorities.
- Summarizing information systems, to help in the decision-making process.
- Adding automatic tools to help the technicians, to help decide what is important and what is not.
- Take advantage from the practical experience from those who lived such extreme situations (since these situations are not very common and we need to be trained).
- Develop tools for practical training (like those for pilots.)
- Include these scenarios in the risk assessment (especially in forecast systems) and planning.
- Transfer the knowledge from the universities to the civil protection, especially at local level.

In terms of *operational tools*, they need:

- More range in the positioned radio network.
- Extend "Anywhere" to other hazards and improve the time in advance we can get the forecast.

- Improve the warning systems to reach all the population.
- Develop an App to warn local authorities to help to improve their management in emergencies.
- Better forecasting.
- Develop real-time monitoring tools for the hazard characteristics (e.g., level of rivers, new satellite imagery and diagnostic tools based on these images…).
- Massive sending of warning to the population through smart phones.
- Develop a platform for better and easier sharing of information between agencies, in a safe environment.
- Use of re-usable data formats.
- Integrated tool which incorporates forecasts and helps to make decisions.
- A tool to know the damages, to manage the recovery stage, including help to those affected, assurances.

In terms of new needs in *data integration*:

- Stronger synergies.
- Sharing data between actors (e.g., affected areas).
- An integration tool (the same for all actors) to help during the event and the recovery.

ISA reported that in the case of extreme events, taking into account CC, different needs were noted:

- The development of an interagency, able to integrate all the necessary skills and make the best use of them. The functioning of the Civil Protection system should not depend on a particular person or group of people, but the decision taken must be universal in its practical application, guaranteeing a constant level of response, regardless of who controls it and the height that it applies. It is also important to conduct an external audit of the civil protection system to improve its efficiency and effectiveness.
- The access to interagency information in the form of a single platform for the various agents of civil protection at different levels (from national to local) and for their communication and vertical discussion.
- A platform should be developed where all participants and stakeholders who carry out prevention activities should record what is done and where. For example, municipalities often do not have access to information on preventive measures carried out by national forest services.
- The collection and in the unification and integration of data. In addition, some of the indicators monitored by various organizations require standardization, organization and rethinking.
- Important to improve knowledge on how to interpret the effects of meteorological variables in combination with geographic ones.
- Increase the number of teams of forest workers, more equipment, more training for the self-protection of the local population, etc.
- Improve public awareness. New forms of interaction with the population are needed, such as their inclusion in the control process.

3.3.2.4 Possible integrated actions/efforts among the different phases of the disaster risk management cycle, if any, for better coping with these new hypothetical scenarios

FVA stated that to face these new challenges a first step is to realize and understand the direction of change. For all interview partners the effects of climate change and resulting challenges for emergency management were quite clear. To acknowledge that preparation is needed is certainly the most important step during the preparation phase of the DRM cycle.

It was proposed to integrate and address novel hazard situations (predominantly forest fires) in the education and trainings of members of the emergency staff. However, the interview partners made a distinction between the levels of competences. At the tactical level (e.g., head of operation, executive leadership) it is necessary to generate a broader understanding and adapt existing structures and ways of planning. At the ground level the focus should not be on specific situations, but rather train the ability to adapt the routines according to the requirements on the spot (e.g., strengthen the capacity to develop creative solutions).

Regular interagency trainings in one district were reported to be a very beneficial activity during the preparation phase for two reasons: 1) the existing structures and processes are practiced, and potential difficulties may become visible; 2) people get to know each other, which builds trust and lowers barriers to reach out and ask for support in case of a disaster.

The creation of a specific task force “Forest Fires” for the city forest of Freiburg (Germany) recently proofed successful. Here representatives of the municipal forestry district, two local fire brigade groups, police and other emergency agencies developed and trained for emergency operations and developed forest fire operation maps (“Waldbrandeinsatzkarten”).

To prevent a hazard (i.e., fire), the local population can be sensitized about the hazard situation and forbid campfires and smoking, as well as asking for support for detection.

In general, most actions and efforts mentioned during the interviews took place in the preparation phase of the DRM to prepare activities during the response phase. This is clearly due to the fact that the interviews focused merely on emergency management, which naturally takes place during the response phase.

BFW reported that the phases of prevention and preparedness, the communication, structure, coordination and information will continue to be crucial and have to be functional. However, this also applies to the phase of response / action.

In addition to these management requirements, the assessment of potential rockfall processes in the official hazard zone plan (so far only avalanche and torrent hazards have been depicted in more concrete terms) was mentioned in particular as a challenge to be mastered in the near future.

Nevertheless, the basic tenor among experts in the field of fast-moving, geogenic natural hazard processes is that major events such as Sellrain 2015 or, in particular, Vals 2017 are hardly "trainable". Hence, such events are hardly calculable as regards prevention and preparedness.

Beyond the operational management of the actors, the preparation of the population in coping with hypothetical scenarios is very important. Besides alerting and evacuation in case of an event, a continuous / climate change-adapted awareness raising is necessary. Suggested were actions to teach the handling of natural hazards and climate change already in primary schools. Self-responsibility regarding private structural precautions will become more and more important in the prevention phase. The wish of a mayor, who was interviewed, was more self-initiative of inhabitants as e.g., the construction of small structural protection measures. This could happen e.g., by the establishment of only 1m high concrete walls on the mountain side of dwellings. He expected this to reduce the efforts required in the recovery phase.

Even before the actual classical prevention (mitigation, hazard zoning, etc.), it is necessary to sensitize high level decision-makers, e.g., from regional planning policy. Undesired settlement developments of the past years should have no place in the future (at this point, for example, the settlement of residential objects in the immediate catchment area of rock slopes that tend to fall down).

CIMA – regarding floods – reported that at all the levels, there is no doubt that a more integrated and efficient link between forecasting and prevention and response activities is needed to face climate change scenarios.

At national level, the interviewed reported some crucial efforts needed and some actions that the civil protection system could done in the prevention and preparedness phases to have a more effective and efficient emergency management and response system, such as:

- in-depth and shared knowledge of the different operating procedures,
- the effective implementation of civil protection planning: some municipalities do not have the plan and moreover it is necessary to evaluate the actual implementation of those developed (the civil protection plans are often not activated or partially activated),
- the constant interinstitutional link,
- the forecast and real-time monitoring of events.
- Improvement of risk knowledge and assessment: knowledge of risk scenarios is often just outlined, mostly in a qualitative way, and on the basis of basin planning documents (such as FRMP) which do not take into account limited hydrogeological and hydraulic phenomena and highly vulnerable areas (underpasses, basements , etc.).

In fact, the interviewed reported that in the case of intense meteorological phenomena, which occur in very circumscribed territorial areas, the activation of civil protection plans, the knowledge of operating procedures and the preparedness of the population are all key factors for mitigating the effects of the aforementioned meteorological events. Regarding this last point, the interviewed highlighted that the role of the population preparedness is fundamental: knowledge of self-protection measures allows to significantly reduce the impact of hydrogeological and hydraulic phenomena on the population. Many hydrogeological and hydraulic phenomena are difficult to predict in terms of time and space and, therefore, it is necessary for the population to adopt self-protection measures before, during and after the event, independently regardless of whether there has been an alert or not. For this reason, communication and information campaigns to the population (e.g., "I do not take risk") must continue and be further extended and strengthened. Moreover, it is important to underline the active and organized contribution that the population can provide to the different emergency management phases by volunteering.

At regional level, they reported the necessity of:

- a shared path of the whole Region that involves those sectors that manage the territory and thus build a relationship of collaboration and coordination with civil protection;
- activation of a post-event feedback mechanism through the improvement of the organization of the incoming data: the data can be provided to those who will then have to plan at territorial level

and to the Municipalities to improve the management of the territory and possibly “build back better”;
- activities of risk awareness raising of population;
- attempt to involve the population in the emergency phase and to understand how to engage them also in a planning phase.

At local level, as possible integrated actions, they proposed:

- an integration between territorial planning and territorial risk data in the ongoing process of intermunicipal urban planning between the municipalities;
- training of technicians and administrators also to encourage the exchange of information and collaboration;
- coordination between the Municipalities and the National Park also in the territorial risk management and for promoting an effective management of the territory.

In particular, to have a more effective and efficient emergency management and response system they would improve their civil protection plans; capacities through training and specifically monitoring capacities also through the definition of the thresholds for the operational phases. Moreover, they recognized that the preparedness of the population plays a decisive role in a context of climate change, above all for the possibility of putting effective self-protection measures into practice and for helping to better manage the territory.

CIMA – regarding wildfires – even in this case stated that both at national and regional level, there is awareness that it would be necessary to build integrated actions and efforts among the different phases of the disaster risk management cycle for better coping with these new hypothetical scenarios.

In particular, at national level, central actions identified by the interviewed would be the exchange of information and coordination and increasing involvement of all the subjects concerned.

The role of population preparedness is fundamental: knowledge of self-protection measures allows to significantly reduce the impact of a fire. Making the population aware of the fire risk and possible self-protection measures makes them able to protect themselves against the occurrence of a phenomenon, mainly of anthropogenic cause, for which it is not possible to know where and when it will happen. Furthermore, being a trigger phenomenon mainly of anthropic nature, the diffusion of knowledge about the phenomenon helps to reduce the causes that trigger the phenomenon.

In fact, the interviewed highlighted that in areas particularly exposed to fires, it is necessary to have a system made up of institutions and citizens where each of the subjects is aware of the condition they face; therefore, the tool needed is a good civil protection plan where citizens and institutions collaborate in drafting.

At regional level, the interviewed reported some actions that the civil protection system and emergency management could done in the prevention and preparedness phases to have a more effective and efficient emergency management and response system, such as:

- improving the forest fire prevention system based on the alert level;
- training and acquisition of skills;
- improving the knowledge of the territory to better intervene in the territory.

More in general, the interviewed noticed that the balance between prevention-preparedness-response efforts/actions could be improved through an interinstitutional technical table at national level to coordinate the extinguishing phases (Fire Brigade and Region).

PCF reported that response clearly absorbs most of the efforts and economic expenses of the emergency cycle. Without any doubt, this situation should be shifted. Prevention and preparedness should receive more attention (through human and economic resources).

In the case of forest fires, the big step will come with the investment of budget in prevention actions linked to a territory model fostering rural and bioeconomy. A better prevention in terms of forest management will make easier the emergency response, and it will be more cost-efficient than spending budget in suppression resources.

The implication and awareness of society will make the suppression and civil protection tasks easier, as well. For instance, avoid civilians trapped in a road, 25 meters strips in the WUI, etc.

Society role is key. In Catalonia, a scenario similar to the events lived in California 2018 or Australia 2019/2020 would compromise the safety of thousands of civilians, and the fire service response capacity would be overwhelmed. People must learn wise actions and procedures to keep their own safety during an extreme fire.

Society is a non-aware stakeholder of the emergency. They have a role in all emergencies, so they must be aware and train their decision-making capacity so that fire service can expect wiser decisions of the society during the fire. Fire service do not have the capacity to safe everybody or anything. We must adapt to new scenarios, build resilience and accept that mega-fires will occur, and we need to learn how to live with that.

CTFC reported that special emphasis was posed in risk awareness and communication as a way to reinforce the prevention and preparedness to improve and make more efficient the response during the emergency. In that sense, awareness campaigns could be reformulated, looking for an increased impact. More attention should be focus on the limits that public service has, and the need of proactive collaboration of citizens during the emergency, increasing the credibility and trust. More resources in preparedness and risk awareness to have exposed population better prepared (self-protection actions well defined and identified, taking part of the responsibility in risk management) in case of emergency would be also necessary.

Beyond the population, also companies and private sector are in some cases approaching to the civil protection. They see how economic activity is endangered by natural hazards more and more and this is opening new “windows of opportunity” to engage them in having a more resilient system.

DGPC CAT as possible integrated actions and efforts proposed:

- More prevention to reduce exposition.
- Stronger laws in urban planning and permit management for companies, to avoid buildings in dangerous areas.
- Cleared safety areas around urbanized areas and houses to avoid forest fires impacting on humans
- Population should be more responsible, better informed and more aware.
- Warning systems.
- Better communication between actors and with population.
- Better forecast tools will help the act before with stronger preparedness.

- More resilience.
- Help to believe the population that new extreme devastating scenarios may happen.
- Fed the emergency management system with experiences in other events (so after-event lesson-learnt protocol will help). They need statistics and data mining to get improvements to be introduced in the system to help making decisions.
- Extract knowledge from the experiences and store it in some way.
- Use of Business Intelligence and AI (Artificial Intelligence).
- Better knowledge of the territory and more detail in this knowledge.
- More planning and risk analysis.

ISA, regarding preparation for wildfire risk management, reported that access to information on preliminary intervention in the territories is important. Knowledge of the treated areas and the methods used makes it easier to predict and control fire behaviour. In addition to this, the inter-municipal standardization of fire risk control is also important.
In the other hand the impact of CC and changes in the wildfire regime has not yet been fully understood by society. This misunderstanding leads to a delay in the implementation of a set of measures, based on society.
The first agents to fight the fire are local residents, which means that population is also an important part of the civil protection service. Therefore, more should be invested in improving this point, developing a culture of self-defense and the tools necessary for this. This can be achieved, for example, through work / projects with schools, NGO, social networks. Risk perception depends on experience and observation. Residents of rural areas do not yet notice changes in the climate to such a level that they are aware of the risk and all the associated threats.

No less important is the continuous improvement of the current "Safe Villages" program. The diversity in age, education and background makes it difficult to effectively engage people in these strategies. And therefore, there is a need for more effective methodologies for engagement and collaboration with local communities.

3.3.3 Risk managers

3.3.3.1 Overview of the interviewed profiles

The overall number of the risk managers interviewed is 27. These experts also in this case have different profiles and come from different authorities operating at different administrative levels – local, regional and national level - among countries involved, as showed in Table 7.

Table 7. Administrative level and authorities interviewed (risk management stakeholders)

Country (Partner): risk analysed	#	ADMINISTRATIVE LEVELS	AUTHORITY / PROFILE
Austria (BWF): Rockfalls & Landslides	11	Local, regional and national	• Political decision-makers • Representatives of public authorities, • Support organizations of the federal states • Fire brigades and CP and disaster management
Italy (CIMA): Wildfires	1	Regional	• Regional department of agriculture, tourism, training and work policies in the internal areas, forest fire fighting, foresting, parks and biodiversity (Liguria Region)
Italy (CIMA): Floods	1	Sub-national	• River Basin District authority of northern Appennine
Spain (PCF, DGPC CAT, ICGC, CTFC): Wildfires, Avalanches and Floods	10	Regional	• Cartographic and Geological Institute of Catalonia (ICGC), • Catalan Water Agency (ACA, in Catalan), • Urban agenda and Territory Secretariat, • General Directorate of Rural Agents, • Forest fire prevention section of the Agriculture Department, • Catalan Meteorological Service.
Portugal (ISA): Wildfires	4	Local	• Technicians working in municipalities from North to South of Portugal, in the littoral and mountainous areas

CIMA conducted 2 interviews, one related to wildfires and one to floods. In particular, they include one technician from the Regional department of agriculture, tourism, training and work policies in the internal areas, forest fire fighting, foresting, parks and biodiversity of the Liguria Region, involved in risk planning, in coordinating the fire suppression volunteers and the shutdown managers during an emergency. The other interviews involved one technical officer from the River Basin District (RBD) Authority of the Northern Apennines (that covers part of the Tuscany and Liguria regions), whose main duties are prevention and mapping of hydrogeological risk (in particular flood risk), realization of hazard maps through hydrological and hydraulic modelling, regulatory application and drafting of some parts of the Flood Risk Management Plan (FRMP, according to the EU Floods Directive).

In the case of Spain, local partners coordinated to conduct the interviews, tackling main risk management bodies in the target region of analysis of Catalonia.

PCF conducted 1 interview with the head of the forest fire prevention section of the Agriculture Department. His main duties are related to prevention actions, mainly at administrative and legislative way. For instance, he is in charge of establish and control action plans and preventive infrastructure service plans, elaborate the catalogue of the zones of risk, recreational areas and urbanisations, manage the register of forest defence groups and manage aid to these entities, manage the database of water points and housing developments, analyse and diagnose the causes of forest fires and manage the fire database, as well as carry out mapping and statistical work on burned areas and execute controlled burning plans for fire prevention and habitat improvement.

CTFC conducted 4 interviews, 2 with the Catalan Water Agency (ACA, in Catalan), 1 with Urban agenda and Territory Secretariat, both from Territory and Sustainability Ministry of the Government of Catalonia and 1 with the General Directorate of Rural Agents, from the Agriculture and Livestock Ministry. ACA representatives are involved in flood risk planning (prevention phase), basin water management supply and risk (floods and droughts), water innovation planning and applications in the internal watersheds of Catalonia and, planning the risk and having direct contact with Civil Protection. The Urban Agenda officer has experience in urban and land planning and have been involved in the experiences regarding the integration of risk (specially wildfire and flood) in these planning. Finally, the Rural Agent director has experience in the investigation of wildfire causes, risk awareness and communication campaigns, application of an operative procedure to define the prevention actions according the different wildfire alert levels, and control of fire ignitions, among others.

DGPC CAT conducted 1 interview with the head of the forecast area in the Catalan Meteorological Service.

Finally, **ICGC** interviewed 4 risk managers of the Cartographic and Geological Institute of Catalonia (ICGC): 2 specialist of the Avalanche Prediction Unit, 1 specialist of the Seismology Unit and the last one of the Geological Risk Prevention Unit. The head and the technician of the Snow Avalanche Prediction Unit have extensive experience (> 30 years): their main jobs concerns avalanche forecasting and mapping including assessing avalanche danger in the Pyrenees of Catalonia (Daily Avalanche Danger Bulletin), mapping of avalanche areas, databases and developments in the field of nivo-meteorology, design and implementation of the Civil Protection Plan of Catalonia for Avalanche (ALLAUCAT). The head of the Seismology Unit develops the following duties: surveillance of seismic activity in Catalonia, being in contact with Civil Protection and contributing to emergency management. Finally, the head of Geological Risk Prevention Unit develops risk prevention studies, risk identification and prevention associated with Civil Protection.

Regarding Portugal, **ISA** collected information through 4 interviews with 2 Municipal CP Operational Commanders (Seia and Portimão) and 2 Coordinators of the forestry technician's municipal offices (Monchique and Viana de Castelo).

As a conclusion, the number of interviews seems quite high and seems enough to draw a picture of the current needs, improvements and weaknesses in relation to Civil Protection and the emergency management. Obviously, it has to be pointed out that each country has different organizational schemes implying different degrees of autonomy for the regions and municipalities

3.3.3.2 General description of the extreme events - considered as proxy for climate change with special attention on territorial vulnerabilities and best practices implemented for facing it

CIMA – regarding floods reported that along the interview one extreme event - considered as proxy of climate change - was discussed: the Livorno flood of 9-10 September 2017 (Tuscany region). It is related to a flash flood (intense and concentrated event) with cumulative rainfall (260 mm in a few hours) never recorded in historical series, related to an event with a return period of more than 200 years.

Regarding the Livorno flood, the interviewed identified some territorial vulnerabilities that have increased the impacts and damages, related to:

- Anthropized territory also from the hydraulic point of view with two main streams buried (Rio Maggiore and Rio Ardenza) and urbanization;
- Insufficiency of the sewer network.

On the other hand, he highlighted two best practices developed in the territory that have in some way mitigated the impacts and damages and that should have favored the emergency management:

- Presence of a retention basin for controlling flood upstream of the buried part of the stream (however, it was designed for events with return period of 30-100 years and therefore insufficient for such an event);
- Presence of hazard maps as an element of knowledge (the FRMP had just been adopted and those areas fell within the hazard classes P1, P2 according to the EU Floods Directive).

The interviewed moreover reported some results of studies on climate change in the Northern Appennine River Basin District area: a decades-long trend that predicts a modest decrease in total rainfall, but an increase in intense and concentrated events.

CIMA – regarding wildfires reported that one situation was discussed: a forest fire and WUI occurred between the 25 September and 14 of October 2017 in the territory of two provinces of the Ligurian Region (Imperia and Savona). During this event 125 hectares were burned and the main cause was the high drought of forest biomass. During the interview, no mention was made regarding territorial vulnerabilities or best practices.

PCF reported that Catalonia has suffered several episodes, specially in 2005, 2009 (Horta de Sant Joan), 2012 (La Jonquera). Maybe the worst one was La Jonquera fire 2012 because it has Civil Protection implications since the fire affected urban areas simultaneously. That fire brought fire legislation to the edge and overcame it plenty of times. For instance, the legislation was overwhelmed in regard to protection strips of urbanizations, because the fire easily jumped them. The fire behaviour and propagation in urban areas overcame the legal framework causing a review of it. After the fire also emerged the lack of knowledge and awareness of affected population, that did not have fires as a main concern. There were not guidelines and protocols on how to response to these situations, and the fire service as well as other emergency bodies had to evacuate people instead of fighting the flames. Apart from that, some cases of non-compliance of the regulation arise after the fire.

About 1994 fires in central Catalonia, municipal level fire prevention plans did not work because of two reasons. On the one hand, the lack of coordination between neighbour municipalities. On the other hand, the dimension of the fires was too big to face them only taking advantage of infrastructures planned at municipal level. The need of having prevention plans at landscape level arise after these events.

A deficient landscape planning legal framework brought the current situation of vulnerability, with plenty of urbanizations and isolated houses located in the wildland-urban interface. Urban legislation was approved in 1980. Before this year, a lot of houses were built in high fire risk area without any constrain or penalisation. There was no planning and risk was not considered as a criterion. With 1980 law, fire risk started to be considered when building and planning new constructions. However, there are countless of urbanization build before 1980 that are currently legal and generates a very risk situation with thousands of inhabitants living in a very risk area without any preventive or preparedness measure and without any awareness of the risk.

Fire is one of the main risks in the Mediterranean basin, and the trade-off between planning and risk made citizens very vulnerable. Fire services have to deal with very complicated scenarios, with too much vegetation charge and human lives and property involved.

Another factor of vulnerability is rural abandonment linked to the primary sector production and economic sustainability. In general, agricultural surface is gaining terrain across Catalonia because of the increment of agricultural land in central Catalonia. That is a positive point in terms of fire management. But in southern part of Catalonia, the overall agricultural land has been severely reduced due to the lack of economic income of the plantations.

Fire law has currently 25 years and it has been very difficult to collect positive results. The main success of the law is the reduction of ignitions. Nowadays, there are 1/3 of the ignitions compared to 25 years ago. However, the territory is more vulnerable.

The reduction of ignitions is a key point, since fire services cannot afford more than 10/15 simultaneous events. Catalan emergency bodies do not have enough personnel and media to attend them.

Most part of ignitions occur before the fire season. During fire season, pla ALFA (a plan that establishes different daily fire risk categories per county) has contributed a lot. Pla ALFA must be wisely used. Agriculture Department cannot set the maximum risk “just in case”, because people normalize the situation and the positive effect in terms of ignition reduction is lost.

CTFC focused the interview on two different events that have been highlighted. First, 2020 Gloria storm and the previous storm in l’Espluga de Francolí / Montblanc (same week). Second, the 2010 snowfall in almost all the Catalan territory. In the interviews are also considered wildfire emergency situations.

- Regarding Gloria Storm, the main territorial vulnerabilities (and difficulties) were the lack of risk perception and the excess occupation of the land, specially the fluvial areas (presence of exposed elements in flood areas). Specially in l’Espluga de Francolí, an important factor that made the situation more serious was the plugging of the bridge due to the sediments’ and wood accumulation.
  Regarding the best practices developed, were described from the available tools for risk planning and early warning system (as A4Campsite app, its target audience are the stakeholders exposed at risk -camping-), to self-protection plans in order to mitigate the dimension of the emergency, or the risk planning tools as MAPRI, which were used to select the areas to evacuate during the emergency. In this last case, is interesting to consider how prevention plans were used as emergency management tool.
  Other interesting practice exposed is the integration of flood risk in urban planning, limiting the possible urbanization in risky zones to avoid the possibility to have exposed and vulnerable elements at risk. Thus, analysing and identifying as prevention measure, the location of the possible exposed elements.
- Regarding wildfires, the main territorial vulnerabilities are the exposed and vulnerable elements on the territory as wildland urban interface settlements and isolated rural buildings and, the lack of “security zones” as areas for self-protection or confinement. Also, was highlighted the

overcrowding of natural areas/forest massifs, that makes difficult the evacuations and emergency management. Thus, a prevention measure is to get people out of the risky zone these days with high wildfire risk.
Regarding the best practices developed, was mentioned the coordination with agricultural activities to avoid hazard ignition in high risk days, resulting a directly relation in decreasing the number of ignitions/wildfires. The management system to control the access to natural areas/forest massifs as a measure linked to the wildfire risk level, was also described as a best practice to avoid critical emergency situations. Finally, the cleaning of buildings surrounded areas in forest territories, decreasing the vulnerability of these elements was also mentioned.

- Regarding snowfall, no mention was made regarding territorial vulnerabilities or best practices. This episode was exceptional, and during the interview the focus were its emergency situation (see next questions).

The main concern common to all these situations is related to the current exposed and vulnerable elements (“preexistence”) that normally suppose a big challenge in terms of risk management because there is a need to invest in all phases of risk (prevention, preparedness, response and recovery) to protect them. In case there is available information to integrate risk in urban and land planning, could be possible to avoid this “extra-effort”, only investing in prevention (opportunity cost of non-build/develop some areas).

DGPC CAT reported that some events were discussed with the Catalan Meteorological Service. The most important and the only multi-hazard event even in this case was the Gloria storm from 20th to 24th January 2020. It had some differential characteristics:

- It was a very long event with 5 days of phenomena whereas it normally lasts for 2-3 days.
- It gathered different hazards: heavy torrential and long-lasting continuous rain, snowfalls at low altitudes, heavy winds and big weaves on the sea.
- The intensity of each hazard was very strong.

Other mentioned events where single hazard:

- Heavy winds on the 24th January 2009 with 140-150 km/h.
- Storm on the 26th December 2008.
- Snowfall on the 8th March 2010: at low altitudes and many road cut-offs.

Best practices mentioned were civil protection plans (which are very technical base), the communication of these plans to the population and actors.

Best tools mentioned were meteorological forecast models at short-term and mid-term, monitoring tools (radars, automatic weather stations, lightning detector network, Meteosat (satellite), human observers, nowcasting tools (combination of radars and lightning network) and severe weather warnings.

ICGC reported that different typologies of extreme events were discussed.

- With the Avalanche Prediction Unit, the main extreme event considered took place during 95/96 winter season. It started with heavy snowfall without wind at the begging. At the end of the episode the wind started to blow being crucial for the avalanche release. Initially a great amount of new snow was accumulated at the top of the mountains in a very uncertain “stability” of the snowpack.

At this phase of the episode there was no avalanche activity. It was only at the end of the episode, with the wind, when all the avalanches started to trigger.
One of the major avalanches that occurred during this episode was the one in Arinsal (Andorra). It affected population, buildings, forest, etc. It has been one of the biggest recent events ever in the Pyrenees. In the Catalan Pyrenees this situation affected the whole area. The return period calculated after the event was more than 80 years using dendro-cronological methods. The main challenge for the forecasts was the lack of knowledge on such type of events, lacks in the data (in the space and in the time).

- The Seismology Unit referred that in Catalonia in recent decades there have been no earthquakes that have generated an emergency. In 2004 there was an earthquake in Queralbs (Ripollès, Catalonia) that destroyed a chimney and other minor damage. The most important earthquakes in Catalonia occurred during the Middle Ages (1427 and 1428) in Camprodón (Pyrenees) (magnitude 6.5) and the consequences were catastrophic.
- The Geological Risk Prevention Unit reported that the biggest single natural hazard took place in Sallent (Bages, Catalonia). The collapse of the Sallent mines. The cause of this extreme situation was natural (karstic cavity with a lot of water circulation, dissolution and collapses inside the cavity) and anthropogenic, as the village was built on top of an old mine. This situation began in 1997 and remained active until 2011. In 2009 there was an acceleration of the movement and the population was evacuated. Other extreme situations: a storm (December 2008) triggered a rock fall on the tracks of the "Cremallera" train in Montserrat (Catalonia).

Regarding territorial vulnerabilities, the main concern reported is the increased occupation of risk areas and poor land-use planning. There are a greater number of mountain activities (winter sports), buildings, infrastructures, economic activities, etc. The risk has not been analyzed in many occupied mountain areas (i.e proliferation of many non-earthquake-resistant constructions).

Concerning best practices, in all cases, they are those linked to the elaboration of emergency plans by Civil Protection and Risk Managers (avalanches - ALLAUCAT, earthquakes - SISMICAT, etc.), the inclusion of natural hazards in municipal action plans, the 2005/06 town planning law integrates natural risks, Geological risk prevention mapping (1:25.000), available information and communication of avalanche danger (avalanche bulletin), avalanche risk training courses provided by Avalanche Warning Services or Non-Profit Associations, Cross-border projects are also currently being developed: POCRISC (earthquakes).

ISA reported that the opinion of the interviewees is based on the experience obtained in controlling different wildfires: event of 2017 in Seia; the wildfires of 2016; the big wildfire in Monchique in 2018 and Pedrogão and Lousa EWE in 2017.

According to the respondents, the main territorial vulnerabilities that affected the management of emergencies are:

- abandonment of forest management and the occupation of burnt forest stands by bush and woody. In this way, very homogeneous landscapes are created, which increase the level of fire hazard;
- confused goals in the management of rural areas by private owners make it difficult to control fire risk. Hence the weakness in the implementation and compliance with the measures planned for risk prevention;

- the predominance of elderly people in the population make the application of the “Aldeia Segura” program difficult. Therefore, the main problem in most current emergencies is evacuation management;
- poor attention to the consequences of fires, such as soil erosion in mountainous areas or occupation by invasive alien species, can cause landscape degradation and loss of biodiversity.

However, the following best practices have been developed on the territory:

- the execution of more specific interventions and more immediate responses to risks;
- distribution of forest rangers throughout the municipality and application of prescribed burning;
- development of the Municipal Forest Fire Protection Plans in collaboration with other local organizations;
- developing a sense of unity among colleagues from different municipalities and organizing meetings to share knowledge and experiences.

3.3.3.3 Main concerns highlighted in terms of risk management regarding the extreme events considering CC

CIMA – regarding floods stated that, given this kind of very concentrated and intense events, and considering them as a proxy of a hypothetical CC scenario, the main challenges and needs in terms of risk assessment and risk management the interviewed reported in order to face this CC scenario are:

- The necessity to define a methodology to consider and evaluate climate change in the FRMPs (as required by the EU Floods Directive). For example, the RBD authority of the northern Apennines developed a methodology for mapping flash flood susceptibility (considering morphological and rainfall criteria) in 4 classes; however the interviewed highlighted that there is still an issue with the regulatory reference for these sensitive areas.
- The need for more detailed hydraulic and risk analyses – even in urban areas - that lead to a more refined “risk knowledge framework” and can orient more effectively the flood management and control interventions.

Regarding this second point, the interviewed highlighted that detailed hydraulic models in urban areas require a long computational time, availability of trained technicians, financial resources, collaboration with Municipalities and Region (the RBD Authority is unable to cover this greater detail on its own).

CIMA – regarding wildfires and the event considered, an important constraint mentioned by the interviewed was the operational capacity due to the change of the entity that would have faced the fire event as a responder. In 2017, there was in fact a change of competence between the fire department and the forest rangers who previously dealt with the extinguishing and reconnaissance of fire damage. This made the system work slower and hinder the organization of civil protection.

Giving this kind of events, and considering it as a proxy of a hypothetical CC scenario, the main challenges and needs mentioned are:

- ensuring the availability of vehicles;
- gaining a greater competence and knowledge of new scenarios by the emergency management personnel;

- rising the knowledge and awareness of the population;
- improving the integration of procedures.

One of the main new need reported in this scenario in terms of operational management is the development of operating procedures that best identify roles and actions, while regarding operational tools, the need is more related to new or better forecasting and monitoring tools. The new need expressed in this scenario in terms of data integration is to have and exchange information from other institutions such as municipalities or national or local agencies.

PCF reported that Jonquera 2012 fire was a critical event (highway collapsing during touristic season, urbanizations, isolated houses, towns, etc). Apart from that it occurs under simultaneity with other fire events. The fire had the potential to open its right flank to a large special area of conservation (Alta Garrotxa) taking advantage of the sea breeze. The fire overwhelmed the extinction capacity. Firefighters had to put efforts on people and property protection instead of fire suppression.

The problem is that, currently, the strategy would be the same. From the operations point of view, they did everything that was on their hands considering the landscape and the scenario they had. There are two solutions in case it occurs again. On the one hand, create a more resilient and managed landscape. On the other hand, to work on community awareness at citizen and decision-makers scale.

Society must be prepared to face these events. Awareness must not come from individuals, but from a society as a whole.

After the Jonquera 2012 fire, some legislative changes were done: protection strips in the WUI, farms, isolated buildings. Fire risk report are prepared weekly (and daily if the risk is high). These reports are spread across all the involved stakeholders and some mechanisms are activated according to the level of risk.

Impact of fire is traditionally associated with the number of hectares burnt, but this must change, since small fires can burn properties and cause lives losses. Agriculture department ask for research, but needs are not always accomplished. There is not an urgent need to have new tools or technologies, but there is the common need to solve already known situations.

Legislative tools are needed to foster the achievement of resilient landscapes. For example, Sentinel satellite has been recently added to risk management and it really works. There is also the need to integrate local research at a broader scale. But this is complicated, not only technologically, but economically and legally. A better spatial resolution of fire risk maps (currently 5 km pixels) as well as temporal resolution (better weather forecasts) would be a step forward. However, it is operationally unnecessary, since at management level there is not the need to work on risk pixels with less than 5 km side. At temporal scale weather forecasts improved a lot during last years and improvements have been well integrated to risk managers.

CTFC - regarding floods, reported that during the interview was highlighted that the return periods (defined in the Flood European Directive) will become obsolete or will change, that could suppose a big change on risk management as we know it now. There is a need to know more about the intermediate periods or to forecast the relation between precipitation and river flow. Thus, new models should appear to face CC scenarios. For flood risk managers an important change would be the risk management conception from “protect all”, to “living with” risk.

Regarding wildfires, was highlighted the need to adapt the risk levels and warning management to climate change context, which anticipate longer risk seasons, with more critical days and more extreme events. Thus, the risk levels as we know it now, will change with new situations, seasons and events.Also, there is a need to find new methodologies to integrate in the urban and land planning these risks that are not currently integrated (e.g. wildfire risk).

The main common challenges emerged are related to the increase of exposed and vulnerable elements in the territory, as new prone areas will appear, as well as extreme events will be more recurrent.

Other challenges will be to progress to an emergency management tools to guarantee basic supplies (mainly, electric power) in case of extreme event.

The finding of new information to take decisions (which uses can be in a specific territory, linked with land and urban planning) will be also necessary.

Regarding the needs, some of them are:

- Governance: need to involve all the stakeholders (with special attention of exposed and vulnerable actors/activities) in the risk management processes. The governance and participatory approaches will be very important in a climate change context. There is a current need to stablish and well-define a bottom-up engagement/perspective. All actors have concluded that there is no good risk management without participatory approaches.
- Knowledge: need to know more and better the possible effects and impacts of CC in risks, to plan and take decisions according new possible scenarios. Also, to improve the predictive models in order to be able to anticipate extreme events.
- Instruments: need to have general cartography or specific studies (per each urban development planned) where to include the risk analysis and the compatibility between risk management and urban development in a specific area.
- Approaches: related to prevention (currently far from allowing it), fluvial areas and flood zones recovery (leaving space for flooding), following the French and Nederland model.
- Measures: need to stablish compensatory measures/insurances to enhance the resilience and to compensate the maintenance of the territory (e.g., agricultural zones).

DGPC CAT reported that from the perspective of the interviewed the main changes and challenges will be to face multi-hazard events and more intense phenomena. Also theses events will be more frequent and probably longer.

It implies an increase in resources, especially staff, as the length will bring fatigue to the staff.

It would be necessary an improvement of the forecast: nowcasting tools (what is going to happen in the next 2-3h), mid-term (2-4 days) and long-term (necessary to plan in advance).
It would be necessary to move from a deterministic forecast to a deterministic and probabilistic forecast.

There is the need for more end user tools to help in the decision making process: for better integration of data, to add rare phenomena (e.g. the clogging of rivers by sea waves on the coast) and to forecast other hazards like hydrology and forest fires as products of the weather forecast (or fed by the weather forecast).

They will have new needs in terms of risk assessment tools:

- Improvement of the knowledge on the interaction between weather and hydrology and between weather and forest fires.

- Better forecasts.
- Research: better knowledge of local and severe phenomena (hail, tornados etc.).
- Improvement on the knowledge of vulnerability.

They need to Anticipate our response before (get the forecast and take actions before). It is important to go ahead the phenomena and make decisions in time.

They need to make more investment in forecast: better weather models, better observations (monitoring) and nowcasting.

ICGC reported that climate change generates concerns, needs and challenges. For example, the need to monitor the mountain slopes most affected by climate change (especially sunny slopes), monitor the snow cover (persistent weak-layers), re-analyze extreme situations of the past and present, analysis of multi-risk situations (fires-avalanches, floods-extreme snowmelt and wet snow avalanches, torrential rainfall-geological risk), increase resources in prevention and emergency management, improve meteorological models and expand studies on the effects of climate change on natural hazards. In general, the interviewees need to increase knowledge and improve risk follow-up (monitoring).

Related to the risk of avalanches, it is necessary to reinforce the regional and local prediction and incorporate the extreme scenarios in the forecast and the civil protection plan (ALLAUCAT). Municipal action protocols (confinement, evacuation and closure) must be up to date. New and old constructions must take risks into account and reinforce the protection of vulnerable areas. The Geological Risk Prevention Unit emphasize the need to analyze synoptic situations that generate extreme events. The Seismology Unit emphasizes the need to increase resources in prevention and to regulate new and old constructions (so that constructions take risk into account).

ISA reported that the main changes and challenges of risk managers in order to face of CC scenario:

- the collection and integration of all information for quick and effective operation. Command posts sometimes do not have satellite communication channels, which makes it difficult to exchange information, for example during the fire;
- the need to expand the circle of specialists from different fields;
- updating the knowledge of the involved specialists on the state of risk and methods of its control;
- the proximity or connection between those who develop the tool (scientific community) and those who use it in practice (operational and technical community) must be improved;
- the involvement of public in both control planning and fire risk prevention;
- lack of water due to the influence of CC and, as a consequence of the difficulties related to fighting fires, supplying the population, development of the local economy.

3.3.3.4 Possible integrated actions/efforts among the different phases of the disaster risk management cycle, if any, for better being prepared in the context of these new scenarios

CIMA – regarding floods reported that the interviewed agreed that it would be necessary to build integrated actions and efforts among the different phases of the disaster risk management cycle for better coping with these new hypothetical scenarios.

In particular, the interviewed noticed that some actions can be improved in the prevention phase, such as:

- continuous knowing and updating the hydrology also in terms of pluviometric possibility lines based on the rainfall events that have taken place;
- enhance the preparedness of stakeholders and authorities for these intense and concentrated events, also in terms of civil protection.

Regarding this last point, the interviewed reported that risk managers can provide themselves contributions to the civil protection system, such as the cited flash flood susceptibility maps. By this information, the territories that fall into the high and very high flash flood susceptibility classes should acquire these data in the civil protection plans which should be in turn adapted to this kind of events.

In conclusion, in order to improve the balance between prevention-preparedness-response efforts/actions, the interviewed highlighted/proposed these changes needed:

- improving coordination between the institutions (RBD Authorities and Regions-Civil Protection): the systems (RBD Authorities provide the "risk knowledge framework" + Regions adopt the risk knowledge framework for civil protection purposes) were not initially designed to collaborate. [this is visible both in the FRMPs and for example in FloodCat];
- regulatory coordination at national level that foster the coherence of the different instruments;
- change of mentality / cultural leap of institutions. For example river contracts can be useful in this sense;
- greater diffusion of the knowledge of hazard and risk in the territory (e.g., WebGIS) and dissemination of data;
- involvement of schools and the population for rising awareness;
- working on a local / municipal scale.

CIMA – regarding wildfires reported some actions that the civil protection system and emergency management could done in the prevention and preparedness phases to have a more effective and efficient emergency management and response system, such as:

- improving the forest fire early action based on the alert level;
- training and acquisition of skills;
- improving the knowledge of the territory to better intervene in the territory.

More in general, the interviewed noticed that the balance between prevention-preparedness-response efforts/actions could be improved through an interinstitutional technical table at national level to coordinate the extinguishing phases (Fire Brigade and Region).

PCF stated that everything would come under a new legislation. There is too much legislation and it is not applicable. After Jonquera fire 2012 new legislation was pushed. All sectors has their opinion and finding common points is a difficult task. All sectors should concede a little bit in order to find a satisfactory agreement.

Catalan legislation is reactive. After a severe fire some voices arise to change it. A more proactive legislation is needed, probably looking on what is happening in other world regions. But a legal framework is needed to start an active legislation.

The rural sector should have facilities to carry out their work instead of spending too much time doing administrative forms.

Delimitation plans, urbanizations register, population, shared databases, etc., are currently used.

Agriculture department needs a technological jump, but this should come together with an increment of the budget.

It is very important to recognize the tasks that everyone is doing. Emergency bodies has economic potential, but in terms of prevention the invested budget is very small. Prevention actions from fire services and agricultural department should be unified.

Certification is also a key point. Questions like “Are all the actions done under fire prevention management really working?” are too common.

Since agriculture department is the fire prevention responsible, all preventive actions should come from these department.

CTFC reported that some points of prevention and preparedness actions that could be developed to improve or help the response actions were mentioned (among others):

- Regarding flood:
    - In case the extraordinary/sever episodes (e.g., Gloria storm) would be more frequent, the social perception of risk will change, and maybe will be possible to take out of the fluvial spaces some land uses and activities currently accepted in flood areas. This is, avoiding to have exposed and vulnerable elements, thus acting in prevention phase. Probably the prevention and preparedness should be more dominant to advance through a “dis-occupy” measures of the riverbeds.
- Regarding wildfire:
    - Keep working in the investigation of wildfire causality to better focus the related policies (in this changing context, probably risk reduction policies will also be modified), as well as identify (new) activities potentially dangerous.
- Common prevention and preparedness actions mentioned are:
    - Improving the communication and coordination with Civil Protection, more than generate new knowledge.
    - Improving the participatory processes and risk governance to enhance and invest more in prevention and preparedness as a way to facilitate response actions.
    - To progress in the identification of vulnerable elements.
    - To progress towards an emergency management system more decentralized, focusing on local administrations and their available basic services.
    - To work in preparedness through the risk awareness and communication to make possible the comprehension to “urban culture” that some prevention actions (forest fuel management, for example) are necessary as a measures to protect ourselves, the basic infrastructures and the landscape values.

DGPC CAT mentioned that as an integrated action, it could be better to integrate the weather forecast service as a part the civil protection system during the emergency, so working in the same place.

ICGC reported that all interviewees agree on an improvement in current knowledge regarding natural hazards.

- The Avalanche Prediction Unit focuses prevention on the study of current knowledge and the analysis of recent trends (identify multi-risk scenarios and cascade effects). This new knowledge is applied to risk management and the improvement of defense structures (i.e., creation of safety margins in arrival areas). The Unit proposes the implementation of a technical work team (by Civil Protection) for critical situations in the field with first-hand data on areas at risk. The development of a new tool that identifies the most vulnerable areas according to the synoptic patterns that trigger large avalanches.
- The Geological Risk Prevention Unit advises to implement mandatory and restrictive measures in territorial planning. The proposal of a specific Civil Protection plan for land movements. The identification of synoptic patterns that trigger landslides, rock falls, etc.
- The Seismology Unit proposes to identify the typology of buildings in risk areas and model the effects of a hypothetical earthquake on these areas.

All interviewees emphasize that greater prevention must be done. Improve warnings, effective communication between all actors involved in risk management, reinforce legislation (mandatory), strengthen building structures, expand knowledge about natural hazards and invest in training and drills.

ISA reported that the current response is adapted to the current level of risk, and this is where civil protection needs to improve its approach - to be prepared to respond to extreme events. The civil protection system has a lot to learn from the military, namely about its approach to scenarios and even the level of use of tools. It is also important to develop the bases for regional logistics to facilitate and accelerate access to the means necessary to predict and/or fight fires.

Also, one of the important things that until now has not worked properly is the circulation of important information between various entities.

In terms of prevention, it is fundamental to improve the responsibility of owners to manage their assets. More investment in prevention by private owners is need. Updating the cadaster can help resolve this issue. In parallel, ways must be found to control fuel, regardless of the type of forest property. It is also important to improve the population's self-protection and keep they updated with information.

And finally, the risk management strategy must be less reactive and more preventive.

3.3.4 Prioritization and analysis of the results

The needs collected have been prioritized by each partner.

In Table 8, priorities for civil protection and emergency management stakeholders identified by each partner are reported.

Table 8. Priorities for civil protection stakeholders identified by each partner, according to the interviews results

	PRIORITIES FOR CIVIL PROTECTION STAKEHOLDERS
STORMS - GERMANY (FVA)	Increasing the need for information.
	Increasing the need for cooperation through changing conditions.
	Increasing the need for communication through changing conditions.
ROCK FALL - AUSTRIA (BFW)	Enhanced information (spatial planning).
	Clear responsibilities.
	Enhanced institutional cooperation.
	Data collection after events supported by civil protection actors.
	Cheaper, faster and easier availability of remote sensing data (e.g., InSAR, laser scan) for monitoring rock faces.
	More consistent and continuous event registers.
LANDSLIDES - AUSTRIA (BFW)	Enhanced information (spatial planning).
	clear responsibilities.
	Early warning systems.
	cheaper, faster and easier availability of remote sensing data (e.g., InSAR, laser scan) for identification of landslide scarps and runout zones.
FLOOD - ITALY (CIMA)	Strengthening of the governance, as an element of strategic importance in consolidating the civil protection system: More collaboration between institutions at different levels and offices of the same agency + greater coordination between local authorities in order to integrate actions in all the risk management phases.
	Improvement of the forecasting and monitoring capacities and systems, which allow to predict with the widest possible time interval, the approaching of meteorological phenomena spatially and temporally concentrated and to be able to determine risk scenarios for the population.
	Advanced tools for managing territorial and geographic data, as well as advanced DSS tools in real time.
	More financial resources to program in ordinary time and more human resources.
	Improvement of the civil protection planning and updated knowledge.
	Rising territorial awareness.
FIRE - ITALY (CIMA)	Long-term planning and integrated planning: based on strategies coordinated at the different territorial levels with the aim of carrying out multi-scope interventions.
	Operational tools able to collect information in real time from the territory and, by combining static and dynamic information, to provide an evolution of the scenarios.
	Exchange of information and coordination and increasing involvement of all the subjects concerned and integration of procedures.
	Rising awareness and knowledge of population.
	Improvement of the civil protection plans, also for the management of tourist flows.
WILDFIRE - SPAIN (PAU COSTA)	Gain knowledge of uncertain scenarios, because these scenarios will cause damages.
	Ensure communications between command and units.
	Specialized Training.
	Learn how to manage wildfire at landscape scale.
	Community awareness to understand fire risk.
	Investment of budget to preventive measure linked to bioeconomy.

	PRIORITIES FOR CIVIL PROTECTION STAKEHOLDERS
WILDFIRE - SPAIN (CTFC)	Improve reliability of communication and power supply systems.
	Forecasting tools to integrate CC scenarios and the recurrence of extreme events.
	Reformulate awareness campaigns to increase their impact.
AVALANCHES - SPAIN (ICGC)	Decision support tools are needed, which integrate information and data from the terrain at risk.
	A catalogue of elements exposed and vulnerable to risk is needed.
	More education and training are needed for the population and the most exposed and vulnerable sectors. Improve protection guidelines, warning signs and information display.
	The forecasts need to be improved as much as possible. Generate a local scale mapping, as the current one is not very precise.
	Analyse extreme situations in the past that can help to better manage future emergencies and studies of future Climate Change scenarios.
	Very short-term forecasting tools (nowcasting).
	It is necessary to integrate Climate Change into territorial and urban planning. Risk zones must be regulated by law, to prevent construction in these areas.
	It is necessary to involve the population in the study of the past extreme situations.
	There is a need to improve the resilience of society through education and training.
DGPC -CAT	Faster response of the emergency management.
	Develop and empower integrated platforms: real time information from field, positioned static information (risk analysis), summarized data, recovery stage, reduce manual process for optimization.
	Improve communication with the population about their exposition and self-protection.
	Include the effect of climate change.
	More staff and more resources in Civil Protection and emergency management.
WILDFIRE - PORTUGAL (ISA)	Interconnection between agencies is crucial. The information in these structures should circulate fluently, and its clarity and quality should be excellent. Also, coordination should be carried out by a body that stands above the rest in terms of independence in the freedom to make decisions.
	There is a need to expand the circle of involved experts from different areas. Collaboration should be designed in such a way that this technical capacity of the different specialists involved ensures the continuity of the process and the availability of all the information needed for quick decision making.
	Collection and integration of all information for quick and effective operation. Meeting the need for high-quality real-time monitoring tools should be a priority. Improve current defence plans by summarizing the most important information and reduce the plan´s duration. Expand the municipal scale of these plans to the regional one. It is also important to r of the current prevention plans.
	At the moment, the greatest concern is drought due to the decrease in annual precipitation under the influence of the CC. This is one of the biggest and most important problems, since water is needed to extinguish fires and supply the population.
	Need to improve internal collaboration in the civil protection structure at regional and national scale. Cultivation of team spirit and integration of all Civil Protection agents and collaborating entities through regular joint meetings that promote interaction between the main actors of emergency action, discussing their roles and integrating them into the protection system.
	Wildfire simulators are always in the process of development and the addition of new variables increase. However, there is no such dynamics in the control of other types of risks. In addition, the new generation of simulators must be multilingual and include information about European landscapes.
	It is important to involve the public in both control planning and fire risk prevention. In addition, it is necessary to increase people's awareness of the various types of risks and their capacity for self-defense.

	PRIORITIES FOR CIVIL PROTECTION STAKEHOLDERS
	Fuel management is the primary variable that we can change facing climate change. What is fundamental in terms of prevention is the responsibility of owners to manage their private forest areas

As showed, some common needs of civil protection and emergency management stakeholders to face climate change mapped by the partners are:

- to strengthen the collaboration between institutions at different levels but also between offices of the same agency (not only during an emergency but in all the phases of the risk management cycle);
- to improve the forecasting and monitoring (capacities and systems) related to the hazards analysed, so improving early warning system;
- to get new real-time tools to manage an emergency and to support decisions (including monitoring tools);
- to gain knowledge of Climate change scenarios and uncertainties;
- to rise risk awareness of the population also by involving the population for example in the civil protection planning process control plans) and reinforcing communication.

However, it is possible to notice that also other needs quite far from the direct competences of the civil protection and emergency management and closer to the risk management, have been expressed, such as the need to foster long-term and integrated planning or to invest budget to preventive measure linked to bioeconomy, highlighting that a better prevention will make easier the emergency response, and it would be more cost-efficient.

All the priorities selected were then clustered according to the phases of the risk management cycle and the SFDRR priorities.

As can be seen in the bar chart in Figure 2, most of the needs are related to preparedness and the focus is more shifted in the prevention and preparedness phases rather than in the response. Certainly, this result does not mean that efforts on response are not necessary, but – according to the interviews - they resulted less of a priority in the context of climate change.

Moving to the SFDRR priorities, according to the bar chart in Figure 3, most of the needs are related to the Priority 4: enhancement of disaster preparedness for effective response, and to Building Back Better in recovery, rehabilitation and reconstruction. Moreover, many issues resulted correlated to the need to better understand and continue understanding disaster risk in a changing and uncertain context, as well as more than the 40% of the needs are related to the necessity of strengthening the governance.

Figure 2. Needs (in %) of civil protection and emergency management stakeholders clustered according to the risk management cycle phases

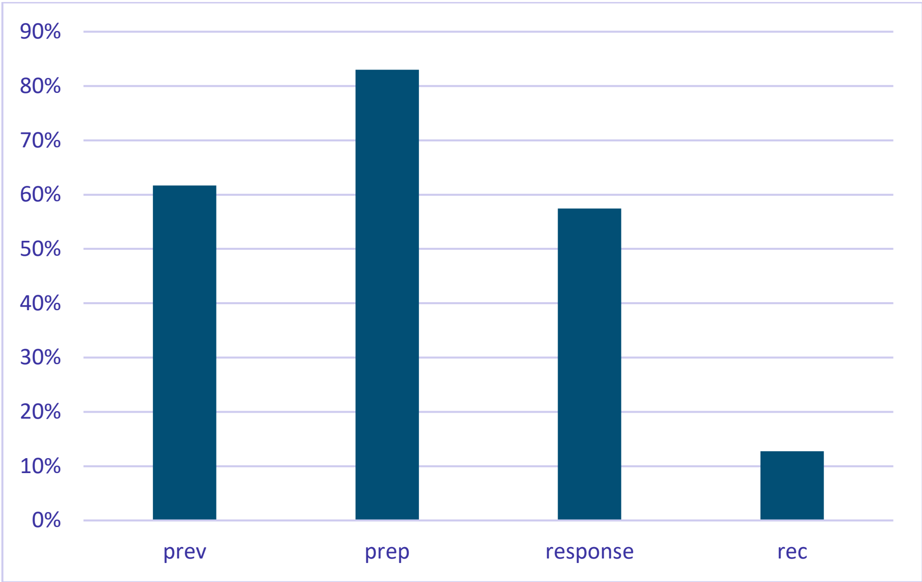
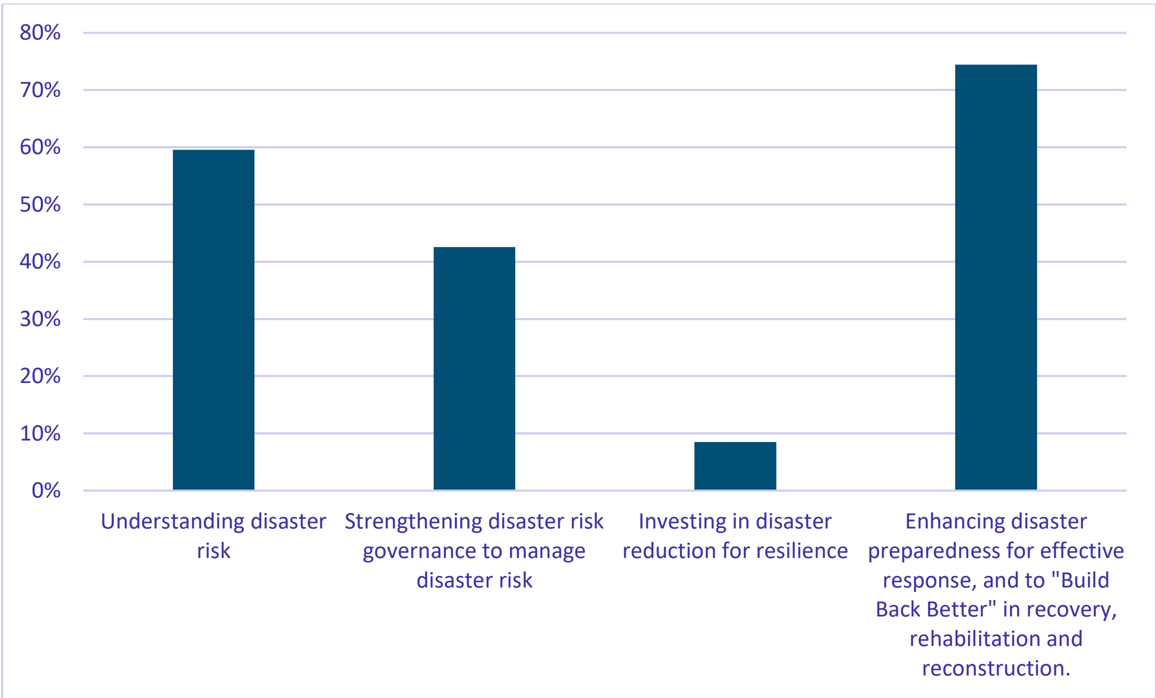


Figure 3. Needs (expressed in %) of civil protection and emergency management stakeholders clustered according to the SFDRR priorities



For risk management stakeholders, priorities identified by each partner are reported in Table 9.

Table 9. Priorities for risk management stakeholders identified by each partner, according to the interviews results

	PRIORITIES FOR RISK MANAGERS
FLOOD - ITALY (CIMA)	Define a methodology to consider and evaluate climate change in the FRMPs (as required by the EU Floods Directive).
	More detailed hydraulic and risk analyses – even in urban areas - that lead to a more refined "risk knowledge framework" and can orient more effectively the flood management and control interventions. (This requires a long computational time, the availability of trained technicians, financial resources and collaboration with municipalities and regions) and continuous knowing and updating the hydrology.
	Enhance the level of preparation of stakeholders and authorities for these intense and concentrated events, also in terms of civil protection.
	Regulatory coordination at national level that foster the coherence of the different instruments and improving coordination between the institutions, promoting also a change of mentality / cultural leap of institutions.
	Greater diffusion of the knowledge of hazard and risk in the territory (e.g. WebGIS) and dissemination of data; Involvement of schools and the population for rising awareness.
WILDFIRE - ITALY (CIMA)	The improvement of the forecast of the flame front propagation and the presence of fire avenues.
	Monitor and evaluate investments and infrastructure actions to verify their effectiveness.
	Implement territorial and agricultural policies integrated in the DRR Framework.
	Promote forest fire mitigation policies able to take into account the local economic development.
	Improve the training for technicians.
WILDFIRE - SPAIN (PAU COSTA)	Fire resilient landscapes.
	Community awareness.
	Classify fires not only considering its size, but also its behaviour.
	Legislative measure to facilitate land management.
	Technological improvements to process and understand information.
WILDFIRE - PORTUGAL (ISA)	Risk control sees the need to expand the circle of involved specialists from different areas. Collaboration should be designed in such a way that this technical capacity of the different specialists involved ensures the continuity of the process and the availability of all the information needed for quick decision making. Also, developing a sense of unity among civil defence colleagues from different municipalities will help improve emergency response.
	Need in involve the public in both control planning and fire risk prevention. Also, the number of sensitized people should be to increase. One other challenge in emergencies is evacuation management in areas dominated by elderly residents.
	Emergency planning in some municipalities is insufficient due to a lack of financial resources and means. Many municipalities suffer from a lack of funds to buy them and human resources to operate them.

	PRIORITIES FOR RISK MANAGERS
	Collection and integration of all information for quick and effective operation. Command posts sometimes do not have satellite communication channels, which makes it difficult to exchange information, for example during the wildfire.
	Confused goals in the management of rural areas make it difficult to control fire risk. Hence the weakness in the implementation and compliance with the measures planned for risk prevention. If nothing changes in the landscape, the fires will continue with a certain cyclicality. If nothing changes in the landscape, wildfires, under the influence of CC, will intensify.
	It is important to always consider the relationship between emergency planning and spatial planning.
	Pay more attention to hazards other than fire. For example, a decrease in precipitation due to the action of CC and, as a result, a lack of water and drought.
FIRE - SPAIN (CTFC)	Reinforce risk perception.
	Avoid the excess occupation of the land (specially in fluvial areas).
	Reinforce the development of self-protection plans.
	Management of the current exposed and vulnerable elements ("preexistences".)
	Integration of CC impacts in risk analysis and mapping.
	Risk management conception change from “protect all”, to “living with” risk.
ROCK FALLS - AUSTRIA (BFW)	Enhanced information (spatial planning).
	Clear responsibilities.
	Enhanced institutional cooperation.
	Data collection after events supported by civil protection actors.
	Cheaper, faster and easier availability of remote sensing data (e.g., InSAR, laser scan) for monitoring rock faces.
	More consistent and continuous event registers.
LANDSLIDES - AUSTRIA (BFW)	Enhanced information (spatial planning).
	Clear responsibilities.
	Early warning systems.
	Cheaper, faster and easier availability of remote sensing data (e.g., InSAR, laser scan) for identification of landslide scarps and runout zones.
AVALANCHES - SPAIN (ICGC)	Identify the various extreme avalanche situations that will favour Climate Change.
	Greater knowledge and understanding of snow behaviour (e.g., wet snow, sunny slopes, persistent weak layers) is needed.
	It is necessary to develop new tools that integrate the extreme scenarios of large avalanches.
	Communication between the stakeholders involved in all phases of risk management needs to be improved and reinforced.
	It is necessary to integrate Climate Change into territorial and urban planning. Risk zones must be regulated by law, to prevent construction in these areas.
	The forecasts need to be improved as much as possible. Generate a local scale mapping, as the current one is not very precise.
	A catalogue of elements exposed and vulnerable to risk is needed.

	PRIORITIES FOR RISK MANAGERS
	The presence of specialist technicians in the terrain is necessary when there is an alert/emergency phase. This allows the collection of first-hand information.
	The information generated in the forecast and warnings must have a more visual and graphic character.
DGPC	Improve knowledge of extreme events and risk.
	Integrate risk managers in the emergency management (staff in the in the emergency room).
	Faster response of the event forecast and monitoring.
	Improve nowcasting midrange and long-range forecast.
	More end user tools: forecast the damage.

In this case, the needs and priorities expressed were more various, however many needs were aimed at:

- integrating territorial & agricultural policies in the DRR Framework (included forest protection) and developing legislative measure to facilitate land management;
- better understanding new risk scenarios and integrating climate change impact in risk analysis and mapping;
- reinforcing the collaboration and cooperation between institutions and innovating the approach of risk management from "protect all" to "live with";
- knowing and managing the actual exposure and vulnerabilities and improving civil protection plans;
- reinforcing risk awareness and risk perception.

Even in this case, the priorities selected were then clustered according to the phases of the risk management cycle and the SFDRR priorities.

As can be seen in the bar chart in Figure 4 and as can be expected, most of the needs are related to prevention and even in this case the focus is more shifted in the prevention and preparedness phases rather than in the response. However, some needs are related also to the response and recovery phases.

Moving to the SFDRR priorities, according to the, most of the needs are related to the Priority 4: "enhancement of disaster preparedness for effective response, and to Building Back Better in recovery, rehabilitation and reconstruction" and to the Priority 1: "understanding disaster risk".

Figure 4. Needs (in %) of risk management stakeholders clustered according to the risk management cycle phases

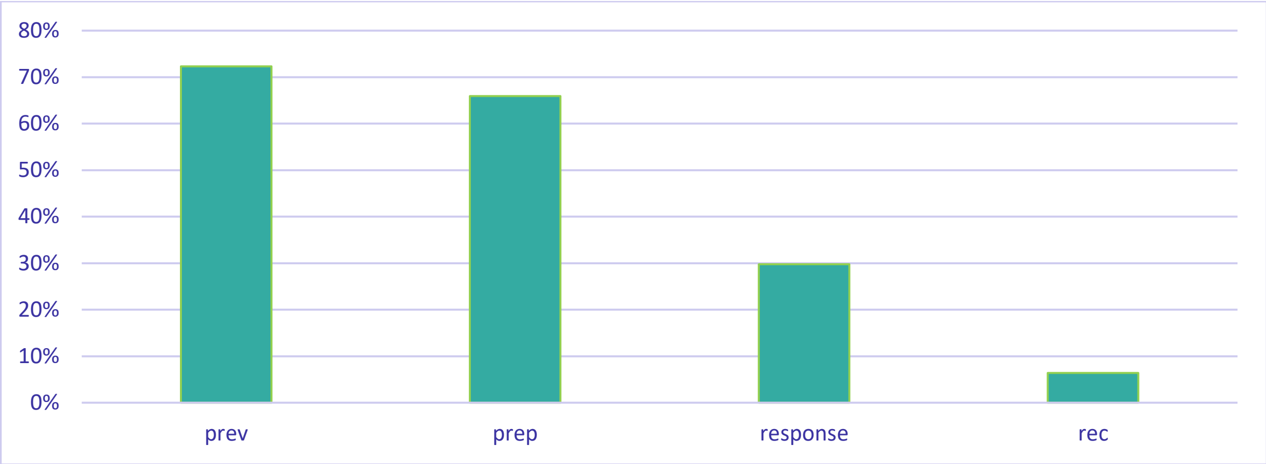
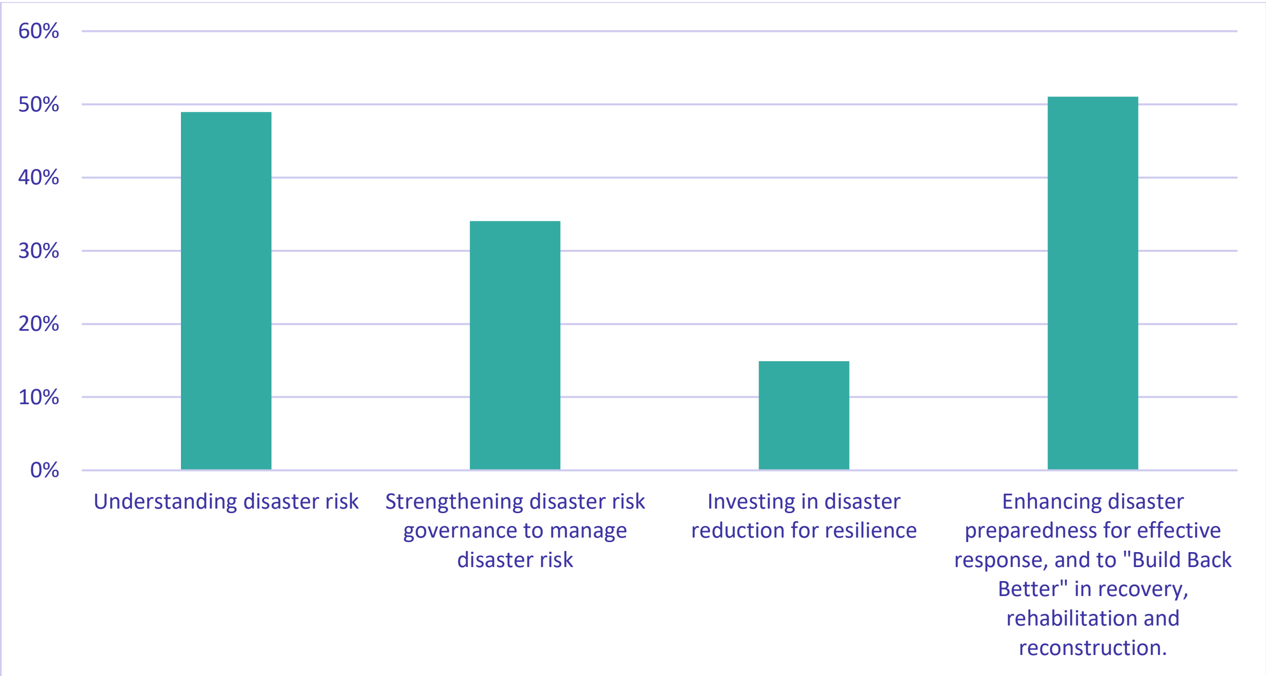


Figure 5. Needs (expressed in %) of risk management stakeholders clustered according to the SFDRR priorities



4 Integration of climate change scenarios into multi-hazard risk assessment and planning

4.1 Objectives

This chapter is corresponding to the task 3.2 Integration of climate change scenarios into multi-hazard risk assessment and planning which objective is to define potential single and multi-risk situations posed by climate change context.

From task 3.1.a, potential situations of **single** and **multi-hazard interactions under climate change** are defined, and risk components and data requirements for civil protection and emergency management from WP2 are evaluated in detail in each scenario following the common frame defined in task 2.1. This is done for the territorial context of each of the partners, and the corresponding risk situations defined. By this way, **gaps and new needs of operational data and risk assessment under climate change will be identified**: for instance, how to re-evaluate in a territory the known vulnerability to recorded avalanches, according the attributes identified in task 2.1 and reported in *Report on data attributes for integrated risk assessment and planning of wildfires, floods, storms, avalanches, rockfalls, landslides and their interactions*, to potential avalanches scenarios posed by climate change or new avalanche-wildfire risk interactions in mountain areas. Or, which **new operational data requirements for efficient civil protection** -task 2.2 , *Report on Civil Protection and emergency management requirements to face natural hazards* – and have to be included in the risk assessment in the case of increased levels of risk, unprecedented hazards interactions or multi-emergencies. This allows to check and update the known solutions of risk assessment and planning to face potential new risk situations in the climate scenarios, both at single and multi-risk level.

4.2 Methodology

The methodology used to carry out task 3.2 is the following:

Firstly, prior to the multi-risk analysis it is necessary to determine how climate change influences the risk of wildfires, storms, floods, avalanches, landslides and rockfalls. Once the interaction between climate change and risk has been determined, we can analyse the multi-risk interaction in the context of a changing climate.

Future climate trends/scenarios for each of the regions of analysis have been taken into account.

For each of the natural phenomena this analysis has been carried out following the outline of task 2.1:

- Re-analysis of the components of risk (Hazard x Exposure x Vulnerability) and how climate change influences the factors that define hazard, exposure and vulnerability.
- Re-analysis of new prevention, preparedness, response and recovery measures to address the impact of climate change.
- Re-analysis of the stakeholders involved in the implementation of these new measures and actions.

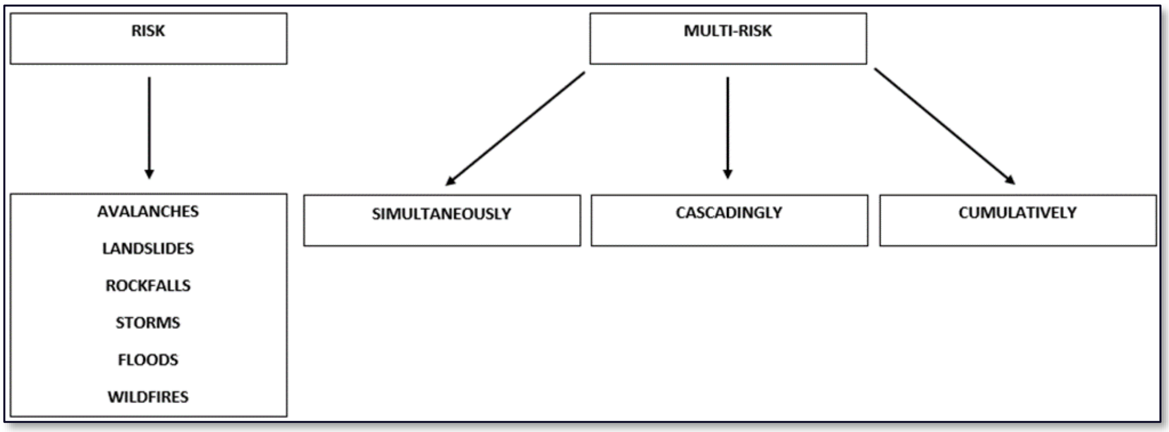
In order to systematise the re-analysed information, a table of contents has been drawn up, where the content for each of the risks is explained. A number of questions have been answered to find out which is the influence of climate change on natural risks that have been analysed (see Annex 1).

The wildfire single risk analysis has been carried out jointly by CTFC, PCF, ISA and CIMA as a partners experts in wildfires, in order to harmonise the information and to avoid duplicities.

Secondly, in order to address multi-risk analysis, it is necessary to define the concept of multi-risk. According to the United Nations Office for Disaster Risk Reduction the definition is as follows:

Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascading or cumulatively over time, and taking into account the potential interrelated effects[18] (Figure 6).

Figure 6. Risk and multi-risk



Then, an internal analysis to determine the interrelations between the risks that define a multi-risk situation has been carried out. The idea is to see which are the common elements from the analysis of each of the risks. Once the analysis has been carried out, a real or possible future scenario (or scenarios) is defined as a result of the multi-risk interaction in a context of climate change. Finally, this future scenario is the starting point for defining a series of measures or action protocols proposed jointly with the emergency management bodies and the risk managers/experts.

The **multi-risk scenarios** analysed are cumulatively over time. In addition, the multi-risk interaction wildfires/landslides-rockfalls can occur cascading:

[18] https://www.undrr.org/terminology/hazard

- **Storms/Wildfires – Wildfires/Storms** (FVA, ISA and PCF): A deep extratropical storm (winter storm) destroys an extensive forest mass. This destroyed forest mass is a dead fuel that could favour and spread a forest fire, affecting new forest areas and urban zones (near forest areas). In addition, insect pests can affect the destroyed forest mass and spread to healthy forest areas. A forest area destroyed by a pest or wildfire is therefore more vulnerable to extreme winds.

- **Wildfires/Floods (Flash floods)** (CIMA, DGPC CAT and PCF): the loss of forest cover due to wildfires leads to increased runoff on the land. Therefore, more intense rainfall (forecasted in the latest Climate Change reports) can generate flash floods with greater frequency and magnitude in those basins affected by forest fires.

- **Wildfires/Avalanches** (CTFC, ICGC and DGPC CAT): This analysis is based on the practical assumption (based on Climate Change trends for the Catalan Pyrenees and land uses changes in the territory) that a large wildfire occurs at the end of the summer in the Pyrenees, affecting several valleys (large surface) and, in addition, that a heavy snowfall is foreseen at the beginning of the winter season (October-November) in those areas affected by the large wildfire where potentially forest cover is lost.

- **Wildfires/Landslides** (BFW, ISA and CTFC): A forest fire in an Alpine area destroys the forest mass and affects the roots, creating a more unstable terrain. This increases the risk of landslides.

- **Wildfires/Rockfalls** (BFW, ISA and CTFC): Expected forest fires in the coming decades may affect the protective function of forests in the Alpine region. It could therefore increase the frequency and intensity of rockfall.

4.3 Results

4.3.1 Single Risk Analysis

4.3.1.1 Storms

STORMS
Storms can have several reasons. In RECIPE we focus predominantly on the type “winter storm” resulting from extratropical low pressure systems at mid-latitude level. This type of storm occurs almost exclusively during the winter months (October – March) due to high temperature gradients between the subtropics and polar regions. In the area where both warm and cold air masses collide, a so-called polar front emerges and more or less extreme low pressure systems form that are moved by westwards currents over the North Atlantic onto Central Europe. Under certain circumstances (e.g., very large horizontal differences of air temperature and water vapour content) intense cyclones can form resulting in hurricane like wind speeds. Characteristically, winter storms have a vast geographic spread (diameter of 1000 km or more), distinguishing them from other, smaller scale storm events.

<table>
<tr><th colspan="2">STORMS</th></tr>
<tr><td colspan="2">The most influential climate variable determining wind disturbance remains the frequency and intensity of strong winds, for which current and future trends remain inconclusive (Seidl et al., 2017). There are indications that climate change influences the occurrence and duration of winter storms and very likely increases frequency and severity (i.e., peak wind speeds) across Europe (Donat et al., 2011; Temperli et al., 2013 in Seidl et al., 2017). Projected changes in extreme wind speeds are indicated to rise in Central and Northern Europe, while slightly declining over the Mediterranean region. Likely, there is a poleward shift of mid-latitude storm tracks. Consequently, areas that were previously untouched by severe windstorms will have to face a new hazard situation.

In addition to greater intensity and frequency of wind disturbance events, a number of related indirect climate change impacts are expected to affect the overall impact of future wind disturbance on forest ecosystems in Europe. These include changes in tree anchorage (e.g., less soil frost) (Usbeck et al., 2010 in Seidl et al., 2017), wind exposure (e.g., tree growth) (Moore and Watt 2015 in Seidl et al., 2017) and overall wind resistance of stands (e.g., tree species composition) (Panferov et al., 2009 in Seidl, 2017).

Forest management decisions made to address climate change induced challenges may also impact future wind disturbance impacts on forests. For example, the desire to move from single-species dominated, even-aged stands to forests with diverse species, ages and structures (Gardiner et al., 2019). The exact effect may vary depending on context. Recent research suggest, natural mixed forests were more resilient to wind disturbance when compared to monoculture forests (Jactel et al., 2017; Morimoto et al., 2019).

Finally, there is evidence for a strong interaction between disturbances: summer drought reduces tree's overall resilience, and facilitates the activity of other disturbance agents, such as insects and fire. At the same time, storm damage in forests in combination with drier and hotter summer months can result in increased biotic threats for trees and forests (e.g., bark beetle infestation, pathogens spread). That way, even small and per se non-severe storm damage in forests provide ideal conditions for pest and pathogen populations to build up and spread to other unaffected parts of a forest. The proliferation of pests and diseases in turn has an impact on wind exposure (e.g., insect disturbances increases canopy roughness), can affect soil anchorage (e.g. pathogens decrease rooting stability) and reduce resistance to stem breakage (e.g. pathogens decrease stability). On the other hand, climate induced changes in vegetation composition and structure can reduce the forest's sensitivity to different disturbances, particularly wind (Seidl et al., 2017; Temperli et al., 2013 in Seidl et al., 2017).</td></tr>
<tr><td>Hazard</td><td>Factors.

<u>Tree height:</u>

Climate change impact on tree growth has shown to be very heterogeneous due to local scale variation of climate warming, nitrogen deposition, water availability, forest composition and more. Charru et al. (2017) found important between-species differences in their response to climate change (measured in based area increment (BAI)): while mountain species' (P. abies, A. alba) BAI increased, lowland and generalist species' (F. sylvatica, Q. petraea) BAI showed moderate or no changes in growth. Furthermore, evidence indicates a strong impact of changes in temperature and precipitation on growth rates: growth rate declines were indicated in warmer and dryer</td></tr>
</table>

STORMS	
	areas, where water is the primary growth limitation; likewise, growth rates increases were noted in colder, wetter areas where temperature is the primary growth limitation (*Charru et al., 2017*). In a wind disturbance context, the interest in tree height relates to a tree's wind exposure and canopy roughness. While the work by *Churra et al. (2017)* provide important insights on the impact of climatic changes on tree growth and heights, its relevance is limited by the fact that it is based on data from single species dominated, even-aged stands. The conclusions reached about climate change impacts on growth and height do not apply to mixed, un-even aged stands (Peterson et al 2012 in Gardiner et al., 2019). Already a management objective in large parts of Europe, the area covered by mixed species, uneven-aged forests is also expected to increase as a result of more frequent disturbance events, and may result in altered species mixtures, associated growth rates, tree heights and canopy roughness (*Knoke et al., 2008; Vacek et al., 2019*). Natural, mixed species forests have proven more resilient to wind and other disturbances (*Jactel et al., 2017*). **Precipitation:** Precipitation patterns across Europe are expected to become more extreme. Summer droughts have covered much of the continent over the past years, and decreases in summer precipitation are expected to become more common in the future. The severity of drought stress on forests depends on the kinds of species present and or the tree species mixture: "In pure stands, spruce has the lowest resistance, but the quickest recovery; oak and beech were more resistant, but recover was much slower and they are less resilient. In mixture, spruce and oak perform as in pure stands, but beech was significantly more resistant and resilient than in monoculture. Especially when mixed with oak, beech is facilitated". (*Pretzsch et al., 2013, p. 483*). At the same time, heavy precipitation days are also expected to increase across Europe (*Field et al., 2012; Rummukainen, 2012 in Lindner et al., 2014*). This combination likely provides fertile ground for future wind disturbance damage to Europe's forests. Stress caused by lack of summer precipitations increases both the populations of insect and pathogen, as well as forest's susceptibility to those disturbances, ultimately increasing susceptibility to wind throw (*Robinet and Roques 2010 in Lindner et al., 2014*). Higher temperatures and precipitation during the winter season furthermore increases wind damage due to poorer rooting, particularly in areas where soils are usually frozen during winter months (*Peltola et al., 1999, Usbeck et al., 2010a in Lindner et al., 2014*). **Soil structure:** Climate change induced changes to soil structure include soils not freezing during winter time, resulting in poorer rooting, and thus making forests more susceptible to wind disturbance (*Usbeck et al. 2010a in Lindner et al., 2014*). Furthermore, extreme winter precipitation events can facilitate flooding and mud slides, also reducing root stability in forests. The mud slide risk is in part dependent on the forest's species composition, with

STORMS	
	flat rooting species posing a greater risk, whereas tree species with a heart or taproot system show increased root cohesion and reduced soil mobilization (*Scheidl et al., 2020*). **Degree of usual exposure to wind:** Once a storm event has resulted in windthrow areas, the remaining trees and newly created forest edges become exposed and subject to future wind disturbance. Protected from wind in the past, these trees have not yet adapted to the mechanical stress of wind (*Moore and Lin, 2019 in Gardiner et al., 2019*), and thus display a lower level of resistance to wind, increasing the chances for further windthrow. **Critical Wind Speed (CWS):** Climate change is expected to lead to storm events of higher intensity and higher top speeds. Storm damages to forests are therefore expected to increase (*Gardiner et al., 2012 in Lindner et al., 2014*). The susceptibility of forests to critical wind speed depends in part on the individual tree species, the mix of species, level of precipitation accompanying the event, and the overall state of the forest (*Seidl et al., 2011* a,b in *Lindner et al., 2014*). **Tree health:** With warmer temperatures, the occurrence of insect outbreaks and pathogen disturbance are expected to increase. Insects' and pathogens' rate of survival and population size increase with warmer (winter) temperatures. At the same time, warmer and dried conditions reduce trees' resistance to such insects and pathogens (*Robinet and Roques 2010 in Lindner et al., 2014*). **Degree of tree species mixture:** Climate change will alter forest composition and structure. Though the exact nature of that change will vary across Europe. The general increase in temperatures, accompanied by a change in precipitation (increase or decrease depending on regional context), climate seasonality and seasonal shifts in extremes will affect the individual elements of forest ecosystems, including species mix, in different ways (*Urli et al., 2013; Dantec et al., 2014 in Lindner et al., 2014*). Shifts in species composition due to species migration has been observed at the leading edge of a species' range as a consequence of rising temperatures. Examples include the up-hill movement of tree line with the associated upward shift of forest wood species (*Lenoir et al. 2008 in Lindner et al., 2014*), as well as temperate and sub-Mediterranean tree species (*Urli et al. 2014 in Lindner et al., 2014*). While these up-ward migratory trends are expected to happen with a certain time lack, the other end of tree species' natural range is showing a more rapid response: in some areas the dieback of low-altitude forest stands affected by drought and or insects and pathogens is not followed by natural regeneration, but rather a shift into a non-forest type vegetation cover (*Adams et al., 2009; Anderegg et al., 2013; van Mantgem et al., 2009; Allen et al., 2010, Jactel et al., 2012, Riglin et al. 2013 in Lindner et al., 2014*).

<table>
<tr><th colspan="2">STORMS</th></tr>
<tr><td></td><td>In a wind disturbance context, tree species mixture is relevant as different tree species vary in their susceptibility to wind disturbance. Lüpke and Spellmann (1999 in Knoke et al., 2008) found that Norway spruce (Picea alba) is ten times more susceptible to windthrow than Oak species (Quercus robur, Q. petreae) and four times higher than European beech (Fagus sylvatica). Differences are attributed to the shallow rooting system and needle retention during winter months, which is when storms tend to occur. Mixed forests have shown greater resistance against damage caused by storm as well as by insect disturbance (Jactel et al., 2017; Knoke et al., 2008; Vacek et al., 2019).

Measures/Actions-New requirements/Stakeholders.

<u>Forest management:</u>

Forest management is key to pro-actively minimize the potential wind disturbance damage mixed species forests. Generally speaking, mixed species, uneven-aged forests are better equipped to withstand wind disturbance (Jactel et al., 2017), in part because of their limited susceptibility to wind-related disturbances, such as insect and pathogen outbreaks. Certain species are more resistant to storm events due to e.g., their rooting system and should be favoured over less resistant species.

Other potential measures include limiting rotation lengths in critical areas to reduce tree heights, integrating soil maps into the planning process to consider their susceptibility to flood events, avoid creating exposing forest stands to wind e.g., by creating new forest edges through harvest operations; implement prevention measures such as the creation of gradual forest edges to stabilize exposed stands,

Given the regional variation in most factors affecting a forest’s wind disturbance risk, forest management practitioners should be supported in their work through detailed information on their forests risk, including e.g., through soil maps, or detailed risk assessment of the area for which they are responsible (provided by forest management research and agencies).</td></tr>
<tr><td>Exposure</td><td>Factors.

<u>Number of people outside in forested areas, places and roads close to trees</u>
<u>(e.g., forest visitors / doing recreational activities, commuters):</u>

Recreational activities in the forest are becoming increasingly popular in many European countries. A growing risk of wind disturbance thus translates into greater potential risk for a growing number of forest visitors.

<u>Proximity to urban areas:</u>

Geographic proximity to urban areas noticeable increases the number of people recreating in the forest. The potential exposure of forest visitors is thus greater than in more rural areas.</td></tr>
</table>

STORMS	
	<u>Direct and indirect economic impact of disaster:</u> Given the expected increase in frequency and severity of wind disturbance, the potential economic impact is likely to increase. **<u>Direct damages to infrastructure:</u>** Given the expected increase in frequency and severity of wind disturbance, the potential for damage to infrastructure is likely to increase. **<u>Number and value of buildings in hazard prone area:</u>** Given the expected increase in frequency and severity of wind disturbance, the size of potentially hazard prone areas and the infrastructure present is likely to increase. **<u>Presence of critical environmental services:</u>** Given the expected increase in frequency and severity of wind disturbance, the potential for negative effects on critical environmental services is likely to increase. This includes e.g., water quantity and quality; up-rooting of trees in large areas due to wind disturbance, and associated soil exposure can result in water pollution, increased run-off and potentially soil mobilization (mud-slide). **Measures/Actions-New requirements/Stakeholders.** **<u>Forest management:</u>** Reduce exposure in key areas, e.g., around critical infrastructure or highly frequented roads through frequent checks of tree health, or establishing tree-free buffer zones (forest management agency). Manage forest areas providing critical environmental services proactively to reduce risk of wind throw trees, e.g., through choice of tree species, limit tree height (forest management agencies, forest owners). Establishing respective regulations for different forest owner types (including private forest owners) to engage in exposure risk reduction measures, and support by forest management agencies to forest owners in implementing risk reducing management practices (national and regional governments, forest management agencies). **<u>Risk assessment and mapping tools:</u>** For forest owners and managers to proactively manage their forest for the purpose of exposure reduction, they require detailed (as in high resolution) information on their respective area's wind disturbance risks, including relevant critical infrastructure, environmental services etc. (see e.g., *Kamimura et al.,2008*) (research, cartographic service providers). **<u>Land use restrictions:</u>** Territorial and urban planning must take into account future scenarios of climate change. In a wind disturbance context, this implies consideration of potential wind

<table>
<tr><th colspan="2">STORMS</th></tr>
<tr><td></td><td>disturbance damage in land use planning to limit potential exposure (regional and national governments, urban planners).

<u>Awareness raising:</u>

Public awareness raising about the potential dangers of storm events, targeting in particular forest visitors with little forest related expertise (civil protection, local authorities, forest management agencies).

<u>Alert system:</u>

Establishing/using storm alert systems to inform the general public about forecasted storm events in a particular area using a variety of media channels, including social media as well as traditional means such as newspapers, TV (civil protection, local authorities, and meteorological stations).

<u>Insurance schemes:</u>

Widespread coverage of forest owners through insurance schemes to protect forest owners from storm-induced financial damages. Support should be tied to proactive forest management measures taken so as to encourage proactive forest management decisions (government policy, insurance enterprises).</td></tr>
<tr><td>Vulnerability</td><td>Factors.

<u>Risk awareness in population:</u>

The more frequent media coverage of climate change, as well as forest related topics may result in greater public attention and possibly also risk awareness among the public. At the very least, greater awareness of climate change impacts may facilitate communication about related risks in the context of wind disturbance and forests (local authorities, disaster and risk management organizations).

<u>General response capacity:</u>

Given the expected increase in frequency and severity natural hazard events, including wind disturbance, securing appropriate local and regional response capacities is essential and may require adjustments or additional support e.g., by developing regional crisis management plans, training, additional equipment and staff (local authorities, civil protection authorities, disaster and risk management organizations).

<u>Financial capacity to recover from negative impact of hazard event:</u>

Given the expected increase in frequency and severity of wind disturbance, securing an economic recovery gains greater relevance (risk assessment authorities, government actors.

<u>Duration of initial and secondary impacts:</u>

Given the expected increase in frequency and severity of wind disturbance, the potential economic damage associated with these events will also increase (risk assessment authorities, civil protection authorities, forest management experts).</td></tr>
</table>

STORMS	
	Measures/Actions-New requirements/Stakeholders. **Public awareness:** Raising awareness about natural hazard risks, in particular the potential dangers associated with storm events, targeting in particular forest visitors with little forest related expertise (civil protection, local authorities). **Securing appropriate response capacities:** Encouraging or demanding the development of regional crisis management plans involving all affected actors, including forest managers and owners, civil protection and local authorities. Furthermore, encourage or demand the implementation of targeted training and drills to prepare a variety of potentially affected actors for a potential storm event. Appropriate response capacities can also contribute to reducing initial and secondary economic impact of wind disturbance events (national or regional governments, local authorities, civil protection organizations).

4.3.1.2 Floods (Flash floods)

FLOODS (Flash floods)
According to the EEA (2017), extreme weather and climate-related events, that result in hazards such as floods and droughts, will become more frequent and intense in many regions and impacts related to changes in precipitation, notably heavy precipitation events leading to floods and landslides, are projected to increase further in the future. Pluvial floods and flash floods, which are triggered by intense local precipitation events, are likely to become more frequent throughout Europe, while in regions with projected reduced snow accumulation during winter, the risk of early spring flooding could decrease. In particular in “Global warming increases the frequency of river floods”, *Alfieri et al (2015)* investigated projected changes in the magnitude and frequency of different hydrometeorological variables to assess future changes in flood hazard in Europe. The results indicate that the change in frequency of discharge extremes is likely to have a larger impact on the overall flood hazard as compared to the change in their magnitude. On average, in Europe, flood peaks with return periods above 100 years are projected to double in frequency within 3 decades. Regarding Italy, as reported in “Risk analysis: climate change in Italy” (*CMCC, 2020*), climate change induces an increase in the frequency and intensity of some atmospheric events that regulate the occurrence of the hydrogeological phenomena. From the combined analysis of these factors and of the climatic scenarios, it is clear that the worsening of a very complex situation is expected. The rise in temperature and the increase in precipitation phenomena localized in space play an important role in exacerbating the risk. In the first case, the melting of snow, ice and permafrost indicates that the areas most affected by variations in magnitude and seasonality of the instability phenomena are the Alpine

FLOODS (Flash floods)	
and Apennine areas. In the second case, heavy rainfall contributes to a further increase in the hydraulic risk for small basins and the risk associated with surface landslides in areas with more permeable soils.	
Hazard	**Factors.** **<u>Heavy Rain</u>** **<u>Land use</u>** **<u>Temperature</u>** At Italian level according to the Italian National climate change adaptation plan (CMCC, 2017), the frequency of river floods will be more impacted in basins with reduced permeability that respond more quickly to meteoric stresses and have reduced mitigating effect against short-term and high intensity precipitation. Urbanization and land use can have a negative impact, contributing to the aggravation of hydro-geological phenomena. The rise in temperature and the increase in precipitation phenomena localized in space play an important role in exacerbating the risk. In the first case, the melting of snow, ice and permafrost indicates that the areas most affected by variations in magnitude and seasonality of the instability phenomena are the Alpine and Apennine areas. In the second case, heavy rainfall contributes to a further increase in the hydraulic risk for small basins and the risk associated with surface landslides in areas with more permeable soils. The analysis of changes in the precipitation regime is complex, as these occur with marked spatial heterogeneity. For this reason, it is necessary to rely on a detailed knowledge of the local context from different points of view. For example, for adaptation actions to be effective and efficient, they must necessarily be based on the interpretation of changes in rainfall regimes on a local scale. Therefore, continuous monitoring of these regimes is necessary, which must be accompanied by an update of knowledge in analyzing and processing such data, also by integrating different data sources. Furthermore, the development of very high resolution climatic scenarios is fundamental both from a spatial and temporal point of view (with high predictability at least on the hourly scale). **Measures/Actions-New requirements/Stakeholders.** **<u>Integrated Planning</u>** **<u>Advanced tools for managing territorial and geographic data, as well as advanced DSS tools in real time</u>** **Monitoring:** Improvement of the forecasting and monitoring capacities and systems, which allow to predict with the widest possible time interval, the

FLOODS (Flash floods)	
	approaching of meteorological phenomena spatially and temporally concentrated and to be able to determine risk scenarios for the population **Define a methodology to consider and evaluate climate change in the FRMPs** (as required by the EU Floods Directive) **More detailed hydraulic and risk analyses** (This requires a long computational time, the availability of trained technicians, financial resources and collaboration with municipalities and regions) **and continuous knowing and updating the hydrology**
Exposure	**Factors.** **Territorial planning/Uncertainty:** In particular, in relation with planning actions to adapt to climate change, the "time" factor must be carefully evaluated. Social development, albeit positive, has an increasingly significant impact on the environment and on society itself. This affects the changes in climate and territory that are manifesting at an unprecedented speed. The natural and social phenomena that determine the evolution of these changes are distinctly non-linear, and therefore characterized by threshold effects and points of no return. Although environmental systems are by their nature capable of compensating exogenous perturbations, the speed at which changes are occurring can limit, or even inhibit, the compensation processes. Such evidence requires rapid development of adaptation actions. Therefore, for the mitigation of the geological, hydrological and hydraulic risk, it is advisable to favor the actions of forecasting, prevention and disaster risk management limiting as much as possible the emergency and restoration actions to those useful for the progressive reduction of the risk, and for the restoration of general conditions of territorial safety. The improvement of current knowledge on the dynamics of change, in terms of frequency and magnitude of impact, with an accurate assessment also of uncertainty - which is fundamental for an accurate risk assessment in support of private and public users - could be of particular relevance for effectively addressing the risk. *(CMCC, 2020, Risk Analysis. Climate Change in Italy)* **Measures/Actions-New requirements/Stakeholders.** **Regulatory coordination at national level** that foster the coherence of the different instruments and improving coordination between the institutions, promoting also a change of mentality / cultural leap of institutions **More collaboration** between institutions or offices of the same agency

FLOODS (Flash floods)	
	Integration between territorial planning and territorial risk data Activation of a **post-event feedback** mechanism through the improvement of the organization of the incoming data: the data can be provided to those who will then have to plan at territorial level and to the Municipalities to improve the management of the territory and possibly "build back better" More **detailed hydraulic and risk analyses** – even in urban areas - that lead to a more refined "risk knowledge framework" and can orient more effectively the flood management and control interventions. (This requires a long computational time, the availability of trained technicians, financial resources and collaboration with municipalities and regions) and continuous knowing and updating the hydrology More **financial resources** to program in ordinary time and more human resources Stronger role of **risk reduction strategies and civil protection planning** in spatial planning, especially in urban planning, in order to reduce or avoid exposure. It should take into account the most vulnerable elements. **Inclusion of climate change effects in risk assessment, civil protection planning and spatial planning** in the sense of foreseeing the increase of exposure originated by changes in hazard extension, frequency and severity. Considering the uncertainty in DSS. A way to better deal with the uncertainty of forecasts is to **apply a precaution principle**. It could be applied as criteria in the DSS. For example, confining the population in basins near those areas identified by the "uncertain" forecast as at higher risk, as the forecast might fail in the place, time and severity of the event.
Vulnerability	**Factors.** **Awareness of population and technicians** **Response capacity** **Behaviour/ uncertainty** Climate change, therefore, contributes to modifying the risk conditions, thus making a series of actions - that include the development of a modern culture of prevention to favor the planning and the integrated management of the territory and of the resources, risk mitigation coordinated at different geographical, temporal and organizational scales and, finally, massive awareness of active participation of the

FLOODS (Flash floods)	
	population - even more relevant. *(CMCC, 2020, Risk Analysis. Climate Change in Italy)* **Measures/Actions-New requirements/Stakeholders.** **Improvement of the civil protection planning and updated knowledge** **Strengthening of the governance**, as an element of strategic importance in consolidating the civil protection system: More collaboration between institutions at different levels and offices of the same agency + greater coordination between local authorities in order to integrate actions in all the risk management phases **Advanced tools** for managing territorial and geographic data, as well as advanced DSS tools in real time **Rising territorial awareness** **Enhance the level of preparation of stakeholders and authorities** for these intense and concentrated events, also in terms of civil protection **Greater diffusion** of the knowledge of hazard and risk in the territory (e.g. WebGIS) and dissemination of data; Involvement of schools and the population for rising awareness **Smart urban planning and building construction**, which should include the possible hazards impacting but also the likely climate change effects. For example, planning evacuation ways. **Including climate change scenarios and multirisk episodes in civil protection planning**, in the sense of foreseeing vulnerability changes due to the increase of exposure originated by changes in hazard extension, frequency and severity. **Increase the resilience of the society**, especially the most exposed population.

4.3.1.3 Wildfires

WILDFIRES
Wildfire or forest fires are fires that burn vegetation, both forest lands (forest and shrublands) and crops, without control. A wildfire can occur due to many factors, that can mainly be divided into natural or anthropic factors. Among the natural factors there is basically lighting and, depending on the region, volcanoes. On the other hand, anthropic ignitions are usually caused by accident, negligence and carelessness, and only a few are intentionally ignited. Once a wildfire is running, it can propagate in the surface fuel (surface fires), crown fuel (crown fires) or the ground (smouldering fires). According its propagation patterns there are also 3 types of fires: wind fires that use the wind power to move,

WILDFIRES

topographic fires that read the orography to propagate and convective fires that use the fuel availability to generate extreme conditions. From the propagation layer point of view, crown fires are usually the most critical fires, while from the propagation pattern side, convective fires are the ones creating worst conditions.

In Europe it is common that fire services suppress all fires as soon as possible after their arrival to the area. However, the high efficiency of suppression actions, together with the rural abandonment, has lead European landscape to a critical situation with a very high fuel accumulation. Therefore, that day that a fire starts, and the fuel availability and weather conditions facilitate high intensity and fast spread fires , fire services cannot control the fire and it gets larger burning in a continuous and over fuel load landscape. This phenomenon is known as the fire paradox, because the suppression efficiency fosters future large wildfires. Therefore, it is key to understand the natural role of fire in the landscapes and its fire regime in each region (frequency and intensity) and manage the wildfire risk accordingly.

With the climate change scenario, it is expected that temperatures in many EU regions will increase, and that dry periods will be more frequent. There is data demonstrating that climate is changing: For instance, in Catalonia, evo transpiration has increased significantly since 1950, it means that it is less likely to rain and that plants loss more water to evaporation (*3rd Catalan report on climate change*). The more extreme temperature, humidity and precipitation conditions foreseen by the climate scenarios suggest that the number, extension and severity of forest fires will increase. The increase in exceptional weather conditions may lead to more frequent fires covering large areas, and to fires in areas where they are at present uncommon or fires in seasons other than summer.

In Italy the increase in temperatures and the reduction in average annual rainfall, and at the same time the greater frequency of extreme weather events such as heat waves or prolonged drought, interact with the effects of the abandonment of cultivated areas, pastures and those that were once managed forests, of the strong exodus towards cities and coastal areas, and of monitoring, prevention and active struggle activities increasingly efficient. Increases in the fire hazard, altitude shift of vulnerable areas, extension of the fire season and an increase in extremely dangerous days are expected which, in turn, could translate into an increase in the surfaces travelled with a consequent increase in gas emissions greenhouse and particulate matter, therefore with impacts on human health and the carbon cycle. (*CMCC, 2020*).

One of the common impacts of climate change in fires is the increase of days with fire risk. Fire season gets longer year by year. While some decades ago fires where mainly concentrated in the Mediterranean during June, July and August, nowadays fire services has to tackle fire outbreaks from April to October. In fact, the larger wildfire of the known European history occurred in Portugal, in October.

Another common finding of studies related to climate change and wildfires is the increment of the annual burned area. It seems that the higher the temperature, the higher will be the burned area. Particularly, Turco *et* al. 2018 estimated that an increment of 3ºC may duplicate the annual burned area in Catalonia.

Regarding fire behaviour (flame length, propagation rate, etc) it is widely agreed that, in places that the accumulation of fuel is high, the fire behaviour will extremely increase, having higher flames (suppression capacity is 3 metres) and more rapid propagation rates (1 km per hour is approximately the suppression capacity). Consequently, the increment of the high intensity fire behaviour will affect the fire service suppression capacity, the burned area will increase and the impact on ecosystem and human settlements can be devastating. On the other hand, places with less fuel accumulation will probably increase the fire frequency, burning at low intensity with a smaller rotation period.

<table>
<tr><th colspan="2">WILDFIRES</th></tr>
<tr><td colspan="2">All the climate change impacts affecting wildfires that have been mentioned are related to the fire regime. European ecosystems are better adapted to a specific fire regime that is already influenced by humans 8through landscape management, prescribed burns and other activities), however, climate change is leading a rapid switch of fire regimes. Therefore, new ecosystems and habitats may be generated due to the new fire regimes.</td></tr>
<tr><td>Hazard</td><td>Factors
<u>Forest stand density and fuel continuity:</u>
Climate change may influence forest fuel continuity. Despite the uncertainty and controversy, some authors suggest that the south European weather is changing towards a polarised wet/dry seasonality. Under this situation, during the wet season light fuel (grass, fine shrubs branches, etc.) will rapidly grow. Light fuel is responsible of rapid propagation of fires, and it created a very continuous shrub layer that facilitate fire propagation with medium to high intensity. Once the wet season is finished, the long drought periods of summer easily dry light vegetation and during the drier season, light fuel would rapidly ignite and drive wildfire propagation.

Heatwaves:
It is widely accepted that climate change will raise temperatures in southern Europe. Apart from that, heatwaves driven by the entrance of hot air masses from Africa are likely to occur with more frequency. Most of the European worst and larger wildfires occurred under this synoptic situation, which bring very hot and dry air to the continent and makes fuel available to burn. This is likely to occur particularly from May to September. However, hot waves synoptic situations are starting to be common during other months (April- October).
In Italy, for instance, under a high emissions scenario, mean annual temperature is projected to rise by about 5.1°C on average from 1990 to 2100. If global emissions decrease rapidly, the temperature rise is limited to about 1.6°C. Under a high emissions scenario, the number of days of warm spell is projected to increase from about 10 days in 1990 to about 250 days on average in 2100. If global emissions decrease rapidly, the days of warm spell are limited to about 75 on average. Moreover, under a high emissions scenario, the number of days with very heavy precipitation (20 mm or more) could increase by about 4 days on average from 1990 to 2100, increasing the risk of floods. Some models indicate increases outside the range of historical variability, implying even greater risk. If global emissions decrease rapidly, the risk is slightly reduced. Finally, under a high emissions scenario, the longest dry spell is indicated to increase from an average of about 30 days to just under 45 days, with continuing large year-to-year variability. If global emissions decrease rapidly, there is little change in the length of dry spells (WHO, 2018).

<u>Drought periods:</u>
Hydric stress of vegetation caused by longer periods without rain will be more and more frequent in the coming decades. This is relevant because increases fuel availability and flammability, generating more probabilities to have a fire and more extreme behaviour once the fire has started. Under a warming climate, fuels are likely to suffer the consequences. Stressed and unhealthy forests are also more vulnerable to pest and diseases, generating a cascade effect that can generate large tree mortality adding dead biomass and dry fuels.</td></tr>
</table>

WILDFIRES	
	Around the Mediterranean region, climate change will reduce fuel moisture levels from present values, increasing the weather-driven danger of forest fires. Furthermore, areas exhibiting low moisture will extend further northwards from the Mediterranean, and the current area of high fuel moisture surrounding the Alps will decrease in size. Projected declines in moisture for Mediterranean countries are smaller with mitigation that limits global warming to 2 °C, but a worsening is still predicted compared with present (*PESETA III Project, JRC https://ec.europa.eu/jrc/en/peseta-iii*). **<u>Windstorms and snowstorms:</u>** Although there is high uncertainty on it, it seems that extreme weather events will increase with the climate change. Windstorms can affect large surface felling down thousands of trees in few hours. Heavy snowfall specially with fresh snow in low altitudes are also able to crash and fell down trees in large surface (like the 2010 event in NE of Catalonia, with 120.000ha affected). In both cases, roads and forest roads are collapsed, and large amount of biomass becomes available in the fire season if is not removed. **Measures/Actions-New requirements/Stakeholders** Measure to address factor influenced by climate change are basically the same that are being or that should be currently implemented. The following section summarize them. **<u>Reduction of fuel load continuity:</u>** To face the increasing hazardous conditions, it is going to be key to keep working on breaking fuel load continuity to avoid high intensity fires behaviour, embedding fuel removal activities as wood mobilisation or understory grazing into wildfire risk management strategies. In those vulnerable landscapes where bioeconomy cannot reduce the risk of large wildfires, to generate opportunities for the fire services for controlling the fire propagation and reduce the impact of fires becomes a priority. It is especially important to have a strategic management in wildfire triggering points; places where the fire change its behaviour into worst conditions. Since climate change is enlarging fire-prone conditions across territories, strategic management in cooperation with the fire services will become more necessary to reach as much forest and settlements protection as possible, considering that the reduction of vulnerability to large fires at landscape level takes time. **<u>Maintenance and creation of mosaic landscape:</u>** Mosaic landscape is understood as an active landscape where human activities take place to generate an heterogeneous pattern of habitats and forest/agriculture structures. In such cases, forest fires find very different fuels, discontinuities and propagation patterns that reduce the potential of large fires, facilitating the work of fire services since the propagation rate and flame length get reduced to manageable numbers. On that sense, maintenance and creation of mosaic landscape can strategically planned and supported by the public services (from rural development to fire and civil protection services) in cooperation with producers and manufactures (i.e., farmers, wine cellars, etc.) and consumers (i.e., citizens, restaurants, etc.), generating bioeconomy meanwhile prevention wildfires.

<table>
<tr><th colspan="2">WILDFIRES</th></tr>
<tr><td></td><td><u>Choose of species better adapted to climate change:</u>
Climate change will drive changes in the habitats. Therefore, it is key to understand which species will support the new climate conditions and which will not be able to grow in certain areas anymore. This is especially relevant in the ecotones edge areas, where dryer conditions can overstress the vegetation generating more fire-prone environs. In addition, it is important to consider the new fire regimes that will clearly impact on the vegetation of a given area. Forest land planners and managers and fire ecologists will have to address these issues and generate recommendations based on studies

<u>Long-term strategic planning:</u>
Based on strategies coordinated at the different territorial levels, also supranational, with the aim of carrying out multi-scope interventions able to conduct integrated wildfire risk management approaches.</td></tr>
<tr><td>Exposure</td><td>Factors.
<u>Inhabitants:</u>
The presence of inhabitants in a fire-prone area is probably not influenced by climate change. However, in central Europe areas where fires are not a common disturbance today, may be a major threat in the coming decades because of climate change. In consequence, there are plenty of areas in central Europe that have communities in the middle of the forests, and they will be under risk of suffering a WUI fire.

Moreover, climate change is expected to further exacerbate specific components of fire risk, resulting in impacts on exposed people, assets and ecosystems in the most vulnerable areas. Increases in the fire hazard, altitude shift of vulnerable areas, extension of the fire season and an increase in extremely dangerous days are expected which, in turn, could translate into an increase in the surfaces travelled with a consequent increase in gas emissions (CMCC, 2020).

<u>Habitats:</u>
Habitats will be influenced by climate change since its current distribution is adapted to current conditions. With climate change habitats are expected to move into higher latitudes and altitudes. Consequently, alpine habitats (Pyrenees, Alps) are likely to reduce its distribution. In addition, wildfires are likely to burn in a dryer vegetation causing more damaging effects. Therefore, the biggest problem arises when the impact gets into a no return point.

<u>Primary sector activities:</u>
Rural activities such as agriculture and livestock are activities that can be affected by extreme wildfire posed by climate change. Every year farmers and ranchers from Mediterranean countries suffer important economic losses due to the effects of wildfires that burn their harvest. Extreme fire behaviour posed by climate change is likely to throw hotspots able to burn patches of crops and affect farms.

However, in some low-medium intensity fires, rural areas with effective forest management can be opportunities to stop or control fires. Consequently, this kind of activities, together with forest management should be incorporated by society with the support of rural development departments.</td></tr>
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WILDFIRES	
	Environmental services: The changes in the structure and continuity of plant communities and in the landscape mosaic, especially in the fragile urban-rural interface areas (1.1) characterized by a massive presence of residences immersed in vegetation, create the predisposing conditions for greater exposure and vulnerability with respect to the passage of fire and therefore the generation of large events (*Bovio et al., 2017*), extensive and destructive, with repercussions on anthropogenic goods and ecosystem services. (*CMCC, 2020*). The increase of the severity of fire events and the extension of fire-prone areas can jeopardize the provision of several ecosystem services as cultural ones (e.g., loss of landscape beauty, recreation activities linked to forest cover, etc.) or regulation of water cycle, the soil protection or, globally, forest protection function generating multi-risk situations such us accumulative wildfire and avalanche risk, or cascading wildfires and floods risk. **Measures/Actions-New requirements/Stakeholders.** **Fuel breaks around fire sensitive sites and species:** In case of having fire sensitive sites (e.g., tourist resorts and places with many people) and species, considering implementing a fuel break around them should be an effective option. However, it is important to be aware that fire can throw hotspots in the vegetation anyway. But it is an effective measure for surface fires, eliminating the exposure if this fuel breaks are supported with the extinction in case of fire. For high intensity fires, exposure is not reduced at all, nevertheless, this fuel breaks can help the fire control and reduce potential damages. Alternatively, they can be applied in such enough surface able to eliminate the potential of crown fires and, consequently, the secondary fires emission. In this case, the exposure to the impact of large fires is considerably reduced. This kind of actions should be pre-planned according the fire patterns in the territory to be effective, and it can includes the restoration of mosaic landscape around sensitive sites as WUI areas, aimed at protecting people and settlements, or protection forest to ensure the protection function. Together with the forest and fire service and private stakeholders related with fuel management (forest owners, shepherds, farmers, etc.), urban planners and risk managers are also involved, integrating prevention measures to increase the system resilience to climate change impacts. **Fuel management to avoid crown fires:** The transition from surface to crown fires is highly important and very likely to occur under climate change and not managed forests masses. Fuel continuity allows this transition and, since fuels will be dryer, flame are expected to be longer and easily get to the crowns. In this case, as it is done nowadays, one of the main aims of forest fire preventive actions is breaking the so-called horizontal continuity to avoid crown fires and flame lengths stressing the suppression capacity. Several research in the Mediterranean, for instance, show the multi-benefits of managed forest in a climate change context where fuel management increases the efficiency of water regulation, which will be also a tricky issue in many forest lands in drier environ (e.g., *LIFE MEDACC, http://medacc-life.eu/*).

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<u>Early warning systems:</u>
Wildfires will get faster with the climate change and the increment of dry light fuel. Therefore, early warning systems will play a major role in terms of alerting population under risk by giving them the opportunity to leave the area or to properly prepare for the impact of the flames. Of course, early warning systems should be developed by the public administration, but with the collaboration of technology developers.

<u>Close access in high fire risk days and places:</u>
This measure has been already implemented in certain parts of Europe. However, knowing in advanced that fires are getting faster thanks to fuel availability and that the reaction time gets reduced, it is important to work on population awareness and make society understand that there is a risk when a group of people spend a day in a fire-prone area under a high risk day. This also can be extended to the organisation of outdoors activities mobilising hundreds of participants.

<u>Reinforcing fire suppression and emergency management capabilities:</u>
Fire suppression must be improved in order to reduce people exposure and vulnerability. However, it must be improved not only with increasing fire engines, or aircrafts where needed, but by improving the capacities of firefighters as well as technology like simulators of fire propagation and population evacuation protocols, etc, adapted to new fire behaviours posed by climate change. In addition, it is key to understand fire propagation through an accurate fire analysis procedure. Finally, safety protocols have to be updated among fire service to deal with such an extremes fire behaviours.

<u>Long-term strategic planning:</u>
As it was mentioned in Hazard chapter, integrated and long-term planning based on strategies coordinated at the different territorial levels, also supranational, with the aim of carrying out multi-scope interventions, are need to face the multi-dimension of climate change impact on landscapes and wildfire risk management.

</td></tr>
<tr><td>Vulnerability</td><td>

Factors

<u>Inhabitants and tourists with low risk awareness:</u>
With climate change, fires will affect areas where they were not usual in the past or they will have unprecedent extreme behaviours collapsing the existing prevention measures. That have the potential to generate complex situations with population facing a disturbance they are not used to. In addition, tourists visiting fire-prone areas are more vulnerable because of the lack of territorial knowledge and emergency procedures.

Moreover, nowadays, it is easy to start a fire even in current Mediterranean conditions: climate change will facilitate the ease of ignition even more compared to now. For this reason, the main causes of fire should be minimized, which includes looking at the social and economic factors that lead people to start fires, increasing awareness of the danger, encouraging good behaviour and sanctioning offenders (San-Miguel-Ayanz et al, 2017).

<u>Habitats and tree species not adapted to fires:</u>
Climate change can stress habitats that are not used to water stress and high temperatures. Consequently, these habitats are more threatened by climate change and can suffer the impact of a wildfire in an irreversible manner. When habitats suffer from

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</table>

WILDFIRES	
	hydric or temperature stress, they get more vulnerable to disturbances such as fires and they have more problems to recover from the disturbance. Even low intensity fires can generate tree mortality in those species with thin barks not able to protect them from the fire heat. **Rural activities in non-productive areas:** Land abandonments due to the lack of economic income of extensive agriculture and livestock has been a widespread problem in Mediterranean countries that has been enlarged these lasts years by the effects of climate change. Some fertile regions are starting to be less productive and consequently, they get more vulnerable to wildfire posed by climate change. In addition, the abandonments of these activities must be seen as an important threat to communities that benefit from these fuel breaks generated by crops and grasslands. **Response capacity:** Despite the strengthening over the decades of all regional forest fire extinguishing systems (AIB) and of the Civil Protection at national level, the difficulties in managing fires in years of extreme weather are such as to compromise the stability of the system, instead efficient in years mild meteorology (*CMCC, 2020*). **Measures/Actions-New requirements/Stakeholders** **Implementation of low fuel load areas and fire shelters to be used as a safety area:** Low fuel load areas generate a reduction of fire behaviour and they can even stop propagation in some cases. The implementation of these areas in fire-prone regions (massifs, coastal and tourist areas, etc) with advertising signals can be used by people caught by fires during the emergency and used them as a shelter. That has been used in some countries (i.e., Australia) having positive results. To implement this solution, it is necessary to engage stakeholders like fire service, forest service, landowners, private stakeholders and land planners. **Confinement protocols:** Most of fatalities during wildfires occur when people try to leave areas too late. In case of climate change driven fires, running faster than usual, it is key to understand when is to moment that leaving the area is more dangerous than staying. Confinement protocols and its dissemination among potential communities will be an important step to reduce the risk to be done by public authorities like civil protection. **Training of communities:** Programs like firewise (USA) or Safer Together (AU) are being implemented and working on society resilience, particularly in those communities located in high risk WUI areas. The objective is to engage them to carry out preventive tasks as well as training their capacities when facing wildfires, especially the decision-making part. Again, public administration could have a key role on that by implementing this kind of initiatives together with fire services, civil protection, rural officers, land planners or, for instance, forest defense volunteers or local associations.

WILDFIRES	
	<u>Foster mosaic landscape in risk areas:</u> Preventive infrastructures should include and be planned according to vulnerability assessments. It means that some prevention and recovery actions can have synergies. It is particularly interesting under climate change scenarios, since wildfires will get larger and, consequently, fuel reduction areas will have to be larger. That why the concept of mosaic landscape has been introduced. This concept helps to implement preventive actions at the same time that rural areas activities are reinforced, for example, with extensive livestock. Mosaic landscapes prevent wildfire at the same time that generate several ecosystem services like biodiversity or cultural landscapes. **<u>Development of operating procedures:</u>** Since wildfire risk management is getting more complex under climate change scenarios (more severe and extended events, to reinforce and develop operating procedures that best identify roles and actions are needed, while regarding operational tools, the need is more related to new or better forecasting and monitoring tools. **<u>Exchange information from other institutions:</u>** Based on the increased risk management complexity, the exchange of information among actors such as municipalities or national or local agencies will contribute to a more efficient risk management. **<u>Development of operational tools able to collect information in real time:</u>** These tools should be able to collect information from the territory and, by combining static and dynamic information, to provide an evolution of the scenarios. **<u>Improve governance system and participatory approaches:</u>** Develop a governance system made up of institutions and citizens where each of the actor became aware of the condition they face; therefore, the tool needed is a good civil protection plan where citizens and institutions collaborate in drafting. Awareness campaigns should look for an increased impact focussing on the limits that public service has, and the need of proactive collaboration of citizens during the emergency, but also in prevention and preparedness. **<u>Improving the forest fire early action system based on the alert level:</u>** The alert system should permit to harmonize the activities at risk in forest landscapes, adapting them to the different levels of alert. Due to the extension of fire season in the territories, economic and recreation activities have to be prevented in an efficient way while building trust and culture or risk and limiting the opportunity cost as much as possible in a “living with risk” context. **<u>Improving the knowledge of the territory to better intervene in the territory:</u>** The extension of fire-prone areas and increase of fire severity make necessary to improve the knowledge of the territory at different levels: Better management in case of emergency; better capacity to create synergies with local activities to contribute to fuel management and risk reduction, public and private stakeholders involvement in the risk management cycle, etc.

WILDFIRES	
	Reinforce the basic supply network: Expecting more and unprecedent extreme events affecting large areas, surface, new risk prone areas, and thus, new risk situations, it is necessary to work on reinforcing the basic supply network since it is a basic resource/service for population and the emergency services and management. For instance, pre-planning the necessary resources "in case of emergency", updating the inventories frequently and establishing agreements with private operators. **Develop and promote insurances schemes:** The expected increase of wildfire severity and the recognised capacity limit of the suppression generate an extensive exposure of goods and services to the potential impact of fires. Since to change fire-prone conditions takes time and needs high resources (not always available), in highly vulnerable landscapes to large fires the insurance promotion may enhance the resilience of the system and the post-fire recovery.

4.3.1.4 Avalanches

AVALANCHES
Avalanches are movements of snow masses by gravity that start on slopes with a determined gradient (28°-45°). An avalanche occurs due to a destabilisation in the snowpack. This destabilization can be superficial or internal and is the result of an imbalance between the resistance capacity and the overload produced. This binomial depends on the stratification of the snowpack, defined by the type of snow grain and the diameter, density, humidity and hardness of the overlapping snow layers. These variables evolve continuously according to atmospheric conditions: basically, the energy balance of the snowpack and the increases, both positive and negative, in the thickness of the snow on the terrain. Therefore, any change in weather and climate conditions implies a change in the conditions of stability of the snowpack and the occurrence of avalanches. Climate change can affect both avalanche occurrence and typology (*3rd Report on Climate Change in Catalonia, 2016*). A probable increase in avalanches in the Western Alps above 2500 metres is expected, caused by a possible increase in the frequency of heavy precipitation (*Castebrunet et al., 2014*). Research concludes that there is a positive temporal trend on an annual scale, statistically significant, in the occurrence of large avalanches for the whole of the Pyrenees of Catalonia (*García-Sellés et al., 2010*). In the last nineteen winters, an increase in the number and magnitude of wet snow episodes has been detected (*3rd Report on Climate Change in Catalonia, 2016*). In the Pyrenees, in the last forty years a statistically significant negative correlation has been observed between the occurrence of large avalanche cycles and the negative phases of the NAO (*García-Sellés et al., 2009*). However, at regional level, different responses have been detected, since the most eastern area (Mediterranean climate domain) maintains a higher level of large avalanche activity during negative phases. In contrast, in the north-western part (Atlantic climate domain) there is no relationship between avalanche activity and the NAO. In recent decades, an increase in positive phases of the NAO has been detected. According to these forecasts, a reduction in the large avalanche cycles in the Pyrenees can be expected during the 21st century. However, because of the interannual variability of the NAO, extreme years of avalanche activity have been observed during positive phases on a decadal scale, due to the occurrence of a winter with an

AVALANCHES	
exceptional negative phase. Therefore, the uncertainty in future avalanche activity is very high and extreme years of avalanche activity in the coming decades cannot be ruled out (*García-Sellés et al., 2009*).	
Hazard	**Factors.** **Snowpack:** To determine the future trend of the avalanche risk as a result of climate change, future temperature and precipitation forecasts must be taken into account. In addition, altitude, orientation and slope angle (topographical characteristics) will determine the response of the snowpack to Climate Change (*López-Moreno, et al., 2014*). *Temperature and precipitation* Climate models project an increase in temperature in the coming decades (*IPCC 2014*). The expected increase in temperatures will lead to a decrease in the duration (days) of the snowpack and the thickness of the snow (cm) (*López-Moreno, et al., 2014*). A decrease in the snowpack is detected on the southern slope of the central Pyrenees due to a decrease in precipitation. Also, a great interannual variability in duration and thickness is observed (*OPCC-CTP, 2018*). In the Swiss Alps, future increases in temperature are expected to lead to an extreme decrease in the snow cover at low altitudes (90%) and a significant decrease at medium altitudes (50%) by the end of the 21st century (extreme scenario >4°C) (*Beniston, M.; et al., 2003*). Also, in Swiss mountain regions will be less duration of snow even at high altitudes in a warmer climate (Uhlmann, B. et al., 2008). *Altitude, orientation and slope angle* It is expected that as the temperature increases the thickness of the snowpack will decrease, especially at low altitudes and sunny orientations. At high altitudes the amount of snow will not decrease even though the temperature will rise. Therefore, in avalanche starting zones the amount of snow is expected to be very similar to the current one (*Reuter, B.; Bellaire, S. et al., ISSW 2020*). Snow melting processes on sunny slopes are expected to advance in the calendar as the average temperature rises. On shady slopes, snow melting processes are advanced in the calendar from 2ºC increases in temperature (*López-Moreno, et al., 2014*). Increased projected temperatures are expected to reduce the duration of the snow cover especially on sunny slopes (*López-Moreno, et al., 2014*). The reduction in the duration of the snow cover would not affect the large avalanche cycles, since large avalanche events basically occur during the months of least sunlight (December-February) (*López-Moreno, et al., 2014*). *Climate Change Projections* The climate change projections (RCP 4.5 and RCP 8.5) foresee a reduction in the thickness of snow, especially at low and medium elevations in the Catalan Pyrenees until the end of the 21st century. Regarding the reference period (1981-2010), a decrease in the snowpack is expected by 2030 of between 45-63% (RCP 4.5) and up to 63-81% (RCP 8.5) in the Pre-Pyrenees of Catalonia. By 2050, reduction of between 63-81% (RCP 4.5) is expected in the low altitudes and eastern sector of the Pyrenees in Catalonia and 63-81% (RCP 8.5) in all the low and medium-altitude sectors of the Pyrenees. In 2070 it is expected that the snowpack will be reduced in the whole of the Pyrenees at low levels by 63-81% (RCP 4.5) and by 81-100% (RCP 8.5) at low and medium levels in the whole of the Pyrenees. Finally, in the 2090 decade a reduction of 63-81% (RCP 4.5) and 81-100% (RCP 8.5) in low and medium altitudes is expected (OPCC-CLIMPY, 2019).

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Terrain:

In recent decades, a displacement of the upper limit of the forest of about 35 meters has been detected. According to the Climate Change scenarios, the *Pinus uncinata* species will have suitable bioclimatic areas at altitudes higher than the current ones (2200 metres). In the SRES A2 scenario the upper limit of the forest would reach 2472 metres and under the B2 scenario 2342 metres (OPCC-CTP, 2018). An increase in erosion is expected in the coming decades due to the greater frequency and intensity of floods associated with the expected increase in precipitation intensity (OPCC-CTP, 2018).

Weather:

The increase in temperature in mountain areas is higher than in flat areas. There is greater variability in precipitation. Dry years (which have predominated in recent decades) alternate with wet years that are clearly above the average climate. Hypothetically, in the future, a drastic decrease in precipitation, a decrease in the frequency of rainy days, a notable increase in the duration of dry periods and an increase in the intensity of extreme events are expected (OPCC-CTP, 2018). The climatic projections of precipitation in the Catalan Pyrenees in 2030 are expected to increase slightly with values up to 10-20% (RCP 4.5) and 5-10% (RCP 8.5) higher than the reference period 1961-1990 in medium altitudes. In the year 2050, precipitation is expected to increase slightly with values up to 10-20% (RCP 4.5) or remain unchanged (RCP 8.5). Finally, by 2070 and 2090, increases of up to 10% (RCP 4.5) or no change (RCP 8.5) are expected.

Climate projections of temperature in the year 2030 show increases (reference period 1986-2005) of up to 2°C (RCP 4.5 and RCP 8.5) and especially at low altitudes. By 2050, increases of up to 2°C (RCP 4.5) and up to 4°C (RCP 8.5) are expected in the Catalan Pyrenees. Punctual increases are expected by 2070 (RCP 4.5) and in the whole of the Catalan Pyrenees (RCP 8.5) of up to 4°C. Finally, by 2090, increases of up to 4°C (RCP 4.5) and up to 6°C (RCP 8.5) are expected in the whole of the Catalan Pyrenees (OPCC-CTP, 2018).

The spatial resolution of these forecasts is not appropriate for a system such as the Pyrenees, since mountain systems have their own climate and the Pyrenees are characterised by a great diversity of climates (OPCC-CTP, 2018). It seems clear that Climate Change is favouring greater ripples in the jet stream (*Viñas, J.M., 2020*).

Overloadings:

Climate change will imply a higher intensity of precipitation, which could lead to more frequent avalanche triggering situations. In addition, the lower amount of snow expected at low and medium altitudes may imply a greater concentration of people in avalanche starting zones (OPCC-CTP, 2018). In Andorra is projected a reduction on the ski season length and the drop of the number of skiers especially in the lowest elevation ski resort of this region (*Pons, M. et al., 2012*).

<table>
<tr><th colspan="2">AVALANCHES</th></tr>
<tr><td></td><td>Measures/Actions-New requirements/(Stakeholders).

<u>Monitoring:</u>
There is a need for greater follow-up and monitoring of avalanche areas, especially those most sensitive to rising temperatures, such as sunny slopes in low-mid altitudes. Installation of new snow and weather sensors. (Risk Managers - ICGC). (RECIPE, 2020).
It is necessary to control and monitor the evolution of the forest and its upper limit (Forest Managers).

<u>Modelling:</u>
It is necessary to model in a context of Climate Change the potential impact and extent of large snow avalanches in the most vulnerable areas (Risk Managers – ICGC, Civil Protection, Ski Resorts). (RECIPE, 2020).
Model in a context of Climate Change how the forest and its upper limit will evolve (Forest Managers).
Weather forecasting models need to be continuously improved (RECIPE).

<u>Snowpack Stability Assessment:</u>
It is necessary to monitor continuously the evolution and structure of the snow cover in the areas most sensitive to the effects of Climate Change (especially persistent weak layers) (Risk Managers – ICGC, Ski Resorts). Analyse the response of the snow cover to climate change (increase in temperature). (Risk Managers – ICGC, Ski Resorts). (RECIPE, 2020).

<u>Avalanche Protection:</u>
A continuous check and maintenance of the avalanche protection structures is necessary (Civil Protection, Local Authorities, Ski Resorts).

<u>Avalanche Terrain Assessment:</u>
Avalanche mapping needs to be updated to a more detailed scale (1:5000 or 1:2000). (Risk Managers - ICGC) (RECIPE, 2020).</td></tr>
<tr><td>Exposure</td><td>Factors.
<u>Number of citizens, workers, tourists, etc:</u>
In the future, according to the climate trend, the number of people at low altitudes in ski resorts is expected to decrease (Pons, M., et al., 2012). Therefore, more exposure is expected in avalanche starting zones.

<u>Access to information and knowledge about avalanche risk</u> <u>(new studies, research, reports, projections, conferences, trainings, etc.):</u>
Climate Change may favour a greater proliferation and diffusion of knowledge on avalanche risk (new studies, research, reports, projections, conferences, trainings, drills, etc.).

<u>Risk behaviour/attitude (uncertainty):</u>
Climate change can lead to greater awareness of avalanche risk. It can therefore help to improve behaviour in risk situations.</td></tr>
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AVALANCHES	
	<u>Urban and land planning:</u> Territorial and urban planning can become outdated in a Climate Change context, as new climate change scenarios are not present in current planning. **<u>Infrastructures, buildings, critical facilities, economic activities, environmental services:</u>** Avalanche areas, in a context of Climate Change, can be overtaken by an extreme avalanche and therefore affect elements of the territory located outside the avalanche areas. Climate Change will imply changes in infrastructures, buildings, critical facilities, economic activities and environmental services in avalanche areas (i.e., new economic activities, infrastructures, etc.). **Measures/Actions-New requirements/(Stakeholders).** **<u>Avalanche Safety Programs:</u>** Improve the regulation and control of access to avalanche risk areas (Civil Protection, Local Authorities). **<u>Public issue of avalanche forecasting (regional and local):</u>** Increase the dissemination of the Avalanche Hazard Forecast through social networks (Instagram, Facebook, Youtube, etc). (Risk Managers – ICGC, Civil Protection, Local Authorities, Ski Resorts). Generate much more visual information and integrate large avalanche scenarios, to improve decision-making. (Risk Managers - ICGC). **<u>Scientific knowledge</u>** <u>(reports, studies, research projects, publications):</u> More studies are needed on climate change and its effects on natural risks and their management. (Risk Managers - ICGC) **<u>Avalanche terrain assessment</u>** <u>(avalanche path maps, thematic cartographies on avalanche terrain) and databases:</u> Avalanche mapping needs to be updated to a more detailed scale (1:5000 or 1:2000) (RECIPE, 2020). (Risk Managers - ICGC). A mapping of the elements exposed and vulnerable to the risk of avalanches is necessary. Identify those elements of the territory that have been affected by avalanche episodes. (Risk Managers – ICGC, Civil Protection, Local Authorities). A mapping of avalanche protection systems, Avalanche Intervention Plans (PIDA), resources (Daisybell, etc.) is necessary. (Risk Managers – ICGC, Civil Protection, Local Authorities). **<u>Land use restrictions:</u>** Territorial and urban planning must take into account future scenarios of Climate Change. In a context of Climate Change, poor territorial and urban planning can generate greater exposure. This new context makes it necessary to review territorial and urban

AVALANCHES	
	planning and adapt it to the new future scenarios of avalanche risk. A mandatory law/regulation is needed to regulate territorial and urban planning in avalanche areas. (Land planners, local authorities).
Vulnerability	**Factors.** **<u>Information, knowledge and preparation of citizens, workers, public workers</u>** <u>(forecasters, forestry guards, police, rescue teams, ...),</u> **<u>tourists, visitors, mountainers, climbers, hikers, economic activities and environmental services in mountain areas:</u>** Climate Change may favour a greater proliferation and diffusion of knowledge on avalanche risk (new studies, research, reports, projections, conferences, trainings, drills, etc.). **<u>General response capacity:</u>** Climate change poses new future scenarios of avalanche risk that will affect overall response capacity. The response to a risk is defined in the Civil Protection Plan for Avalanches in Catalonia. **<u>Avalanche Protection Systems:</u>** Climate Change will not imply changes in avalanche protection systems. Climate Change will imply a new approach in the use of protection systems, since we will have different snowpack, terrain and weather conditions (i.e. advanced melting processes in the calendar, wet snow). Therefore, we will have new avalanche patterns. **Measures/Actions-New requirements/(Stakeholders).** **<u>Information, education and training:</u>** In a context of Climate Change more 'aggressive' dissemination of avalanche forecasting, mapping, information booklets, education and training on avalanche risk to specific and more vulnerable groups is needed. (Risk Managers – ICGC, Non-profit Organisations, Civil Protection, Local Authorities, Ski Resorts). **<u>Civil protection plan protocol:</u>** Review and update the Civil Protection Plan for Avalanches in Catalonia (ALLAUCAT) and municipalities (DUPROCIM, PAM) taking into account the knowledge and information on the influence of Climate Change on avalanche risk. (Civil Protection, Risk Managers – ICGC). **<u>Avalanche Protection Systems:</u>** Review the avalanche protection systems and analyse if they adapt correctly to possible future scenarios and influences of Climate Change (i.e., higher impact pressures). (Civil Protection, Local Authorities, Ski Resorts).

4.3.1.5 Landslides

4.3.1.5.1 Optimistic scenario

LANDSLIDES

Optimistic scenario:
Temperature: +2°C (**RCP 4.5, 2090**)
Precipitation sums: Stabil to slight increase of precipitation sums per anno, largely constant distribution over the year
Heavy rain events: No significant increased intensity and sums.
Wind/storm: No significant changes

Introduction

Landslides are movements of loose and/or solid rock on sliding surfaces (*Dikau and Glade, 2002*). They vary in a wide range of volume and movement speed. Within RECIPE, we focus on hydrological driven, spontaneous, +/- shallow rapid mass movements (landslides) in the loose material layer. They are triggered by the increase of shear stress (e.g., erosion at the toe of the slope, earthquakes, and modification of slope), the decrease of shearing resistance (e.g., water infiltration, raising pore water pressure, weathering, removal of forest vegetation) or both together. Triggering causes a sudden loss of stability for infrastructure and buildings on it. The transportation time is usually short (within minutes range), thus measures have to focus on conditions, which favour landslide occurrence (prevention, preparedness). Once landslides are triggered, it is too late to take any measures.

Heavy precipitation over a longer time span (several hours to days) reduce inner friction angles, raise specific weights of soils and increase the pore water pressure. Thus, trigger landslides (e.g., 1999, 2002 and 2005 in Tyrol and Vorarlberg (Austria), 2018 northern Italy and the south of Austria). Therefore, climate change has significant influence on the occurrence of landslide events.

Anyhow, the development of precipitation sums, seasonal distribution and in particular magnitude and frequency of heavy precipitation in the course of climate change is very insecure. Estimations are, contrary to temperature development, almost qualitative, in parts contradictory and may change from region to region (*Böhm et al. 2010, Einhorn et al. 2015, IPCC 2012*). One must rely on regional and local analysis according to the situation of the area (*APCC 2014, Cloutier et al. 2012; Gariano and Guzzetti 2016; Hagen and Andrecs 2016; Huggel et al. 2012*).

For Austria most analyses predict an increase of heavy precipitation, even more pronounced in the winter half-year (*APCC 2014*), which indicate increasing landslide-activities. At the same time, increasing temperature cause increasing evapotranspiration, resulting in decreasing soil moisture contents and "better system conditions" at the begin of precipitation-events (*Hagen et al. 2020*).

If landslides occur in areas further up the valley, they often reach channels and may develop to, and being assessed as debris flows.

Thus, basing on cost benefit considerations, there are mainly limited efforts to minimize the landslide risks. In many areas, there is no consistent and suitable documentation of landslide events avalilable. This complicates preventive measures as well as the data-based verification whether landslide activities increase as a result of climate change or not.

Hazard	Factors **Internal friction:** The internal friction of soils is determined by the soil characteristics (solid and liquid phase, represented by the grain size distribution and the soil moisture content (SMC)).

LANDSLIDES	
	Temperature rise: Defrosting of permafrost areas (only in high altitudes, above forest line) causes the reduction of internal friction and thus the destabilisation of the loose material layer. 1°C raise of temperature is roughly estimated to shift the permafrost border about 150 m. Hence, the area between the current permafrost line and 300 m above is intended to show (medium term) increasing landslide activities. Besides, rising temperatures in lower altitudes lead to increased evapotranspiration and thus to lower soil water contents leading to lower landslide susceptibilities. If sufficient information on soil properties is available, the effect of temperature rising and decreasing SMC might be simulated for defined sites with soil water balance models. These changes of SMC can be the input for physical based approaches to calculate the change of the internal friction angle. However, there are barely one study dealing with this issue. Summed up, the direct effects of temperature rise on landslides are assumed to be low, due to the comparable small affected area of thawing permafrost. Antecedent precipitation / SMC: Wet system pre-conditions (caused by wet weather conditions over longer periods and/or snowmelt prior to the event) increase the SMC and hence reduce the amount of precipitation, necessary to trigger landslide events. The relevance depends largely on the soil properties as grain size distribution and layer thickness. Up to now, the development of this factor in the course of climate change is discussed controversial. For this scenario no substantially change is assumed. With increasing specific weight (of the soil-layer above the sliding zone) driving forces, as a function of to the slope inclination, increase. It develops parallel to the soil SMC, since the gaseous phase is substituted by the liquid phase. Both increase in the course of rain events. Previously to now, the development of this factor in the context with climate change has rarely been addressed. For this scenario no substantially change is assumed. Heavy precipitation events with high intensity often cause surface runoff, which results in less strong increase of the SMC. During longer precipitation periods (several hours to a few days) with comparatively moderate maximum intensities but high sums, most of the precipitation is infiltrated. These events result in the decrease of internal friction and are the most common triggers of shallow landslides. For this scenario no substantially change is assumed. Strictly speaking, roots do not influence the internal friction; however, they stabilize slopes in a comparable way by basal and lateral reinforcement (Cohen and Schwarz 2017). The effect is influenced by anthropogenic measures (forest management) as well as by climate change in different ways (droughts, beetles, wildfires, wind throw...). Regarding climate change, effects are discussed within the multi-risk hazard chapter. Event analysis showed a striking accumulation of landslides (triggering points) close to (forest) roads as a result of changed (steeper) slopes; a thicker loose material layer (embankment on the valley side) and changed slope water conditions (slope water concentration at sensitive points, *Tilch et al. 2011*). A proper planning and construction of forest roads is essential. The influence of climate change in this regard seems to be negligible.

<table>
<tr><th colspan="2">LANDSLIDES</th></tr>
<tr><td></td><td>
<u>Pore water pressure:</u>
Increasing pore water pressure reduces shear strength due to the buoyancy force, exerted by water (in saturated soils).

<u>Temperature rise:</u>
Rising temperatures cause increasing evapotranspiration, tending to lower soil water contents and increasing storage capacities. Generally, the effect is largely depending on the soil characteristics and the associated storage capacities (strong loose material layers will be more affected than shallow once). The effect of temperature rising on the pore water pressure and its influence on the landslide-activity is low.

<u>Antecedent precipitation/ SMC:</u> Wet system pre-conditions (caused by wet weather conditions over longer periods and/or snowmelt prior to the event) increase the SMC (reduction of storage capacity). This reduces the amount of precipitation, which is necessary to trigger landslide events. The relevance depends largely on the soil properties as grain size distribution and layer thickness. Up to now, the development of this factor in the context of climate change is discussed controversial. For this scenario no substantially change is assumed.

<u>Heavy precipitation events</u>: During longer precipitation periods (several hours to a few days) with comparatively moderate maximum intensities but high sums, most of the precipitation is infiltrated. These events result in the increase of pore water pressure and - in dependence of hydro-geological conditions - are common triggers of shallow landslides especially in areas with slope water concentration (e.g., lower part of slopes, Tilch et al. 2011).

In summary, no significant change is assumed for this scenario. This is due to the assumption of largely unchanged heavy precipitation events.

Measures/Actions, New Requirements/Stakeholders
According to the hazard not clearly changed within this climate change scenario, the measures, requirements and stakeholders are more or less the same as at present (mayors, forest managers, spatial planners, torrent and avalanche control, rescue services, landowners). Regardless of climate change effects, the management of landslide events is, so far, not optimally implemented in Austria. A proper forest management is necessary to preserve the protective effects even in this scenario, basing on the enhanced information of the spatial-temporal distribution of landslide-probabilities. Generally, recommendations, given for the pessimistic scenario are also suitable to improve the current state.
</td></tr>
<tr><td>Exposure</td><td>
Factors
<u>Development of settlements and infrastructure:</u>
Problems mainly concern the mobility and accessibility in the alpine valleys: Roads and railways might be blocked (Einhorn et al. 2015). The development of the <u>number of citizens</u> and associated infrastructure depends on many factors, especially socioeconomic development. Probably, (also) due to climate change there are regional attempts to consider landslide hazards in <u>spatial planning.</u> However, information on the threat from landslides is usually insufficient, climate change scenarios are not considered. Climate change may affect the number of population; however, the impact
</td></tr>
</table>

LANDSLIDES

seems to be only moderate as Fig. 1 indicates. The change of population density in different alpine regions under comparable climate change conditions develops inconsistent. There is a general trend of urbanisation: People tend to leave "isolated" areas, which are often affected by natural hazards and migrate to mostly not or low endangered cities.

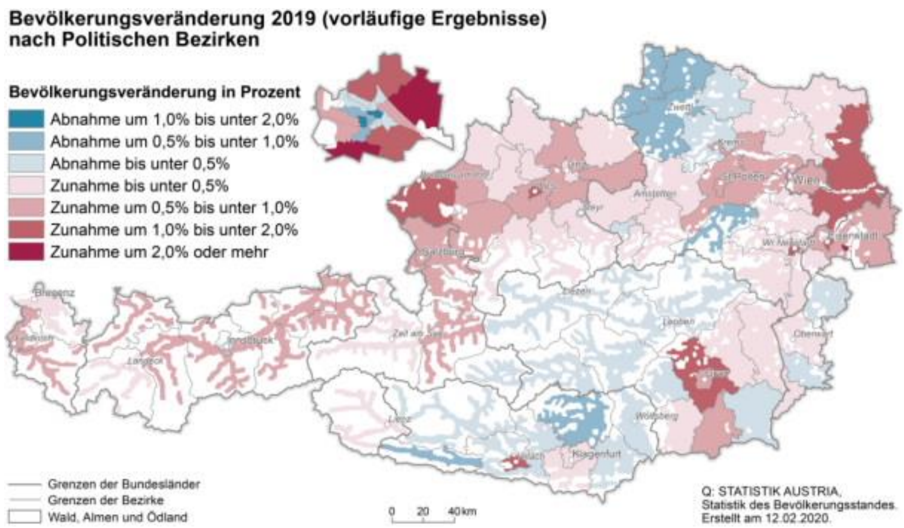

Fig. 1: Population change 2019 of political districts in Austria (Statistik Austria 2020), red: increase, blue: decrease of population.

Anyhow, a large-scale assessment of this issue would extend the frame of this project, no clear changes are assumed.

Development of touristic activities (summer half year):

The development of touristic activities depends on many factors as well: Generally, for the alpine areas summertime and selected regions, a trend of increasing touristic activities is assumed (*BMWFW, 2012*) reasoned by the rising temperatures. However, during extreme precipitation events which cause landslides, usually no significant number of people will be out in the field while the number of people in accommodations or using infrastructure could increase. In sum, we assume a slight increase of exposure caused by climate change in this scenario with clear differences in different regions.

Measures/Actions, New Requirements/Stakeholders

According to the, in sum not significant changed exposure within this climate change scenario, the measures, requirements and stakeholders are the same as at present. Due to the insecurities in this field, monitoring of the ongoing and studies on the further population development is important in order to take suitable and timely actions.

Vulnerability

Factors

Infrastructure and population:

There is no indication for a changed vulnerability of infrastructure due to climate change. Population and tourists could be sensitized to natural hazards through climate change. However, landslide events are (still) rare, thus no significant change is to expect.

LANDSLIDES	
	Response capacities: In the course of climate change due to a lack of consideration of relevant scenarios in the planning, unexpected events (locations, courses of events) will affect response capacities of involved institutions. In addition, increasing challenges in other sectors (e.g., health care) may make it difficult to ensure the availability of sufficient resources, which may lead to a moderate decrease in response capacities. **Mitigating negative (economic) effects:** Within this scenario, the change of the existing disaster event management system seems not to be essential, but in some cases advisable, concerning e.g., financial support of damage management and recovery, which differs from region to region and is to a certain extent "random". The establishment of a uniform mandatory insurance for natural hazards (already existing in Switzerland) could help to reduce the (economic) vulnerability of the population. Summed up, a slight increase of vulnerability in this scenario is likely. **Measures/Actions, New Requirements/Stakeholders** According to the in sum only slight increase of vulnerability within this climate change scenario, the measures, requirements and stakeholders are mainly the same as at present. Information of population, tourists, and decision makers in the course of climate change can increase the readiness dealing (also) with hazards caused by landslides, accepting restrictions and providing necessary resources.

4.3.1.5.2 Pessimistic scenario

LANDSLIDES	
Pessimistic scenario: Temperature: +4°C (**RCP 8.5, 2090**) Precipitation sums: Decrease of precipitation sums per anno (approx. 10%), adverse distribution of precipitation over the year with concentration in winter and long dry periods in summer Heavy rain events: Significant increased intensity and sums (+25% -according to +7%/°C potential air moisture). Wind/storm: Increase of storm events. **Introduction** Analyses and assumptions for this scenario refer to the first scenario (optimistic) and focuses on deviating facts.	
Hazard	**Factors** **Internal friction:** Temperature rise causes the defrosting of permafrost areas. 1°C raise of temperature is roughly estimated to shift the permafrost border about 150 m. Thus, the area between current permafrost line and 600 m above is intended to show (medium term) increasing

landslide activities. In this scenario, areas with higher soil moistures, rising temperatures lead to increased evapotranspiration and thus to lower soil water contents resulting in lower susceptibilities. In dryer regions, this effect might be low due to the already limited water supply. Summed up, the direct effects of temperature rise on landslides are assumed being moderate due to the comparable still small affected area of thawing permafrost.

Root reinforcement is affected by climate change in this scenario directly and indirectly in several ways. Longer drought periods will weaken the trees and thus root reinforcement, especially if the forests are already not optimal adapted on the site conditions. This is e.g., the case for a lot of picea abies stands in lower Austrian altitudes. Furthermore, a decrease of root reinforcement caused by beetle calamities, wind throws, and wildfire is predictable. However, these chains of effects are seen as multi hazard risks. The effect of wildfire on land slide activities is discussed in more detail in the multi-hazard scenario

Increasing intensities or frequencies of storm events will not influence landslide susceptibility directly. More air circulation increases evapotranspiration and can lead to better system conditions before events. However, this effect is assumed to be small.

Antecedent precipitation / soil moisture: Wet system pre-conditions might become less frequent. Thus, a higher amount of precipitation will be necessary to trigger events, the relevance of this factor gains importance with the increasing storage capacity of the loose material layer above the sliding zone. The result will be a moderate decrease of landslide susceptibility in these areas.

Heavy precipitation events**:** Steep, instable slopes are in a state of equilibrium. Comparable minor increased precipitation sums and/or intensities of heavy precipitation events may cause disproportionate effects. Hence, the rise of 25 % event precipitation will increase the landslide activity significant!

Summed up, for this scenario, a significant increase of landslide activity is predicted, reasoned by the increasing magnitude of heavy precipitation events and concentrated on slopes which are currently just stable.

Measures/Actions, New Requirements/Stakeholders
Challenges for the institutions involved in the different sections of the risk management will increase.

Knowledge and methods:

This task mainly contains preventive measures. Currently, landslide hazards are only partially included in existing hazard maps. Event documentation is incomplete and partly unsuitable.

First of all, the event documentation needs to be improved as a basis for completed and homogenized landslide hazard maps. With help of new available technologies, information on the spatial pattern of soil properties and soil moisture are to compile, since the main problem for modelling landslide susceptibility (for large areas) is the lack of “model input data”. Sufficient spatial data of soil characteristics allow the use of physical based models for landslide disposition modelling, followed by the modelling of range and spreading of the triggered landslides (determination affected areas). Basing

	on a comparison of status quo- and scenario-results (including climate change effects), areas with significant increased landslide activities (in future) can be identified. In a final step, practical approaches to gain maps considering climate change scenarios and risk assessment, need to be developed, tested and implemented. The measures themselves may vary according to local conditions and must be developed by experts on the basis of appropriate information on relevant factors. At least, proper management in forests with protective function is necessary to preserve and strengthen the protective effects. However, this effect is limited. Technical measures for landslides are usually complex and expensive (slope drainage, protection of objects) and require suitable information about the landslides (location, forces, etc.). **Involved institutions and stakeholders:** Enhanced support is needed for the bundling of scientific capacities of various disciplines across national borders. The intensified contact between science and practitioners is a further task to overcome future challenges in a (more) efficient way with the focus on prevention and preparedness. As the root reinforcement can be mainly seen as a function of forest density and breast height diameter (BHD), forest managers and responsible authorities should care for well structured, site adapted forests with continuous rejuvenation. Research is challenged to improve information on suitable mixes of tree species, regarding the changed climate conditions and the root reinforcement effects. So far, information in the literature is rare and inconsistent. Area-wide information of the spatial-temporal distribution of landslide-probability with focus on “new endangered areas” has to be compiled.
Exposure	**Factors** **Development of settlements and infrastructure:** How the number of citizens and thus the associated infrastructure will develop under the assumed adverse climatic conditions is not clear. The negative impact of climate change on the socioeconomic development and increased natural hazards may lead to a downward trend in population, particularly in rural areas. Due to the increase of endangered areas, a raise of exposure is likely, which will vary on a local scale from marginal to significant. **Development touristic activities (summer half year):** Generally, for the alpine areas and selected regions, a trend of increasing touristic activities is assumed (BMWFW, 2012) based by rising temperatures. Due to a possible global adverse impact of climate change on the economy, this could be countered. On average, we assume a moderate increase of exposure caused by increasing endangered areas in this scenario. **Measures/Actions, New requirements/Stakeholders** Although the increase of exposure due to landslides is estimated as in sum moderate within this climate change scenario, effects can vary widely on a local scale. Thus, new or significant more endangered areas need to be identified. The gained hazard maps (procedure described in the chapter methods and knowledge) need to be intersected with spatial information on infrastructure to identify areas at risk.

	Besides, spatial planning to keep areas free that will be at risk in the future, hazard reduction measures (preventive), early warning and evacuation plans can reduce the exposure of people. In Austria, the mayors are responsible for the implementation of such tools. They are supported by federal or national institutions (development) and rescue forces (practice, execution). Due to the insecurities in this field, monitoring of the ongoing and studies on the further population development is important.
Vulnerability	**Factors** **<u>Infrastructure and population:</u>** Population and tourists could be sensitized to natural hazards through climate change. However, in areas where the endangerment by landslides is new or significant raised, people might be more endangered, since they are not used to deal with this new hazard-situation. In such areas also settlements and infrastructure might be more vulnerable, because this kind of hazards was not taken into account during construction. Thus, in average a slight increase of vulnerability can be expected. It will vary on a local scale from marginal to significant depending on the experience in dealing with landslides. **<u>Response capacities:</u>** In the course of climate change due to a lack of consideration of relevant scenarios in the planning, unexpected events (locations, courses of events) will affect citizens and response capacities of involved institutions. In addition, increasing challenges in other sectors (e.g., health care) may make it difficult to ensure the availability of sufficient resources, which may lead to a moderate decrease in response capacities and resilience. Summed up, a moderate increasing vulnerability in this scenario is likely, mainly depending on the (assumed) socioeconomic development. **Measures/Actions-New requirements/Stakeholders.** **<u>Information and preparation of population:</u>** Information of population, tourists, and decision makers in the course of climate change can increase the readiness dealing (also) with hazards caused by landslides, accepting restrictions and providing necessary resources. **<u>Legislation and organisation:</u>** Clear competences and responsibilities (for landslide management) have to be established, which institutionalize the cooperation of the actors. A concentration of responsibilities and the availability of sufficient resources in times of economic challenges have to be aimed continuously. Hazard maps in combination with settlement and infrastructure information must be the basis to adapt existing operational plans. **<u>Mitigating negative (economic) effects:</u>** Within this scenario, the establishment of a uniform mandatory insurance for natural hazards (as already existing in Switzerland) is recommended to reduce the economic vulnerability of the population and companies.

4.3.1.6 Rockfalls

4.3.1.6.1 Optimistic scenario

ROCKFALLS

Optimistic scenario:
Temperature: +2°C (**RCP 4.5, 2090**)
Precipitation sums: Stabil to slight increase of precipitation sums per anno, largely constant distribution over the year.
Heavy rain events: No significant increased intensity and sums.
Wind/storm: No significant changes.
Wildfire: No significant increase of frequency and magnitude.

Introduction

Rockfalls are gravitational mass movements in falling, rolling or bouncing motion, which release in existing solid rock formations or from loose material layers (slope debris, debris fans, moraines, etc.). The basic prerequisite (predisposition) for the formation of rockfalls (from rock faces) are weaknesses like fissures, schistosity, bankings, which were already formed millions of years ago by sedimentary deposition (bankings), ductile deformation (schistosity) and brittle tectonics (fissures). In the course of the natural rock cycle (orogenesis - erosion - deposition), these cracks form the "predetermined breaking points" for the formation of rockfalls. Gravitational mass movements are mainly controlled by gravity. However, climatic conditions play a major role in triggering and partly also in terms of process dynamics (*APCC, 2014*).

Relevant triggering factors - i.e., for crack failure - are material fatigue (failure of material bridges within the rock formation), mechanical destabilization by vegetation (penetration of roots into fissure systems) and fissure or pore water pressure as well as freeze-thaw cycles (freeze-thaw changes), earthquakes, storms (leverage by tree roots) and human construction activities such as slope undercutting.

Heavy precipitation, freeze-thaw cycles and storms may in future have more triggering moments, although this development is still uncertain regarding increasing the frequency and magnitude of rockfalls. The so far unproven correlations between increased heavy precipitation events and increased rockfall activity (*Gruner, 2008 & Sass and Oberlechner, 2012*) are based on a look into the past and therefore do not mean that no significant correlations can be established in the future.

Among other things, it is also postulated that an increase in activity can be observed especially in those process groups in which water is involved as a driving force (Fuchs, 2010). The more water enters the atmosphere due to increased temperatures and is released by the atmosphere as precipitation, the greater the possibility of triggering moments will be, even if rockfall is not only triggered by meteorological influences (material failure, earthquakes, etc.). There are indications of increasing heavy precipitation, which are even more pronounced in the winter half of the year and in Central Europe (*Coumou and Rahmstorf 2012; Hoegh-Guldberg et al. 2018; Madsen et al. 2014*).

The degradation of permafrost due to rising temperatures will be highly relevant. The increase of rockfall frequency above the permafrost boundary is (with high agreement and medium evidence) very likely (APCC, 2014). Increased rockfall activity is seen as a direct and possibly surprisingly fast reaction to warming in permafrost regions (Gruber et al., 2004a).

<table>
<tr><th colspan="2">ROCKFALLS</th></tr>
<tr><td colspan="2">Permafrost limits the depth range of destructive processes such as frost cycles and the deep penetration of water into the rock (www.slf.ch). In addition, heavy rainfall above rockwalls with permafrost can lead to large amounts of lateral energy and cause the ice in cracks to warm up. Studies by Harris et al. (2009) show, that the shear strength of a rock system decreases already at temperatures around -1.5 °C, thus the rock stability is affected (APCC, 2014).

The zones of maximum frost change intensity will shift upwards. In the short term, therefore, a higher rockfall intensity can be expected at the corresponding altitudes due to the heavy disassembling of rock surfaces. But in the medium term (in decades to centuries) a stabilization can be expected (APCC, 2014).

These forecasts - and thus an increased frequency of rockfall above the current permafrost limit - are in turn contradicted by the assumption that the presence of permafrost in rock faces generally increases the effectiveness of frost weathering (Murton et al., 2001), which is why even higher rates of rockfall can be observed in rock faces filled with permafrost (Sass, 2010).

However, the interpretation of past events suggests that an increased frequency of rockfalls due to climate change from areas of degrading permafrost (especially in north-exposed locations) can be regarded as fairly certain, while in permafrost-free areas (e.g., those of the Austrian alpine region) no increase in rockfall events has been observed in recent decades (APCC, 2014). It should be noted here that event data collection was very inhomogeneous, especially in earlier decades, and that the event documentation in recent times is being carried out more comprehensive.

In areas below permafrost, e.g., where protection forests are located between potential release areas and potential assets, the forest structure will play an immensely important role, especially under the influence of climate change. In areas where forest disturbances occur (wildfires, bark beetle infestations, etc.), a large-scale reduction of the protective effect can be the consequence, and therefore the risk potential and the number of values exposed to the danger can be considerably increased.</td></tr>
<tr><td>Hazard</td><td>Factors
<u>Rise of temperature - degradation of permafrost:</u>
With a future temperature increase of +2° and under the greatly simplified assumption of a linear relationship between permafrost distribution and air temperature, the lower permafrost limits would rise by around 300-400 (Schrott et al., 2012b).

The general permafrost limit in the Alps is currently around 2500 m above sea level (www.slf.ch), preferably in northwest over north- to northeast exposed terrain. The underlying assumption would therefore correspond to a shift in the permafrost limit from 2500 m to 2800-2900 m.

<u>Wind, wildfire, precipitation:</u>
The hardly changing scenery of wind speeds, susceptibility to forest fires and heavy precipitation does not suggest an increase in associated rockfall activity or magnitude increase.

Measures/Actions-New requirements/Stakeholders

<u>Mainly affected assets:</u>
Due to the widespread occurrence of permafrost starting at an altitude of around 2500 m, areas with increased rockfall activity would increase significantly (in high alpine</td></tr>
</table>

<table>
<tr><th colspan="2">ROCKFALLS</th></tr>
<tr><td></td><td>regions). In particular, ski resort infrastructures or alpine tourism facilities would be exposed to an increased risk of rockfall.

<u>Possibilities of process prevention:</u>
General measures that prevent processes can hardly be taken in such high mountain regions that are affected over such a large area. The establishment of technical protection structures cannot counteract this widespread phenomenon. On the one hand, biological forest measures are fundamentally to prevent rockfall (since the mechanical action of roots tends to have a triggering effect in the area of the rockfall) and, on the other hand, these measures for protection in the transit area cannot be implemented due to the altitude.

For the affected stakeholders (ski area operators, mountain gastronomy, alpine clubs, hunting, etc.) the direct technical prevention of increasing rockfall is only possible and financially reasonable on selectively hotspots (with explicit reference to buildings).

<u>Maps and monitoring:</u>
It is important to establish reliable, area-wide permafrost maps and permafrost monitoring. Permafrost maps are primarily important for the geotechnical support of construction sites in high mountain areas and also as an indicator for future rockfall and landslide processes. Permafrost monitoring (which is already being carried out at high-altitude research stations) will provide far-reaching and ongoing insights into the response to climate change.</td></tr>
<tr><td>Exposure</td><td>Factors
<u>Alpine tourism:</u>
The extent to which changes in exposure can be attributed to future climate change impacts cannot be estimated at this point. Whether, for example, lower-lying ski resorts and lifts will have to close due to lack of snow.

It´s a fact that leisure activities in alpine terrain show an increasing trend in many regions. One indicator of this is, for example, a time series of overnight stays in the core alpine regions of North & South Tyrol, which shows, that they increased by 10% in the decade between 2005 and 2015. A further illustration of the increase in the number of overnight stays by individuals, especially in alpine terrain, is provided by an estimate of the Association of Sports Goods Manufacturers and Sports Equipment Suppliers in Austria. They assume that 600,000 - 700,000 active ski tourers exist in Austria, which corresponds to a share of almost 8% (!) of the total population. In Germany the number of ski tourers has tripled in the last 15 years. The trend is upwards (https://www.tt.com). Even if the rockfall hazards have so far affected ski tourism to a lesser extent due to seasonal occurrence, the previous figures are an indicator of the generally increasing exposure of people in alpine terrain.

But it is not only the lively ski tourism that causes a large number of individuals in the alpine region, but also the presence of hiking and cycling tourists in the summer months. These individuals are not only exposed to potential rockfall hazards while practicing the sport itself but also when travelling to the starting points of their tours.</td></tr>
</table>

ROCKFALLS

The German Alpine Club provides a very up-to-date indication of the increased stay of people in the alpine region. The association notes, for example, that in the course of the corona virus pandemic and the end of the restrictions on access to the starting point in spring, more people than ever before have been in the Alps (https://www.spiegel.de).
In the Swiss Alps, a long-term average (1946-2016) of 1.2 people per year die as a result of rockfall (Andres, 2017). This number could rise as the number of visitors increases and the permafrost in the mountains thaws.

Traffic routes relevant to permafrost also exist at high-altitude alpine passes. Therefore, passes in Switzerland, Italy or Austria are repeatedly affected by rockfall. With the naturally increasing volume of traffic, exposure and risk could also increase if the frequency of rockfall increases due to permafrost. However, this assumption cannot be seriously quantified.

Construction activities in alpine terrain:

The construction of alpine infrastructures and the establishment of protective measures for alpine infrastructures lead to an increased exposure of construction workers and construction site traffic to alpine natural hazards.

Measures/Actions-New requirements/Stakeholders

High alpine construction sites and additional alpine infrastructure:

This increased exposure can cause potential problems, especially for tourist infrastructure and exposed transport routes (*Lan et al., 2010; Krumm et al., 2011*). For high alpine construction sites, temporary technical protection measures against rockfall and other alpine hazards would have to be installed to reduce exposure.
Particularly in the alpine mountain areas, that have already been developed for tourism, there is still a continuing trend towards the development and expansion of facilities and alpine "leisure parks" (https://www.alpenverein.at). In the Alps - especially in Western Austria - a large number of new kilometers of ski slopes, mergers of existing ski areas, construction of water reservoirs for snow farming, new construction of alpine gastronomy, etc. are currently being planned. Every gondola station, restaurant or bike park, which is additionally integrated into the alpine landscape will, under the condition of a rockfall hazard in the catchment area, initially represent a significant increase in exposure and, with corresponding exposure and numbers of visitors, an intensification of vulnerability. Therefore, such projects must also be examined as to their absolute necessity.

Recreational behaviour:

Based on the scenario of increased rockfall activity and simultaneously increased frequency of individuals in the alpine area, it is of great importance to sensitize the population.

The individuals must be able to accept e.g., future closed routes due to hazard potential and to either pass or avoid self-perceived danger areas quickly. The relevant stakeholders must increasingly communicate the rising danger situation (also in their own interest) and also take risk-reducing measures in the future. Specific risk analyses at hotspots in the alpine region (e.g. by means of "R.A.G.N.A.R" - Risk Analysis of

<table>
<tr><th colspan="2">ROCKFALLS</th></tr>
<tr><td></td><td>Gravitational Hazard in alpine Regions) could already help to reduce exposure (e.g. seasonal road closures).</td></tr>
<tr><td>Vulnerability</td><td>Factors

Change of vulnerability?
Regarding to this study it´s not possible to assess whether a change in vulnerability per se will occur in the context of climate change. To achieve that, future developments and achievements in the field of construction technology would have to be examined.

In general, vulnerability must be reduced to a minimum by means of the current technical state-of-the-art. Official requirements to ensure the safety of and in buildings continue to play a central role.

Measures/Actions-New requirements/Stakeholders.

<u>Structural defence and authority requirements:</u>
For many years, geotechnical investigations have had to be carried out during construction activities in the high mountains. This concerns on the one hand the suitability of the building ground / the building ground risk due to the permafrost in the building ground per se (subsidence in the building) and on the other hand the latent rockfall activity above the infrastructures in some places and increased due to permafrost degradation.

In many places, developed for skiing, protective dams and protective nets must be installed not only to prevent and ward off avalanches, but also to protect against rockfall hazards.

The high-altitude construction sites pose a particularly great challenge: Shortened construction time windows due to the exposure and the earlier onset of winter or later start of possible construction activities in spring/summer as well as the difficult accessibility (construction site traffic).

<u>Required spatial planning:</u>
Should the trend towards permafrost melt continue, those responsible (railroad companies, restaurateurs, alpine clubs, etc.) would have to take more account of rockfall in their infrastructures. Instead of technical measures, they would have to rely more on spatial planning measures or avoidance strategies. Here the building authorities have to set the right guidelines which support by clear regulation.</td></tr>
</table>

4.3.1.6.2 Pessimistic scenario

<table>
<tr><th colspan="2">ROCKFALLS</th></tr>
<tr><td colspan="2">Pessimistic scenario:
Temperature: +4°C (RCP 8.5, 2090)
Precipitation sums: Decrease of precipitation sums per anno (approx. 10%), adverse distribution of precipitation over the year with concentration in winter and long dry periods in summer.
Heavy rain events: Significant increased intensity and sums (>25% - according to +7%/°C potential air moisture).
Wind/storm: Increase of storm events.
Wildfire: Increase of frequency and magnitude.</td></tr>
<tr><td>Hazard</td><td>Factors
<u>Rise of temperature - extensive degradation of permafrost even in the highest mountain regions:</u>
With a future temperature increase of +4° and under the greatly simplified assumption of a linear relationship between permafrost distribution and air temperature, the lower permafrost limits would rise by about 600-800 m (Schrott et al., 2012b).

The general permafrost limit in the Alps is currently around 2500 m above sea level (https://www.slf.ch), preferably in northwest over north- to northeast exposed terrain. The underlying assumption would thus correspond to a shift in the permafrost limit from 2500 m to over 3300 m, thus reaching the topographically highest areas in many regions of the alps.

<u>Increased respectively more intensive water input due to heavy precipitation:</u>
Global warming means that the atmosphere can absorb a higher amount of water vapor, which in simple terms can lead to more precipitation. A temperature increase of 1° allows the atmosphere to absorb 7% more water vapor. At 4° this corresponds to a value of 28%, or almost a third.

As already mentioned, water in the form of precipitation and melt water is usually the driving force of mass movements (APCC, 2014). The intrusion of water into existing fissure systems of rock formations increases the hydrostatic fissure water pressure, which often drives the dynamic disassembling process (Krähenbühl, 2014) and prepares or triggers rockfall. Increased loads on the rock system due to an increased frequency and magnitude of heavy precipitation events can be assumed. In addition, with a temperature rise of 4°, precipitation will also fall more frequently in higher regions as water instead of snow. In contrast to snow fall, fissure systems are more concentrated and faster doped with water through heavy rain events.

<u>Increase of storm events:</u>
Even if a general increase of ground-level winds cannot yet be sufficiently proven (APCC, 2014), this is a factor in the development of the rockfall risk situation. Regionally increasing wind speeds or more frequent storm events, in combination with e.g. (still numerous existing) spruce monocultures, can be triggering factors for rockfall.</td></tr>
</table>

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	In the course of a wind throw in a forested area, for example, stones and small blocks adhering to the root plate can be mobilized by levering out the root plate. As a result, areas where stones and small blocks can be detached are no longer limited to terrain steeper than 50° (*Mölk & Rieder 2017*), but can also increasingly occur in forested areas with an inclination of down to 34° (*Perzl et al. 2015*). **<u>Increased risk of forest fire, increased fire severity:</u>** The general risk of forest fires will increase due to lower rainfall amounts over the year and presumably more frequent, longer-lasting droughts (especially at south-exposed locations in inner-alpine dry valleys). Although forest fires have hardly any direct impact on frequency and magnitude of rockfall hazard, the risk of rockfall can be significantly increased by a high loss of the protective function of forests after severe fires. Science assumes a reduction of up to -80 % of the basal area of a stand after severe fires (*Maringer et al., 2020*). This significantly increases the run-out lengths and energies of rockfall components. **Measures/Actions-New requirements/Stakeholders** **Measures in high alpine terrain:** As already in the optimistic climate change scenario, the widespread occurrence of permafrost from an altitude of generally around 2500 m above sea level would lead to a marked increase in areas with increased rockfall activity (to over 3300 m above sea level). This will cause also a significant increase in the highest located infrastructure, such as the Sonnblick observatory in Austria or cable car stations and summit restaurants of the ski resorts located in the central alps. In addition to the measures already mentioned in the optimistic scenario, buildings in the highest alpine terrain would have to be increasingly stabilized by e.g., shotcrete injections. Gondola stations would probably have to be founded on hydraulically adjustable foundations (as in the Tyrolean Ötztal) as standard in order to be able to react to the rapid changes in the subsoil conditions caused by melting permafrost (https://www.derstandard.at). The challenges and measures in the high alpine terrain would be comprehensive, but due to the far-reaching effects of permafrost melt, not all of them could be mastered with the help of structural engineering solutions. **<u>Measures in lower areas near settlements, industry and transport infrastructure:</u>** For the pessimistic climate change scenario, it can also be assumed that primary protection measures such as e.g., bar anchors, cross-linkages, concrete seals, etc. will have to be carried out more frequently also in the area near the valley far below the permafrost line, since heavy precipitation, wind, freeze-thaw changes, etc. also destabilize ice-free rock faces more frequently.
Exposure	**Factors** **<u>Tourism and recreational activities:</u>** Due to permafrost degradation above 2500 m the danger of rockfall is most significant for individuals in alpine winter and summer tourism, especially in sectors exposed in the north-west to north-east. Because of more often heavy precipitation

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	events and also increased rockfall triggering by wind influence, not only alpine recreational activities but also activities taking place in the valley bottom area are added to this risk. The number of visitors in climbing gardens, high ropes courses, roller coasters, golf courses, bathing lakes etc. is probably increasing - regardless of the climate change scenario. Just in July 2020 a rockfall in the Austrian "Bärenschutzklamm" (a highly frequented canyon) caused 3 deaths. Exposure will also increase in valley locations away from the areas affected by permafrost. **<u>Settlements, Traffic, Transit:</u>** If the frequency and / or magnitude of rockfall also affects the settlements and transport areas due to increased precipitation peaks, more severe forest fires and storms, society's exposure to rockfall would also increase many times over. The amount of land available for settlements is limited, especially in alpine valleys, and will become even more limited in the light of a new threat posed by climate change. Increasing mobility of our society (commuters, leisure time activities, etc.) and steady growth in traffic volume alone would entail a higher exposure (probably independent of a climate change scenario). International transit (via motorways and train connections) across various alpine axes, would also be increasingly severely impaired due to the increased hazard potential along the transport routes. Especially large forest fires would lead to suddenly increased exposure by losing the comprehensive protective forest effects against rockfall. The run-out lengths and energies of rockfall would be considerably increased after severe fires. **Measures/Actions-New requirements/Stakeholders.** **<u>Individual behaviour:</u>** In the pessimistic scenario a sensitization of the population is not only necessary with regard to rockfall hazards in high alpine terrain, but also in settlement areas, in homes and industrial areas. In order to reduce the exposure to rockfall hazards, planning considerations are also necessary. For example, exposure within one's own living area can be reduced by locating frequently inhabited rooms such as bedrooms and living rooms on the side of the house facing away from the (rockfall) slope. These measures could also be made compulsory by official regulations. With regard to roads that are particularly prone to falling rocks (which are already known in some regions), the population should be sensitized to greater attentiveness and personal responsibility as well as awareness of the dangers. For example, on a voluntary basis, journeys that are not absolutely necessary should be avoided during heavy rainfall or storms. **<u>Authorities:</u>** In the past decades, a number of building sins have been committed with regard to the building up of houses and entire settlements. This must not be repeated, especially if the hazard situation becomes more acute due to climate change. This is where local and regional spatial planning, i.e., from the mayor to the responsible persons in the districts and the federal states, are responsible to take the right steps.

<table>
<tr><th colspan="2">ROCKFALLS</th></tr>
<tr><td></td><td>If sudden and/or persistent rockfall events occur in areas frequented by people, politicians are increasingly called upon to take measures such as official bans on access. This has already happened in the Tyrolean municipality of Gries am Brenner, where a church and a football field were closed due to regular rockfall. (https://tirol.orf.at).

The authorities and experts should also increasingly monitor transit hotspots on a permanent basis (e.g., weather warnings) in order to block roads and reduce exposure (e.g., at Hahntennjoch in Imst, Tyrol).</td></tr>
<tr><td>Vulnerability</td><td>Factors

Settlements:
The change in vulnerability of e.g., facilities such as industrial buildings, housing estates etc. cannot be assessed at this point. It´s clear that in locations where the potential for rockfall is present, buildings must be constructed in a safe manner to minimize vulnerability. The severity of the impact on a building depends particularly on its magnitude. Due to a number of uncertainty factors, this magnitude can´t be approximated in the context of this climate change scenario.

<u>Leisure facilities integrated into nature:</u>
A high degree of vulnerability would be particularly relevant for leisure facilities. These facilities are often freely accessible or not separated from the outside terrain in terms of structural engineering:
Users are therefore often exposed to natural hazards without protection. The extended development of climbing gardens, adventure parks, football pitches, etc. can considerably increase vulnerability. This would affect above all regions with a relevant tourist character.

Measures/Actions-New requirements/Stakeholders

<u>Traffic routes:</u>
Traffic routes are extensively networked and often run underneath steep rock sections. In order to reduce the vulnerability of facilities and road users these routes should be increasingly protected by technical measures (e.g., currently the L76 Landecker Strasse in Tyrol - https://www.tt.com).

<u>Settlements:</u>
Rockfall protection nets above existing settlement areas, which is becoming increasingly necessary anyway, would have to be continued due to greater vulnerability (many houses, indeed entire settlements, are located below unstable rock formations).

Municipalities should take local spatial planning in conjunction with the hazard zone plans. The currently only undifferentiated areas for rockfall and landslides ("brown reference areas") would have to be taken up in a more differentiated way and re-mapped on the basis of physical process simulations.</td></tr>
</table>

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	This should make it possible to determine rockfall energies more precisely. On this basis, building regulations should be issued and less susceptible buildings should be constructed. The services provided by protection forests in the face of natural hazards should be integrated even more into risk-based natural hazard management. The establishment of well-mixed protection forests with a highly differentiated tree age structure is the basis for maintaining the preventive effect. Where technically and biologically measures could not prevent rockfall events (due to their frequency and/or magnitude), avoidance strategies (e.g., building ban zones) become more important in order to reduce vulnerability and, above all, exposure. In many alpine valleys, this poses major challenges for local and regional decision-makers due to population development and increasing settlement pressure.

4.3.2 Multi-risk analysis

4.3.2.1 Storms/Wildfires – Wildfires/Storms

STORMS/WILDFIRES – WILDFIRES/STORMS Cumulatively effect (possibly mediated by insect outbreak)
1. Multi-risk scenario(s). Two years ago, a large-scale winter storm event hit the forest surrounding the city of Freiburg, a densely populated urban area surrounded by forests. It left significant volumes of down timber, as well as patches of standing and lying deadwood interspersed in the forest. Due to another dry and hot summer, this storm-induced debris constitutes a significant fuel load for potential wildfires. Particularly the interspersed patches might allow fires to spread into neighbouring stands unaffected by the initial wind disturbance. Long term, this produces more deadwood and thus fuel for potential forest fires, that can easily spread due to the horizontal and vertical fuel continuity. In the short term, there is a risk of fire spreading into the wildland urban interface. A large scale insect outbreak is exacerbating the risk. Drawn to the wind damaged wood, insects and pathogens have infested the woody debris on part of the area and are beginning to spread into neighbouring stands unaffected by the initial wind disturbance. Furthermore, the large amounts of standing dead wood make it dangerous to work in these areas, limiting options for e.g., proactively creating fuel breaks. Because the forest is popular among the locals for recreating, there is a certain risk for ignition caused by careless behaviour, e.g., cigarette buds or camp fires that – while officially not allowed during the summer months - do occur in designated and undesignated spots.

If a fire does ignite, it would likely lead to a temporary reduction in air quality, but more importantly, a further reduction in forest ecosystem services, such as water provision and quality, erosion control, scenic beauty, and potentially reduce chances for successful (natural) regeneration.

2. Measures/Actions.

Measures proposed were developed collaboratively by project partners: FVA/Carolin Maier (STORM), and the project's fire experts from ISA/Conceição Colaço and Iryna Skulska, Pau Costa/Guillem Canaleta, but without consulting civil protection experts.

Key issues to consider due to multi-risk situation – storm (winter) followed by fire (summer):

- Deadwood = amount of fuel increases, horizontal and vertical fuel continuity increases following the storm (natural hazard risk).
- Safety concerns limit active work in stands with standing deadwood such as creating fuel breaks etc. (natural hazard risk).
- WUI context – fire might affect properties not affected by the initial disturbance (storm) (exposure risk, vulnerability risk).

Key issues to consider due to multi-risk situation – fire (summer) followed by storm (winter):

- Burned forest stands are more susceptible to wind and likely to fall in a storm event.
- New forest edges created by the fire are also more susceptible to wind disturbance as the trees have not adapted to the mechanical forces of wind.
- Danger of working in burned areas due to falling branches or trees.

Prevention phase (winter storm, summer fire):

- Informing the public about forest fire risk (e.g., media statements informing fires are prohibited, signs indicating current fire danger etc.) (local authorities, weather service, forest management agencies).
- Checking for violations of fire restrictions in popular spots to reduce risk of ignition (local authorities, forest managers).
- Close access to wind disturbed area when fire risk is high to reduce risk of ignition.
- Establishing fuel breaks, reducing (ladder) fuels in strategic locations (regarding fire behaviour), and around critical locations that are either high risk or would help contain potential fires, e.g., important access routes, popular camping areas. These measures are limited by safety concerns in areas with standing dead wood. Decisions on where fuel breaks are likely to be effective and safely implemented require close collaboration between forest managers /owners, civil protection and firefighters (forest management agency, firefighting units).
- Encouraging private property owners in the wildland urban interface to clear shrubs and tall vegetation around the immediate perimeter of their house (local authorities, insurance enterprises, fire service, rural officers and civil protection foresters).
- Develop and overlay risk maps for fire and storm for a multi-risk assessment (cartographic institute, forest service/ research institute, meteorològic services, civil protection).
- Priority of actions – dependent on forest fire risk (prevention phase) and returning population to normality (Recovery phase after the wind storm, and prevention for the fire risk.).

Additional considerations during the prevention phase (summer fire- winter storm):

- Clear burned trees around essential infrastructure to avoid (more) damage, facilitate access, prune the more fragile tree branches if putting in danger infrastructures.
- Conduct a risk analysis based on fire severity – priority of action in case of wind storm.
- Conduct a risk analysis based on newly created forest edges, burned standing trees.
- Consider CC induced changes in wind direction in risk analyses.

Preparation phase:

- Acquire/maintain appropriate equipment for forest fire fighting – including small vehicles and mobile units (e.g., mobile firefighting unit on a pick up, fire rucksack, patches, shovels etc.) (forest management agency/owner, fire fighting units).
- Train firefighting personnel in the proper use of this equipment, as well as based on analysis of past storm-fire event (forest management agency/owner, firefighting units).
- Implement fire drills to familiarize forest fire fighting personnel (from firefighting units and forest management units) with their tasks and each other.
- Develop an evacuation protocol (civil protection authorities, local authorities).
- Establish and test an alert system to inform the public about a fire event (civil protection authorities, local authorities).
- Develop forest fire risk maps indicating storm/fire risks, as well as indicating areas affected by past storm or fire disturbance (forest management agency, fire department).
- Collaboration between forest owners or managers and fire department at local and district levels to development a forest fire management plan that
    - Assigns responsibilities in case of forest fires;
    - Identifies areas/infrastructure most at risk (e.g., WUI) or critical for containing a potential fire;
    - Outlines firefighting strategy/tactic for different scenarios.
- Collaboration between forest owners or managers and fire department, local authorities, and civil protection authorities to develop a crisis management plan that
    - Clearly assigns responsibilities in case of forest fires, including communication with the public;
- Activate surveillance system, particularly on wind disturbed area, other high risk spots, like camp sites, popular parking lots etc.

Response phase:

- Activate alert system to inform the public (civil protection authorities, local authorities), particularly early warning systems.
- Revision and communication of evacuation zones in case of wildfires /Storms (local authorities, civil protection).
- Implement fire management plan (fire department, forest management agency firefighters)
- Implement crisis management plan (fire department, forest management agency firefighters, civil protection authorities, local authorities).
- Pay particular attention to areas strongly affected by storms as a critical point where fire behaviour can intensify due to fuel accumulation. Fire services should include this information in the decision-making.

Recovery phase:

- Evaluate & improve forest fire management plan (fire department, forest management agency firefighters) - lessons to be learn!
- Analyse past fire events that followed storms to train responders for coming events.
- Evaluate & and improve crisis management plan (fire department, forest management agency firefighters, civil protection authorities, local authorities).
- Integrate forest resilience into forest and wildlife management objectives: e.g., increase forests resilience to fire through silvicultural measures (choice of species for resilience to storm and fire risks) in the restoration of burned areas, pro-active fuel load reduction in critical locations e.g. pruning and thinning along forest roads, etc. (forest management agency/forest owner).
- Implement soil protection measures that will benefit its recovery from the multiple disturbances.

3. Conclusions.

The interaction of wind and fire disturbance increases all dimensions of risk associated with forest fires; the **natural hazard risk** increases as large amounts of dead wood, interspersed in the stand provide ample fuel for potential forest fires. This effect is exacerbated by potential insect or pathogen outbreaks, which can spread into neighbouring stands, thus providing more fuel in the future. In some cases, options to proactively reduce fire risk is limited as damaged forest stands do not permit for safe working conditions to e.g., reduce fuel loads, bring down hanging trees (ladder fuel) or install fuel breaks.

Exposure risk increases as fire may spread to areas unaffected by prior wind disturbance and associated damage. Fires may spread beyond the area damaged by wind, including properties in the wildland-urban interface, or areas subject to subsequent insect outbreak.

Vulnerability risk also increases – in part because infrastructure in the WUI is potentially impacted by fire. Given that forests are a hotspot for recreational activities, and fire is a fairly new phenomena in some areas of Europe, there is a risk of injury or harm to individuals. Furthermore, important forest ecosystem services can be negatively impacted by a fire following a wind event.

To address such a multi-risk scenario requires the close collaboration of multiple entities throughout all phases of the risk management process. Key actors include forest owners and managers/forest management agencies, fire department, local authorities, civil protection organizations.

4.3.2.2 Wildfires / Floods (flash floods)

WILDFIRES/FLOODS (FLASH FLOODS)
Cumulatively over time

1. Multi-risk scenario(s).

Wildfires can considerably change hydrological processes and the landscape's vulnerability to major flooding and erosion events (*Shakesby and Doerr, 2006; Stoof et al., 2012*). Post-fire mudflows and flash floods represent a particularly acute problem in mountainous regions (*Tryhorn et al., 2007*). In fact, vegetation cover is an important factor in determining runoff and erosion risk (*Nunes, 2011*). Its removal by fire increases the raindrop impact on the bare soil and reduces the storage of rainfall in the canopy and the roots, thus increasing the amount of effective rainfall.

Burned catchments are therefore at increased hydrological risk and respond faster to rainfall than unburned catchments (*Meyer et al. 1995; Cannon et al. 1998; Wilson, 1999; Stoof et al., 2012*). Wildfires also affect the hydrogeological response of catchments by altering certain physical and chemical characteristics of the soils, including their water repellent conditions (*Conedera et al. 1998; DeBano et al. 1998; Letey 2001; Martin and Moody 2001; Shakesby and Doerr 2006*).

Increased runoff can lower the intensity threshold and the amount of precipitation needed to cause a flood event and also exacerbate the impact of precipitation. Combined with steep slopes, this can create the potential for flash floods.

Below a brief description of two "real" scenarios occurred:

Esposito, Giuseppe & Parodi, Antonio & Lagasio, Martina & Masi, Rocco & Nanni, Giovanni & Russo, Filiberto & Alfano, Stefano & Giannatiempo, Gaetano. (2019). Characterizing Consecutive Flooding Events after the 2017 Mt. Salto Wildfires (Southern Italy): Hazard and Emergency Management Implications. Water. 10.3390/w11122663.
In the late summer-autumn of 2017, a sequence of four post-fire flooding events affected Montoro village in southern Italy. From 5 July to 12 July 2017, a wildfire affected the area and a total of 221.4 ha were burnt (24.1 ha resulted burned with low severity, 118.3 ha with moderate severity, and 79 ha with high severity).
This episode destroyed a large forest mass and this has favoured the triggering of flash flood. If these forest masses are destroyed by wildfires in these areas the protective function of the forest regarding flash flood is lost. Therefore, vulnerability increases.
After the wildfires of July 2017, the area was hit by a series of rainstorms that started in the month of September. Those that occurred on 2 September 2017, 11 September 2017, 22 October 2017, and 6 November 2017 released sufficient rain to trigger post-fire flooding events.

Giampilieri event of October 2009
In the early hours of the afternoon of October 1, 2009, the Ionian coast of Messina was affected by a very intense rainfall event (250 mm / 6 h) with an estimated return time of 300-500 years in a territory of around 50 km2. Specifically, the Municipalities of Messina and the neighboring Municipalities of Scaletta Zanclea and Itala were particularly affected. Numerous mud and debris flows, landslides and floods led to the loss of 37 human lives and enormous damage to buildings, settlements and infrastructures.
The predictability of the event was very low, in relation to the limited area and the very small spatial scale: the weather models had not reported anything significant.

The 2009 event can be considered multi-risk: in fact, on the basis of the terrain inspections, it has been ascertained that the interface fires that occurred in 2007 had at least a contributing role in the triggering of mud and debris flows.

Baix Montseny summer fires, followed by an autumn flood (Not occurred, but existing potential)
During a very dry summer, after a long period without rainfall and vegetation stress, a fire ignites in the western part of the Montseny Biosphere reserve. The fire comes under a strong, warm and dry westerly winds that from the beginning generate a fire behaviour impossible to control, with propagation rates exceeding 3 km per hour and high intensity flames that burn 100 hours fuel. The fire service needs to prioritise the areas since the fire is overcoming the suppression capacity, consequently, some parts of the biosphere reserve freely burn at high intensity having a very large impact on vegetation communities and soils, particularly those located in upslopes aligned to wind direction.
After the events finishes, the forest service assess the impacts to begin restoration measures, but only a month later (early autumn) a cold air mass in the eastern part of the Mediterranean, together with a low pressure system bring heavy rains to the burned area. Hundreds of mm of rain fall in the Montseny Biosphere Reserve in a few hours, and the run off rapidly goes from the top of the massif to the towns. In addition, the Tordera river increases the water flow and collapses and floods the flat area between the Biosphere reserve and the river (where towns are located). Since the forest is not recovered from the fire effects, the run-off gets exacerbated, increasing the arrival of water at the bottom of the massif and, therefore, creating erosion in very vulnerable habitats.

2. Measures/Actions

The measures reported below derived from literature review, from National CP Department indications and from the interviews to Civil Protection stakeholders done in the framework of the task 3.1.

Improvement of Forecasting and monitoring capacities and systems, which allow to predict, with the widest possible time interval, the approaching of meteorological phenomena spatially and temporally concentrated and to be able to determine risk scenarios for the population and so to act in a more immediate way. All this merges into and matches with the Improvement of the civil protection planning and updated knowledge taking into account the uncertainty.

Even in case of suitable thresholds and efficient real-time monitoring of rainfall, the rapid response of small watersheds, like those characterizing the Mt. Salto area, to localized rainfall pulses might not allow to warn the population with a sufficient lead time. Therefore, as also suggested by Staley et al. [75], the **improvement of rainfall intensity forecasting and monitoring of rainfall conditions upwind of the area of concern are of utmost importance for early warning purposes***. (Esposito, Giuseppe & Parodi, Antonio & Lagasio, Martina & Masi, Rocco & Nanni, Giovanni & Russo, Filiberto & Alfano, Stefano & Giannatiempo, Gaetano, 2019).*

It is therefore of fundamental importance that the civil protection plan is constantly updated, both in relation to the aforementioned transformations of the territory, and in relation to the knowledge of the human and instrumental resources availability on site and the related methods of use in case of emergency.

In particular, the activity of local on-site monitoring teams is of primary importance in areas already vulnerable to disasters and in those affected by forest fires, where there are residual risk conditions that make it necessary to intensify monitoring actions.

These forecasting, monitoring and surveillance activities must be linked with those of contrasting events, mitigating possible damage and possibly managing emergencies through the activation of the civil protection plans, at the various competent territorial levels, which constitute the fundamental tool available to the institutional subjects responsible for civil protection to identify, in correspondence with the issued alerts, the operational actions to be implemented to deal with both foreseen and unpredictable events. *(National Department of Civil Protection, Operational indications 2017).*

In terms of hydrogeological risk, it is also necessary that the Regions and Autonomous Provinces, Metropolitan Cities and Provinces provide technical support to Municipalities for the identification of areas at risk, which must be based on both studies and available surveys (such as, for example, the Hydrogeological Planning Plans or the Flood Risk Management Plans), and on direct knowledge of critical issues, even punctual ones, linked to the evolution of the territory following natural and anthropic transformations, also as a consequence of events occurred previously or temporary conditions. *(National Department of Civil Protection, Operational indications 2017).*

Equally, it is also necessary a feedback from municipality and population as they have more precise knowledge of vulnerability and other local characteristics.

Early warning systems
After an assessment of the burned area, authorities should digitalize the most affected areas in order to set recovery priorities as well as incorporate these areas into emergency cartography.

With the most affected areas digitalized, competent authorities can use the weather forecast to prepare more accurate early warning systems by overlapping the forecast and the damages assessment to alert society exposed to risk and reducing their vulnerability.

Apart from that, there is the need to disseminate the risk forecast among citizens, particularly after a wildfire event, when most of people do not think about flood as a threat after a large wildfire.

Enhance the level of preparation of stakeholders and authorities for these intense and concentrated events, also in terms of civil protection
Greater diffusion of the knowledge of hazard and risk in the territory (e.g., WebGIS) and dissemination of data; Involvement of schools and the population for rising awareness.

The analysis of the Giampilieri event brought out some critical issues: the weakness of civil protection planning, the lack of operational procedures (especially concerning the organization of territorial monitoring teams), the lack of a structured information activity for the population, the inadequate knowledge of the event and risk scenarios, the failure to prepare non-structural measures, etc.

To this end, we highlight the opportunity to prepare the subjects involved in the management of any emergency and to inform the population, providing the necessary information on the correct behavior to be adopted before, during and after an event, as well as to carry out exercises to test the intervention model, to update the knowledge of the territory and the availability of resources. *(National Department of Civil Protection, Operational indications 2017).*

Define smart recovery protocols between events
It is well-known that after severe fire events that have a high impact on vegetation end-up with the protection function of forests. Therefore, it is key to improve the recovery phase by creating smarts and fast solutions after the disturbance to ensure that the protective function of forests, as well as other ecosystem services, are recovered.

Ecologist from the University of Girona developed a set of guidelines to sustainably manage a recent burned forest trough several decision-making steps. By using these guidelines, forest services and landowners can assess the impact of the fire and decide recovery measures according to the results.

This sustainable management sets proper conditions to facilitate forest recovery and, consequently, avoid accumulative disasters in the area. In addition, it is key to apply these kinds of measures in areas that have the potential to cause run-off and civil protection problems: slopes oriented to populated areas and vulnerable habitats. These measures should be executed very fast as the worst case can be a flooding episode a short time after the fire.

In addition, it is key to apply these kinds of measures especially in areas that have the potential to cause run-off and civil protection problems. This analysis should be done by a group of experts in both risks. The best time to conduct this analysis is after the fire episode. Therefore, it should be included in the civil protection plans as a task to be done regularly by the actors.

Strategic forest management
Strategic forest management, particularly in those areas where a change of fire behaviour is expected, is a measure to be considered. Fire service can get overcome by the flames and thus, they need to focus efforts in those areas that they know in advanced, according to the analysis of past events, that they have an opportunity to control the fire. These areas are known as strategic management areas.
The identification of these areas is key to keep fire intensity as low as possible, with the aim of having a low impact on vegetation and soil. By protecting vegetation and soil from strong damages, the recovery phase will be easier and faster and forest will be ready to sustainably suffer other disturbances such as floods. At the same time, communities with potential to be affected by both, fires or flash floods will be safer.

3. Conclusions.

HAZARD:
Long-term (strategic) planning and integrated planning: based on strategies coordinated at the different territorial levels with the aim of carrying out multi-scope interventions (WUI fire and Flash Flood) and able to Deal with Uncertainty of Flood Risk and WUI risk.

Hazard modification, exposure decrease, and vulnerability modification are all (partly) attainable through spatial planning (especially urban planning) oriented to risk mitigation, which should take into account the foreseen changes from Climate Change.

The necessity to coordinate spatial planning, civil protection and sectoral policies is also underlined by the community approach on prevention of disasters (European Communities 2009). Indeed ''linking the different actors throughout the disaster cycle'' is a key issue in the Commission's point of view.
(Sapountzaki, K., Wanczura, S., Casertano, G. et al. Disconnected policies and actors and the missing role of spatial planning throughout the risk management cycle. Nat Hazards 59, 1445–1474 (2011). https://doi.org/10.1007/s11069-011-9843-3).

It is clear that prevention avoids damages more efficiently and with lower costs than urgent actions during an event. So if the risk analysis identifies an area of high risk the best way to avoid economic and personal damages is to avoid urbanization of this area.

In this sense, it would be interesting a better regulatory support from the EU (especially in urban planning), as weak or null support to civil protection and risk reduction strategies are included nowadays in spatial planning regulations, especially for already urbanized high vulnerable elements.

In relation to the need to tackle the uncertainty of forecasts, a way to better deal with it is to apply a precaution principle. It could be applied as criteria in the DSS. Following this idea, an extended area could be locked down or confined when the level of forecasted risk is high, although if the forecast was not able to define the exact location of the event or the forecasted high risk area is near but not exactly there (it is unknown where the exact location, the amount of rainfall and the extension of a shower will be).

For example, if there is a forecast of high risk of flash floods in a valley the population of the valley and the surrounding area should be locked down, not only the population the high risk valley but also the surrounding areas. Another example is to close access in high fire risk days and places. Another example is to close access to creek road crossing when a rainfall event is forecasted without waiting the exact location of the flooding or the exact river behaviour forecast. These type of measures must be preceded by awareness among the population.

Smart urban planning (territorial management that take into account risk management): The most severe events in the sequence, in terms of mobilized material and damage to the urban settlements, occurred overnight (11 September 2017 and 6 November 2017), when people were inside their homes and cars were thus empty. This circumstance helped prevent casualties and fatalities. In our opinion, however, another important condition that limited consequences on people and settlements was the gradual mobilization of unstable material throughout four different flooding events, characterized by a moderate magnitude in terms of mobilized material**.**
(Esposito, Giuseppe & Parodi, Antonio & Lagasio, Martina & Masi, Rocco & Nanni, Giovanni & Russo, Filiberto & Alfano, Stefano & Giannatiempo, Gaetano. (2019)).

In this sense, taking into account future climate change effects should be considered in the urbanization regulation, as well as in building construction technical regulations (e.g. evacuation ways, maximum level of water during major flood events, distances of buildings to forest, etc.)

Tools and methods for collecting past data events: A better understanding of the hydrogeomorphic impacts of fire at catchment level can improve our ability to understand, and therefore possibly predict, the risk of flooding and erosion in burned areas. In fact, when a precipitation event follows a large, high-severity fire, the impacts can cause various kinds of damage on- and off-site including high sediment inputs, downstream flooding, destruction of the aquatic habitat, and damage to human infrastructures.

Moreover, it is important to identify and quantify the potential hazards posed by flash floods and landslides generated by burned watersheds. An analysis of data collected from studies of flash flooding and debris flows following wildfires can answer many of the questions that are fundamental to post-fire hazard assessment—what and why, where, when, how big, and how often.
Soil Erosion After Wildfires in Portugal: What Happens When Heavy Rainfall Events Occur?
(L. Lourenço, A. N. Nunes, A. Bento-Gonçalves and A. Vieira)

VULNERABILITY – RESPONSE CAPACITY

New risk maps: The production of more representative flood hazard and floods risk maps on an operational basis, since both Soil Moisture and fire occurrence are taken into consideration through an innovative and holistic approach. At the same time, the design of long-term and efficient flood risk management plans according to the requirements of EU Floods Directive 2007/60/EC, where adverse initial conditions (i.e., wet SM conditions following a recent forest fire) can also be considered for the generation of flood hazard and flood risk maps.
Development of a methodology for estimation of the dynamic evolution of the flood related hydrological behavior of periurban catchments under post fire condition (Papathanasiou, 2018- Doctoral Thesis).

Operational tools able to collect information in real time from the territory and, by combining static and dynamic information, to provide an evolution of the scenarios. These tools - if integrated with modules capable of simulating the effectiveness of possible preventive interventions - could be the basis for implementing the necessary structural and non-structural actions
Wildfire alters the hydrological response of watersheds, including the peak discharge resulting from subsequent rainfall.
Soil Erosion After Wildfires in Portugal: What Happens When Heavy Rainfall Events Occur?
L. Lourenço, A. N. Nunes, A. Bento-Gonçalves and A. Vieira
Flooding after fire is often more severe, as debris and ash left from the fire can form mudflows. As rainwater moves across charred and denuded ground, it can also pick up soil and sediment and carry it in a stream of floodwaters. These mudflows can cause significant damage.
https://idwr.idaho.gov/files/floodplain-mgmt/Flood-After-Fire-Fact-Sheet.pdf

Early warning systems: An Early Warning Systems for flash floods able to take into account and integrate the combined fire and soil moisture impact on the hydrological response of a catchment will be useful.
Development of a methodology for estimation of the dynamic evolution of the flood related hydrological behavior of periurban catchments under post fire condition (Papathanasiou, 2018- Doctoral Thesis).

Inclusion of multi-risk interactions in civil protection planning, risk analysis and forecast systems: The integration of crossed information (e.g., from fires to floods) needs to be inserted in the civil protection planning, both as a part of the risk analysis and the operational emergency management (interphases between plans). It needs to be added to the operational protocols too.

It is clear that a forest fire has an impact on:
a) the increase of the runoff of this area
b) an increase of debris.

Consequently, the next points should be adapted to these changes:
a) risk analysis
b) forecast systems (warning systems and hydrological models).

Moreover, a rapid cleaning of the debris, at least in the riverbeds and in the most potential dangerous parts, needs to be conducted. Therefore, civil protection planning has to take into account all these tasks.

It implies also the already experienced multi-risk episodes in the different forms in which this can be experienced. In each case different adjustments are needed:

- **Simultaneously**: include interphase scenarios in civil protection plans, especially in relation to organization and protocols. It needs more coordination between different plans and agencies during the emergency.
- **Cascading**: include this scenario in planning, especially in the organization (some actor should hold the function of triggering the preparedness for cascading events) and protocols (all actors should know in advance what to do and how in this case). It should be taken into account especially in the prevention of the next triggered event, but also in the planning of the necessity to face long events (one event concatenated to another may extend too long for the actual human resources) and the preparedness after or during the first event. It needs more coordination between different plans and agencies during the emergency.

- **Cumulative over time**: include this scenario in planning, especially during the after event management. It is needed the identification of this possible scenarios just after the first event which must trigger the crossed analysis form the part of an expert group in both hazards. They should analysis of the likely consequences of the first episode in near future emergencies and the measures to be applied for prevention. It needs more coordination between different plans and agencies at the end of the emergency and after the emergency. This is the case of multi-risk from fires and floods, as both at the same time and as a cascading effect are very unlikely.

In the special case of wildfires-floods multi-risk (similarly to other cumulative in time or even in cascading episodes), some tasks are recommended:

Step 1. A group of expert should conduct an assessment of the effects of the fire in the flood risk (Assessment of the affected area, assessment of the time when new episodes (other hazards) could impact (in this case if the flooding season is near or not, it gives an idea of how much time is available), assessment of the effects on the other hazard (in this case floods), assessment of the increase in exposure and vulnerability and proposed actions to reduce the risk). It is important to focus on areas where the possible increased hazard could be more important in terms of population and vulnerability.
Step 2. Creation of an executive committee with the objective to identify preventive measures to eliminate or mitigate the chain effect. It should be included as a possible organizational scenario in civil protection plans, with the corresponding procedures.
Step 3. Stablishing emergency planning measures for unresolved situations (scenarios) through prevention mechanisms (it could include specific actions like information procedures, cleaning of specific areas, special management urgent measures, restriction of access, …)
Step 4. Implementation of the new operational procedures derived from emergency planning, involving municipalities
Step 5: Assessment of citizen collaboration and information measures.

Including climate change likely effects in risk assessment, civil planning and forecasting systems.
It has to be considered that climate change effects have to be included in the forecast systems, that there is a need of improvement of hydrological forecast (linked to the meteorological forecast systems), and, finally, that the monitoring and forecasting of flash floods need to be deeply improved.
It implies also the possible increase of multi-risk episodes in the different forms in which this can be experienced (simultaneously, cascading or cumulatively over time).

Communication with the population and awareness
During these events population could be confused as these situations are new, rare and they are not probably aware of. So, it is needed to raise the awareness of population of the possibility of multi-risk scenarios and other climate change effects. It should include authorities.
Moreover, old and new technologies may allow better tools for faster and more direct communication with population, both from authorities to citizens but also from citizens to authorities.
Finally, more involvement of population during the planning process is convenient I order the include the view and needs form population, to make all more involved and to help in arising awareness.

Increase the resilience of the society
Especially in case of multi-risk events, as it will be more severe and difficult to face, and in case Climate Change scenarios, as it will imply new and possibly more severe situations.

4.3.2.3 Wildfires / Avalanches

WILDFIRES/AVALANCHES
Cumulatively over time

1. Multi-risk scenario/s.

The *third report on Climate Change in Catalonia (2017)* warns of a trend towards an increase in the frequency of droughts and a notable rise in the average temperature. This situation will probably lead to an increase in the extension and severity of wildfires Both, in current and new fire-prone areas.

In Catalonia at the beginning of the 19th century there was a very prolonged and intense drought. Some villages that were affected by this severe drought are Barcelona or La Seu d'Urgell, located in the centre of the Catalan Pyrenees. This drought was unprecedented during the 20th and 21st centuries. It lasted 12 years and reached its peak in Catalonia between 1812 and 1818 (*Barriendos, M. et al, 2005*). Therefore, in the current context of Climate Change (with high pressure on water resources), it cannot be ruled out that a long-term drought event could once again affect Catalonia and therefore increase the danger of fire. In addition, the increase of fuel loads at landscape level due to the abandonment of agricultural activities in the last century increases the potential of fire spread and intense crown fire levels able to burn all the forest cover.

This scheme is based on the practical assumption (based on Climate Change trends for the Catalan Pyrenees and land uses changes in the territory) that a large wildfire occurs at the end of the summer in the Pyrenees, affecting several valleys (large surface) and, in addition, that a heavy snowfall is foreseen at the beginning of the winter season (October-November) in those areas affected by the large wildfire where potentially forest cover is lost.

2. Measures/Actions.

Following the steps proposed by Civil Protection of Catalonia, after the discussion we fulfil a set of steps commonly used in table tope multi-risk exercises with the corresponding measures:

STEP 1: Risk analysis. Expert Working Group

Time triggering assessment:
In this practical assumption, there is little time available to provide an adequate general response to potential new avalanche risk situation posed by the loss of forest cover due to the wildfire event. Therefore, it is necessary to have an action protocol in advance in case this situation arises.

If the wildfire is very late (at the end of the summer), there will be a shorter response time to a possible advanced situation of significant snowfall affecting all altitudes.

Forest protection function is affected by the large wildfire and, therefore, the increase of avalanche risk is expected. This loss of protection function is directly related to the intensity of the fire and its effect in the remaining forest structure (some trees can survive and accelerate the forest recovery meanwhile in other places all trees are completely burnt where burnt logs are degraded fast in such high mountain environ).

Assessment of affected space with respect to hazard map (hazard):
Aimed at analysing the effects on the protection function, the affected area must be mapped and characterized as follow:

i) Perimeter of the burnt area: The objective is to know the total surface affected. This could be a fast diagnosis Identifying on the terrain the areas affected by the wildfire using satellite images. In most sensitive places, high resolution can be achieved by GPS through field work. Mosaic of non-burnt areas within the perimeter must be defined.

ii) Analyse the state of the vegetation and whether it still maintains its protective function: The objective is to know how the protective function of the vegetation cover is affected (e.g., in those areas where wildfire burns in high intensity, most of vegetation cover disappear). Estimations can be achieved with satellite images (i). Nevertheless, in the most sensitive places, LIDAR cover or the use of drones can help to carry out a precise estimation. The tree and shrubs species distribution according the vegetation cover maps (land use maps, habitats maps, etc.) also gives valuable information to estimate the recovery potential of the vegetation cover (e.g., Ulex spp. has the capacity of resprout, also Betula ssp. On the contrary, Pinus spp. recovery is done from new seeds and takes more time). In any case, normally, the effects of the natural processes of restoration will not be significant before the snowfall event, 2-3 months later.

iii) Integrate into the cartography the new modifications that have produced the wildfires in the avalanche paths and mountain areas: Merging this information would be possible to observe the potential avalanche zones affected by the wildfire. Thus, to know if iii.1) the known potential avalanche zones has changed and how, and iii.2) if potential new avalanche zones appears because of the loss of vegetation cover and its protection function.

Exposure and vulnerability assessment:
Due to the very small time frame, risk management actions should focus on those areas most exposed and vulnerable. Protection of population, main infrastructures, critical facilities, buildings, etc., must be a priority.

The analysis will be carried out from the cartography previously mentioned and adding:

i) Infrastructures and settlements cartography (e.g., Urban Map of Catalonia[19]): The objective is to estimate and identify new potential exposed and vulnerable elements, due to the new avalanche risk situation.
ii) Information/diagnosis from ALLAUCAT plan (Civil Protection Emergency Plan for Avalanches in Catalonia) or Civil Protection municipality plans: Aimed to identify recorded sensitive places. This will serve also as a basis for updating the information according to potential new risk situations.

Proposed actions to reduce the risk:
According the previous analysis on the exposed and vulnerable elements from the cross-links between burnt area and potential avalanche areas, the measures needed to reduce the risk are identified.

This would need a prioritization of the actions to be done, since probably there is no capacity to act in most of areas affected due to i) there is a large surface affected and, ii) there are several limitations to develop forest works in mountain areas, due to the rough terrain, lack of forest roads, environmental conditions or availability of forestry machinery and specialized forest workers in such conditions, among others.

[19] http://ptop.gencat.cat/muc-visor/AppJava/home.do

Firstly, it is necessary to clean/repair/install the avalanche protective structures in the areas of greatest exposure and vulnerability.

It is very important to update the intervention plans for avalanche triggering (PIDA) in order to carry out the relevant actions in the indicated areas. For burned areas susceptible to being affected by avalanches, which do not have any avalanche protection system, it must be determined which protection mechanisms or actions are the most appropriate and effective to reduce the risk in case of avalanche danger (e.g., daisybell, avalancheur, etc).

It is necessary to increase the population's awareness regarding changes in the avalanche hazard. Inform population about changes in the terrain and areas more hazardous due to a wildfire (e.g., within avalanches bulletins with specifications according the burnt area).

Assessment of simultaneity or very short-term triggering:
This multi-risk situation (wildfires - avalanches) is not a simultaneous or cascading situation, it is cumulatively over time. If the wildfire is very late (at the end of the summer), there will be a shorter response time to a possible advanced situation of significant snowfall.

The lack of forest/vegetation covers may also trigger soil erosion, landslides or increase the rockfalls risk in between the snow cover arrives. This situation is not analysed in the current exercise. It has to be taken into consideration that in many areas the existence of old agricultural terraces (at least in medium and low altitudes in mountain valleys) reduce these risks.

STEP 2: Identify preventive measures to eliminate or mitigate the chain effect. Creation of an executive committee.
For each measure has to be identified the: type of measure, temporary viability, economic viability, definition of priorities, bodies involved (experts in the different risks - bodies responsible for preventive or reparative actions, potentially affected infrastructure managers, local authorities, actions and schedule).

The following measures are listed in order of priority. Phase of the risk management cycle and cross-sectoral risk components considered in RECIPE project are indicated.

Normally, all these measures are feasible both temporarily and economically or, alternatively, specific restrictions are mentioned. These measures must be implemented before a significant snowfall is forecasted. First measure has to be carried out in advance, in response to an expected situation of large wildfire.

Measure 1.- Develop a protocol for action in the event of a large wildfire in avalanche paths (Preparedness phase / Risk Assessment, Mapping and Planning Tools): The objective is to prepare in advance the risk management protocol of a multi-risk wildfires-avalanches situation, considering the risk driver factors posed by the land uses changes and climate change in the territory.

In charge of: **Emergency bodies** (General Directorate of Civil Protection, General Directorate of Wildfire Prevention, Extinction and Rescue), **Forest and Risk Managers** (Cartographic and Geological Institute of Catalonia; General Directiorate of Forest Ecosystems and Environmental Management, Forestal Catalana SA, Forest Ownership Centre of Catalonia, General Directorate of Rural Agents)**, Research Institutions** (Forest Science and Technology Centre of Catalonia among others), **Forest owners associations** (Association of Local Forest Owners in Catalonia – ELFOCAT), **Local authorities** (linked to ELFOCAT since in the Pyrenees area, most of forests are from municipality ownership) and other relevant **Private actors** (ski-resorts) in mountain areas.

Measure 2.- Avalanche Terrain Assessment (Prevention phase / Risk Assessment, mapping and planning tools): Aim to 2.1) identify on the terrain the areas affected by the wildfire using satellite images and assessing the terrain (field work) and, 2.2) integrate into the cartography the new modifications that have produced the wildfires in the avalanche paths and mountain areas.

In charge of: **Risk managers** (Cartographic and Geological Institute of Catalonia, General Directorate of Rural Agents), **Emergency bodies** (General Directorate of Civil Protection). Also, **Land Planners** and **Local Authorities**.

Measure 3.- Assess the state (after the wildfire) of the vegetation and forest cover (Recovery phase / Technical Measures): Analysis of the remaining protection function of the vegetation cover partially burnt into the burnt area perimeter.

In charge of: **Forest and Risk Managers** (General Directorate of Forest Ecosystems and Environmental Management, Forestal Catalana SA, General Directorate of Rural Agents), **Research Institutions** (Forest Science and Technology Centre of Catalonia, others), **Forest owners associations** (Association of Local Forest Owners in Catalonia – ELFOCAT) and **Local Authorities**.

Measure 4.- Burnt area forest cover restoration (Recovery phase / Technical measure): Cleaning the burnt areas and recover the vegetation protection cover function in the priority areas for avalanche prevention (according the results of measures 2 and 3). This includes:

4.1) Burnt tree logs removal and branches pilling for soil erosion prevention. Potential use of burnt logs to build temporary snowpack retention structures in the site (technical gap identified that could be transferred from Alpine areas with more experience in avalanche terrains under the tree line. In the avalanche run section, burnt logs should be removed.

4.2) At mid long term, analysis of reforestation and monitoring plans in priority areas according the avalanche risk.

In charge of: **Forest and Risk managers** (General Directorate of Forest Ecosystems and Environment Management, Forest Ownership Centre of Catalonia, General Directorate of Rural Agents, Forestal Catalana SA), **Forest companies** (forestry companies and forest industry), **Forest owners** (Association of Local Forest Owners in Catalonia – ELFOCAT, individual private forest owners) and **Local authorities** (several municipalities in the Pyrenees have biomass district heating. installations where the wood from burnt areas can potentially be destinated).

Measure 5.- Check and restore avalanche protective structures (Prevention phase / Technical Measures): This includes:
5.1) Clean/repair protective elements affected by the wildfire and recover it (this would be a key point since the existing elements are protecting the exposed and vulnerable elements/areas previously identified before the new event) and,
5.2) in coordination with measure 4.1, emergency installation of protection structures in the (new) areas of greatest exposure and vulnerability, considering the short time available before the winter season.

In charge of: **Risk Managers** (Cartographic and Geological Institute of Catalonia General Directorate of Forest Ecosystems and Environmental Management, Forestal Catalana SA), **Private Stakeholders** (e.g., Inaccés, Geobrugg, Ski-resorts), **Local Authorities**.

Measure 6.- Update the Intervention plans for avalanche triggering (PIDA) according to new multi-risk situation (Prevention and Preparedness phase / Risk Assessment, mapping and planning tools). Exposed and vulnerable elements as well as risk management protocols must be adapted accordingly, integrating the information from previous measures 1-5.

In charge of: **Risk Managers** (Cartographic and Geological Institute of Catalonia), **Local Authorities**, **Private Stakeholders** (Ski-resorts).

STEP 3: Emergency Planning. For unresolved situations (scenarios) through prevention mechanisms, assessment of the new scenario in the derived plan (e.g., floods due to forest fires):

- Identification of aggravated episode indicators (multi-risk)
- Definition of specific actions (access control, operative procedures, information procedures, etc.)

Measure 7.- Close the access to potential avalanche zones where it has not been possible to act (Prevention phase / Technical measure): This measure should be applied in specific cases as these days with high avalanche risk (similar to the measures applied in case of high wildfire risk, closing the accesses to the forest massifs).
In charge of: **Forest and Risk managers** (General Directorate of Forest Ecosystems and Environmental Management, General Directorate of Rural Agents), **Emergency and response bodies** (local police, etc.).

Measure 8.- Extend the preventive triggering of avalanches in new risk areas (Prevention phase / Technical measure): This measure should be applied in specific cases as these days with high avalanche risk. It is necessary determine which protection mechanisms or actions are the most appropriate and effective to reduce risk in case of avalanche danger (e.g., daisybell, avalancheur, etc).
In charge of: **Risk managers** (Cartographic and Geological Institute of Catalonia, General Directorate of Rural Agents), **Emergency and response bodies** (General Directorate of Civil Protection, local police), **Private Stakeholders** (Ski-resorts).

STEP 4: Implementation of new procedures - operational information (to operatives):

- In general and through information circuits
- Through specific actions and / or information for the episode
- Municipalities involved

Measure 9.- Update the Civil Protection and Self-protection Municipality Plans according the new multi-risk situation (Prevention and Preparedness phase / Risk Assessment, mapping and planning tools): Revision of confinement and evacuation zones which can be affected by unprecedent avalanche events (e.g. medium slope and size avalanches due to the lack of vegetation cover blocking roads), update the inventory of resources (e.g. need of bulldozers and excavators to remove mixed snow and burnt logs avalanches), etc.

In charge of: **Risk managers and emergency bodies** (General Directorate of Civil Protection), **Local authorities**, **Private Stakeholders** (Ski-resorts).

Measure 10.- Update the ALLAUCAT plan (Civil Protection Emergency Plan for Avalanches in Catalonia) in the burnt area according the new multi-risk situation (Prevention and Preparedness phase / Risk Assessment, mapping and planning tools): Revision of risk zones (include the new risk situation into the DSS) and protocols considering the temporary new multi-risk situation posed by the loss of vegetation cover.

In charge of: **Risk managers and emergency bodies** (General Directorate of Civil Protection, Cartographic and Geological Institute of Catalonia), **Local authorities**, **Private companies** (ski-resorts).

STEP 5: Assessment of citizen collaboration and information measures.

- Local actions. Individual or community campaign
- General information actions. Enrichment of seasonal campaigns.

Measure 11.- Increase population awareness (Prevention phase / Risk culture and communication): New areas at risk must be informed to the inhabitants and users of mountain areas. This includes:

- Avalanche safety programs: regulation of access to areas at risk and allow only essential services; Install safety/hazard signs.
- Awareness campaigns to inform about changes on the terrain and risks (avalanches).

In charge of: **Risk Managers** (Cartographic and Geological Institute of Catalonia, General Directorate of Rural Agents), **Local Authorities** (tourist offices), **Private Stakeholders** (Ski-resorts, mountaineering and sport associations organising outdoor activities, tourist sector and travel agencies, refugees managers, etc.), **Non-Profit Organisations** (Association for Snow and Avalanche Knowledge-ACNA).

ADDITIONAL STEP: For scenarios of simultaneity or assessment of triggering in the very short term.

- Operational assessment of the response.
- Determination of the activation phases, measures to protect the population, information mechanisms, etc.

Once a large wildfire has occurred in mountain areas and avalanche paths, a group of experts should be formed to assess the next steps to be taken. The aim is to respond to an emergency to prevent further risks. See Measure 1.

4.3.2.4 Wildfires / Landslides

WILDFIRES/LANDSLIDES
Cumulatively over time and Cascading

The scenario considered is basically cumulatively over time and could be also cascading. Both are related to the loss of forest cover (and thus, the forest protection function) and roots, as an environmental condition that could affect the landslide hazard.

1. Multi-risk scenario(s).

General conditions of pessimistic scenario (MULTI-RISK SZ2, wildfire-landslides):
Temperature: +4°C (RCP 8.5, 2090)
Precipitation sums: Decrease of precipitation sums per anno (approx. 10%), adverse distribution of precipitation over the year with concentration in winter and long dry periods in summer.
Heavy rain events: Significant increased intensity and sums (+25% -according to +7%/°C potential air moisture).
Wind/storm: Increase of storm events.

General conditions of multi-risk scenario:

Analyses and assumptions for this scenario refer to a significant increase of wildfires in Alpine areas within the pessimistic scenario and focuses on deviating facts compared with the pessimistic scenario described above (see single-risk landslide).

Forest protection effects in the case of landslides are assumed (in dependence of forest behaviour) to be effective, where the slope inclination is not higher than 5-10° than the residual angle of internal friction of the soil (*Schwarz et al. 2012*). Directly after wildfires, the root reinforcement is still available, except in the case of rather rare subterranean fire events (where roots are burned as well). It will decrease continuously in a period of several years. So, there is plenty of time to take measures but not enough time for adequate reforestation which offer comparable root reinforcement effects.

In the matter of forest measures it is noted, that measures which decrease the probability and intensity of wildfires, like single layer forests or areas free of vegetation may increase the landslide hazard or decrease the resistance against other hazards as beetles (e.g. Ips typographis for picea abies in Austria) or storms.

In the multi-risk scenario, a wildfire event in an Alpine area is assumed, effecting the landslide risk due to the loss of forest cover and roots. Thus, the analysis is based on the reduction of landslide risk.

2. Measures/Actions.

HAZARD:

Factors:

Internal friction: Rising temperatures lead to increased evapotranspiration and thus to lower soil water contents, resulting in lower susceptibilities. However, the loss of transpiration via trees will abolish or even reverse this effect. The continuous decrease of root reinforcement will destabilize the equilibrium of forces in sensible slopes and thus increase the landslide frequency (probability of occurrence) significant (mid-term, until new slope equilibrium is established). Figure 2 shows an example, where the probability of landslides with and without forest cover is calculated (using the free online-available model SLIDEFOR_net). The simple model estimates root reinforcement as a function of tree species, forest density and breast height diameter (BHD).

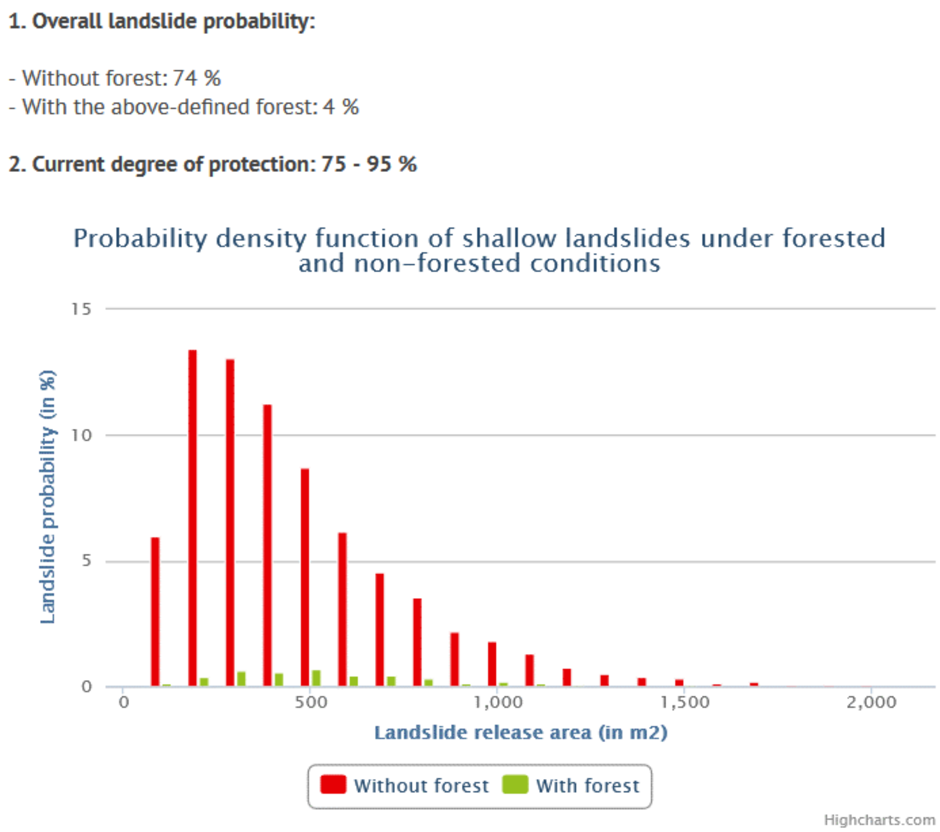

Fig. 2: Calculation of forest protection effects for a steep slope in Haslau (Styria, SE Austria). A dense picea abies stand with an average breast high diameter of 34 cm (age. 100 years) indicate a high protection function of 75 to 95% resulting in significant reduced probability of landslide occurrence compared to deforested areas.

Antecedent precipitation/ soil moisture: It is not clear, if system preconditions in this scenario tend to increase or decrease (after wildfires as a result of changed evaporation). Anyhow, the effect will be probably negligible.

Heavy precipitation events**:** The (significant) influence of heavy precipitation after wildfires is assumed to be more or less the same as without wildfires.

Summed up, for this scenario, a continuous (significant) increase of landslide activities after wildfires at instable slopes is predictable, reasoned by the decreasing root reinforcements.

Measures

Knowledge and methods: This task mainly contains tasks described above for the pessimistic scenario extended to the expertise on wildfires, namely, how to minimize forest fires in occurrence and intensity and what measures after such events are promising to avoid subsequent risks.

The knowledge on the stabilizing effect of different tree species and forest structure in dependence of slope inclination, soil layer depth and water budget need to be improved to allow (quantitative) assessments.

Involved institutions and stakeholders: Challenges for the institutions involved in the different sections of the risk management cycle will increase. Thus, bundling of scientific capacities and communication between various actors in science and practice is required. In countries, which are not so experienced in handling wildfires and its effects, a knowledge-transfer is necessary for both tasks: first, how to minimize forest fires in occurrence and intensity and second what measures after such events are promising to avoid subsequent risks caused by other natural hazards as landslides are.

At present, it is hardly possible to give generally valid recommendations, since measures which decrease the probability and intensity of wildfires may increase the landslide hazard or decrease the resistance against other hazards. The measures therefore must be adapted to the specific situation by experts.

EXPOSURE

Factors:

Development of settlements and infrastructure: How the number of citizens and hence the associated infrastructure will develop under the assumed adverse climatic conditions is not clear.

Due to the increase of endangered areas, a raise of exposure is likely; its effect will vary on a local scale.

In general terms, the negative impact of climate change on the socioeconomic development and increased wildfire and subsequently natural hazards as (among others) landslides may lead to a downward trend of population in rural areas and thus decreasing exposure.

Development touristic activities (summer half year): Generally, for the alpine areas and selected regions, a trend of increasing touristic activities is assumed (*BMWFW, 2012*). The significant increase of wildfires and subsequently natural hazards as landslides may abolish this effect. In sum, a slightly decrease of exposure caused by touristic activities due to landslides caused by wildfire in this scenario is assumed.

In sum, a moderate increase of exposure caused by increasing endangered areas is assumed in this scenario.

Measures:

Although the increased exposure due to landslides is estimated as in sum moderate within this scenario, this can vary widely on a local scale. In addition to the pessimistic climate change scenario, the effect of deforestation in the course of wildfires on landslide activities needs to be considered in planning. There is a time span from the wildfire to the loss of root reinforcement, which allows establishing technical and other measures as the implementation of early warning and evacuation plans. However, responsibilities (at least in Austria) needed to be clarified. Involved stakeholders as e.g., the mayors have to know, where they can get support (by experts) in the case of such events.

VULNERABILITY

Factors:

Infrastructure and population: Generally, the same conclusions are valid as for the pessimistic scenario, whereas on the one hand the more frequent occurrence of wildfires may increase the perception of climate change and its effects. On the other hand, people will not have experience how to deal with the new situation, which may raise the endangerment. Also, settlements and infrastructure might be more vulnerable, because this kind of endangerment was not taken into account during construction.

Thus, in average a slight increase change is to expect. It will vary on a local scale from marginal to significant, depending on the experience in dealing with these events.

Response capacities: In the course of climate change, due to a lack of consideration of relevant scenarios in the planning, unexpected events (locations, courses of events) will affect citizens, actors and response capacities of involved institutions.
The need of additional resources dealing with such events might be countered by increasing challenges in other sectors (e.g., health care) and may make it difficult to ensure the availability of sufficient resources, which may lead to a moderate decrease in response capacities and resilience.

Summed up, a moderate increasing vulnerability in this scenario is likely.

Measures:
Information and preparation of population: Information of local actors as mayors regarding the development of the hazard situation is appropriate. They should know where to get information and support of experts. Also, the further education of responsible persons at involved institutions (how to deal with this situation) can decrease the vulnerability. Science is asked to determine the magnitude supporting decision makers to provide necessary resources.
Legislation and organisation: Clear competences, responsibilities (for landslide management) and communication paths have to be established, which institutionalize the cooperation of all involved actors. The concentration of responsibilities and the hedging of appropriate resource-management in times of economic challenges have to be aimed consistently.
Hazard maps in combination with information on wildfires, settlement and infrastructure data should be the basis for measures.
Mitigating negative (economic) effects: In this scenario, changes of existing systems of support in case of damages are even more recommended. The establishment of a uniform mandatory insurance for natural hazards (as already existing in Switzerland) help to reduce the vulnerability of the population particularly regarding adverse economic developments.

3. Conclusions

The wildfire event will act as a trigger effect on landslide, but not immediately, unless with a temporal shift and continuously.
The measures to mitigate or prevent landslides will be almost the same that in case the wildfire had not been there before. However, with the significant increase of landslide activity, new and/or enhanced approaches are required, that aims on prevention and preparedness to identify new or more endangered areas.

4.3.2.5 Wildfires / Rockfalls

4.3.2.5.1 Optimistic scenario

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

The scenario considered is basically cumulatively over time and could be also cascading. Both are related to the loss of forest cover (and thus, the forest protection function), as an environmental condition that could affect the rockfall hazard.

1. Multi-risk scenario(s)

General conditions of the optimistic scenario:
Temperature: +2°C (RCP 4.5, 2090)
Precipitation sums: Stabil to slight increase of precipitation sums per anno, largely constant distribution over the year.
Heavy rain events: No significant increased intensity and sums.
Wind/storm: No significant changes.
Wildfire: No significant increase of frequency and magnitude.

General conditions of multi-risk scenario:
The negative effects of wildfires on the hazard potential of rockfall are mainly due to structural changes of the protection functions of forests.
By reducing the protective capacity of forests against rockfall (due to wildfire), especially in the first two decades after severe fires, cumulative consequences can occur. Heavy fires thus paralyze the protective capacity of the forest and favour the intensity and probability of occurrence of rock falls.
The exercise is based on the assumption that a wildfire occurs in an Alpine area with a possible effect on rockfall risk due to the loss of forest cover. Thus, the analysis is based on the reduction of rockfall risk.

2. Measures/Actions.

HAZARD

<u>**Factors:**</u>

Wildfire events: Regarding the interaction with wildfire, there is no significant increase in the hazard potential rockfall. Currently, most registered wildfires are very small (0.01 ha). Taking into account similar wildfire events, this means that fire areas of 100 m² and less, as a rule, would not imply a large-scale change in rockfall disposition (Wohlgemuth et al., 2010).

Other factors: Other factors according to the optimistic climate change scenario are mentioned in the single risk optimistic scenario. Mainly areas of permafrost between 2500 m and 2900 m of altitude are affected. No significant change of hazard potential in settlement areas is to expect.

<u>**Measures:**</u>

Technical measures: Regarding wildfire, no notable measures or new requirements against rockfall are necessary. Small scale forest fires with affected areas of a few square meters do not

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

change the rockfall disposition significant. The focus is still on known problematic rock faces, rocky gullys and corresponding disposition areas. Therefore, the management tactics still focus on selective technical measures to avoid rockfall release from critical rock faces (adjacent nets).

Rockfall protection forests: In many alpine valleys with steep slopes above settlements, the protection support of well-structured and dense forests is essential. Forests still decrease the impact energy and runout length of rockfall processes by stopping or deflecting the rocks. Impact marks on the mountain facing side of trunks and by deposited blocks beside trunks (see fig. 1) illustrate that.

Fig.1: Impact marks and stopped blocks by rockfall protection forest (©Plörer)

A mixed tree species composition (including hardwoods, which best absorb the energy of fall processes), early initiation of regeneration (to favour permanent stocking) and the promotion of vertical multi-layering (*Engl et al. 2020*) are extremely important.

In case of the presence of a protection forest, technical measures (like nets and dams) can be concentrated on known hotspots.

EXPOSURE

Factors:

Basically exposure, especially in narrow valleys, depends on future settlement development. However, this is a subject of socio-economic and demographic studies. With regards to wildfire (as an influencing factor on rockfall risk), no substantial deviation of exposure described in the optimistic scenario is assumed.

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

Increasing recreation activities in high alpine regions can change exposure. A notable rise of exposure trough small wildfires and therefore new gaps in the protection forests is unlikely.

Measures:

Regarding exposure, probably no new requirements are needed. Moving persons and traffic is the same as in the rockfall single risk scenario. Exposed persons in settlements below forested areas do not experience an increased risk and therefore no additional activities like raising awareness or closing touring paths in forested areas are needed.

The current rockfall impacts to houses or settlements are often strongly reduced by combinations of dense protection forests in the starting and transporting sectors and technical measures (nets and dams) in the deposition zones (Fig. 2).

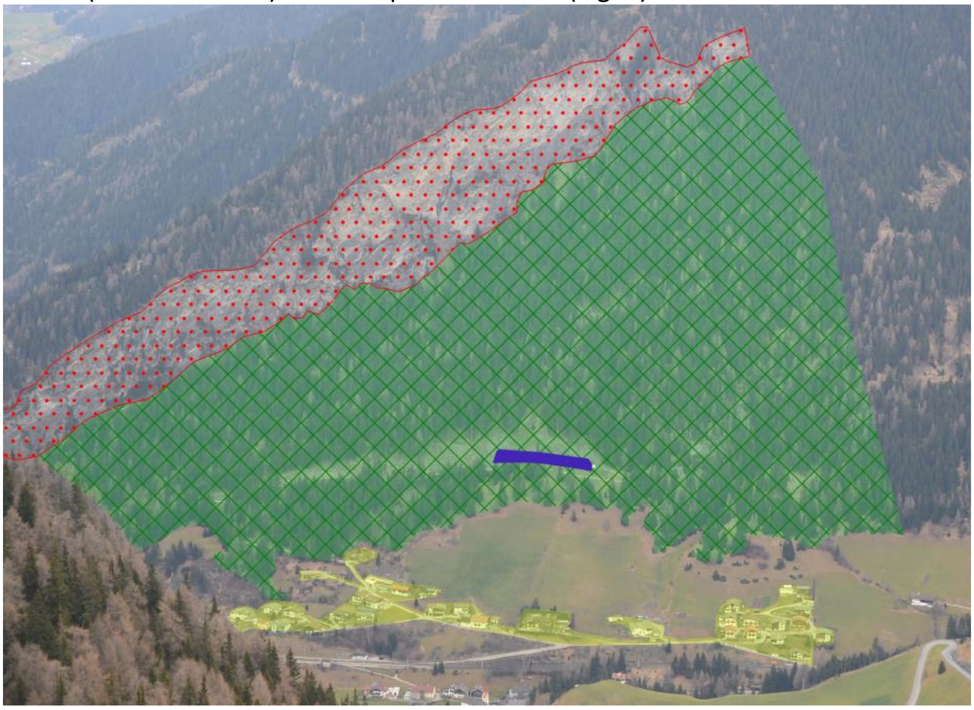

Fig. 2: Example for protection strategy against rockfall impacts in current situation and in case of the optimistic scenario (©Plörer)

VULNERABILITY

Factors:

No substantial deviation of vulnerability is assumed within this scenario. Thus hazard, measures and stakeholders are the same as at the single risk optimistic climate change scenario.

3. Conclusions

In an optimistic climate change scenario, the influence of wildfire events into rockfall risk it is not increased significantly. Thus, current risk factors and measures would be applied.

4.3.2.5.2 Pessimistic scenario

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

The scenario considered is basically cumulatively over time and could be also cascading. Both are related to the loss of forest cover (and thus, the forest protection function), as an environmental condition that could affect the rockfall hazard.

1. Multi-risk scenario(s)

General conditions of pessimistic scenario:
Temperature: +4°C (RCP 8.5, 2090)
Precipitation sums: Decrease of precipitation sums per anno (approx. 10%), adverse distribution of precipitation over the year with concentration in winter and long dry periods in summer.
Heavy rain events: Significant increased intensity and sums (>25% - according to +7%/°C potential air moisture).
Wind/storm: Increase of storm events.
Wildfire: Increase of frequency and magnitude.

General conditions of multi-risk scenario:
The exercise is based on the assumption that a wildfire occurs in an Alpine area with a possible effect on rockfall risk due to the loss of forest cover. Thus, the analysis is based on the reduction of rockfall risk.

2. Measures/Actions.

HAZARD

Factors:

Increased temperature (degradation of permafrost), heavy precipitation events, storms:
The changes in rockfall potential to be assumed on the basis of the pessimistic climate change scenario with regard to temperature increase (permafrost), storms and heavy precipitation events are analogous to those of the single-risk scenario.

Wildfire Events: Due to significant increased potential of droughts and under the estimation of ongoing climate change with increased frequency of heat waves (as e.g., in the summer of 2003 in Austria), area wide wildfires will be triggered more often or even regularly (*Wohlgemuth et al., 2010*).

The basal area (stem density in combination with the average breast heights of trees) of a forest stand is the most important factor of rockfall protection capacity. In case of severe wildfires, by time the basal area can be reduced by up to 80 % (Wohlgemuth et al., 2010). This results in critical phases for the protective effect of the forest. Such critical phases persist in medium and severely damaged stands over a period of 40 years, but are most common between 5 and 30 years after a fire (Maringer et al. 2020). So, for the pessimistic climate change scenario, there is a possibility for a sudden loss of area wide protection forests and therefore the hazard (especially the intensity and the run out length of rockfall) will significantly increase.

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

Estimation of changing protection capacity due to wildfires: The online tool RockforNET (https://www.ecorisq.org/rockfor-net-en) can be used to quantify the reduced protective effect of the forest against rockfall caused by a severe forest fire. Secondly, it provides the optimal characteristics of a rockfall protection forest given those conditions. The degree of protection is the percentage of rocks that is stopped by the forest (ecorisQ).

In the following, fictitious case study we look at an approximately 430 m long, 30° steep, forested mountain slope in western Austria. At the upper end of the slope there are steeply rising rocky areas with rockfall potential (yellow areas in the following figure). At the lower end of the slope there is a settlement with several residential buildings. Between the potential rockfall release areas and the settlement, a dense mixed spruce/pine forest grows (green area in the following figure) which under current conditions acts as a natural rockfall protection system.

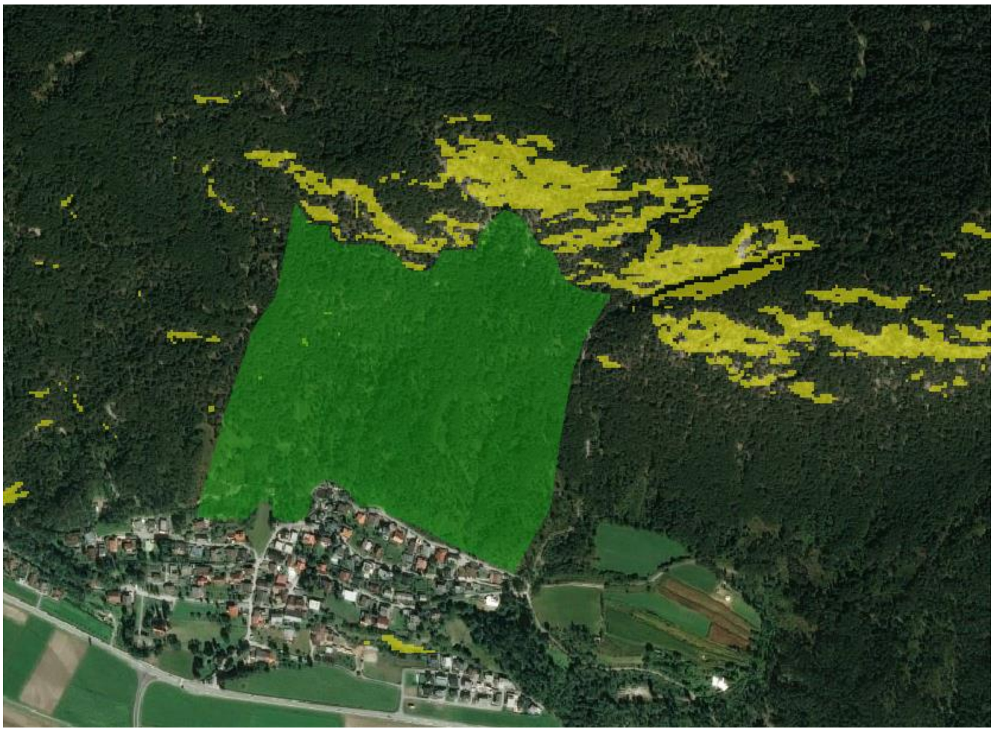

Fig. 3: Potential rockfall release areas (yellow), protection forest (green); source of aerial image: Bing aerial; drawn in QGIS Desktop 3.10.12

In the fictitious case study, a boulder with a volume of 8 m³ releases from a 40 m high rock face. A basal area of 35 m² / ha by 250 stems / ha is assumed at pre-fire conditions:

WILDFIRES/ROCKFALLS
Cumulatively over time and Cascading

Rock characteristics		
Rock dimensions (3x)	2 / 2 / 2	m
Rock density	2500	kg m^{-3}
Rock shape	Rectangular	-
Slope characteristics		
Mean gradient of the slope	30	°
Height of the cliff	40	m
Length of the forested slope (planimetric)	420	m
Length of non-forested slope (planimetric)	0	m
Forest characteristics		
Mean stand density (DBH ≥ 8 cm)	250	ha^{-1}
Basal area (DBH ≥ 8 cm)	35	m^2/ha

1. Current degree of protection: 25 - 50 %

The protection capacity calculated in the RockforNET programme is 25-50% before a forest fire.

Assuming that a severe wildfire reduces the basal area by 50% after the fire and in the following years, the protection capacity is as follows:

Rock characteristics		
Rock dimensions (3x)	2 / 2 / 2	m
Rock density	2500	kg m^{-3}
Rock shape	Rectangular	-
Slope characteristics		
Mean gradient of the slope	30	°
Height of the cliff	40	m
Length of the forested slope (planimetric)	420	m
Length of non-forested slope (planimetric)	0	m
Forest characteristics		
Mean stand density (DBH ≥ 8 cm)	250	ha^{-1}
Basal area (DBH ≥ 8 cm)	17	m^2/ha

1. Current degree of protection: 0 - 25 %

In the post-wildfire scenario, the calculated protection capacity after a severe fire is 0-25 %. It is therefore highly probable that, due to the extensive wildfire, the protective effect of the forest is almost completely lost.

This example is just to be mentioned as a possible kind of a decision support tool, to estimate the future rockfall protection capacity after severe wildfires which could occur in future scenarios. It is intended to illustrate the extent to which there could be an interaction between forest fire and rockfall (intensity) or how (cumulatively) the protective effect of the forest can be negatively influenced by severe wildfires.

Measures:

The measures to be taken on the basis of this scenario would be far-reaching. Up to now, the measures to rockfall has mostly been reactive (response and recovery), which means that technical measures have been taken where damage has occurred.

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Cumulatively over time and Cascading

A sudden large-scale reduction of the protection forest's capacity due to forest fire must be actively and preventively counteracted. And this poses great challenges for civil protection actors. Wherever the protection forest has so far reduced the run-out lengths of rockfalls to such an extent that no technical protection measures was necessary, preventive action is now required. Depending on the dimension of the forest loss, entire valley sides would have to be geotechnically mapped and evaluated. Where the rock faces are weak and loose, rock cross-linking (as an active measure to prevent the triggering of processes) must be carried out.

EXPOSURE

Factors:

Development of settlements and infrastructure: It´s not clear, how the number of citizens and hence the associated infrastructure will develop under the assumed adverse climatic conditions. On the one hand, the negative impact of climate change on the socioeconomic development and increased wildfire and cumulatively rockfall may lead to a downward trend of population in (forested) rural areas and thus decreasing exposure.

On the other hand, the exposure could be suddenly increased due to loss of (up to now) existing rockfall barriers of protection forests. Houses and settlements which have not been exposed to rockfall because a forest stand, could now be affected by impacts of this pessimistic climate change scenario.

Measures:

After severe and area wide wildfires below potential rockfall areas, the exposure of several buildings or whole settlements could suddenly increase, because of loss of the forest’s protective capacity. Therefore, stakeholders must quickly recognize the needs for action. New exposed buildings have to be protected with technical measures or might be evacuated temporary or even relocated. Relocations would be a big challenge for house owners and political decision makers.

In case of endangered highway and train lines, relocation normally is not possible. Technical measures (nets or dams) are necessary and sometimes underground tunnels may be the only way out.

VULNERABILITY

Factors:

According to current estimates, the vulnerability per se will hardly change due to the increased risk of wildfires. However: Since existing protection forests not only reduce the run-out lengths of rockfall, but also reduce the rock fall energies occurring at the potential damage objects, a forest loss when rockfall occurs in the settlement area can lead to increased energy inputs. This is of course a change of the hazard potential and not of vulnerability, but with regard to this mentioned fact, the vulnerability of assets has to be decreased.

Measures:

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To reduce vulnerability, it´s necessary to implement structural measures such reinforcing house walls (reinforced concrete walls instead of garden hedges) or latticework in front of windows to counteract the increased rockfall energies.
Where rockfall runs out in flatter terrain, the rolling type is the main movement mechanism. Therefore, small protective walls (e.g., garden walls instead of hedges) or gabions with even low heights (e.g., 1m) could also reduce the vulnerability.

In the case of a large-scale new exposure of houses to rockfall, these measures cannot be taken by the usual civil protection actors on their own. It is important that political decision-makers communicate the new risk based on the scientific facts to the general public. In the event of the loss of protective forests and the population, it is important to sensitize them to the increased rock fall risk and to create incentives for personal precautionary measures.

3. **Disaster Risk Management Cycle Measures and Actions.**

Prevention:
In the future, it will be necessary not only to consider rockfall hazards reactively, but also to assess the risk in combination with the increased hazard potential after a forest fire (even before events occur). Expert assessments of rock faces should be carried out on the assumption of total forest loss, especially if infrastructure is endangered.
With regard to the multi-hazard scenario of forest fire and cumulatively over time rock fall, special attention must be paid to future early warning, especially where potential areas of detachment of rocks and blocks are located. Even more precise, spatially explicit early warning systems than up to become necessary.
If monitoring or predictability of forest fires can be improved, the question arises whether artificial additional humidification (helicopters with water containers) of forest stands particularly exposed to rockfall could be considered in order to reduce the risk of fires and prevent the effects of subsequent fall processes. This would help to prevent negative cumulative efforts (extensive technical rockfall protection measures) at an early stage.
Fundamental prevention includes above all the preservation of structurally differentiated, species-rich, age-graded protection forest stands. It is important that there is no contradiction between the demands on an optimal rockfall protection forest and the demands on a forest stand that is resistant to wildfire. If it is important to create a mosaic structure (e.g., forest-free aisles) in order to prevent the spread of major wildfires (as mentioned by project partners among others PFC), it must at the same time be ensured that this opening of the stand does not open up new paths for rockfall processes with damage potential. In the same way, if undergrowth and shrubs are removed preventively to reduce flammable fuel, it must be taken into account to ensure that it is not precisely this vegetation that provides additional protection against rockfall at specific locations. Shrubs and bushes are also important for catching stones if, for example, they have already been slowed down by stronger trees before. For preventive measures, therefore, both phenomena (risk of forest fire & rockfall potential) must be coordinated without provoking negative interactions.
The culture of spatial planning is another essential topic in terms of prevention. Local spatial planning must increasingly not only be adapted, e.g., to legally binding single risk plans, but also take into account probabilities such as multi hazard scenarios. Attention must be paid to potential forest loss and subsequent cascade effects at an early stage, already when new building land is designated.

Preparedness & Response:
In the course of incipient or spreading wildfires, there should already be an intensive exchange between the fire brigades (risk managers) and, for example, geologists (hazard planners). Fire

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brigades are often directly in the area of the fire and could identify rock faces or unstable blocks at an early stage and communicate with the geological experts.

Under certain circumstances, stones and small blocks can already release out of root plates during the fire due to falling trees. If this is recognized, an expert opinion on rockfall should be obtained immediately during or at the latest immediately after the fire event. In case of rockfall during the fire event, it could be useful to already cut trees crosswise to the slope (inside intact forest below the fire), in order to provide spontaneous / provisional protection against smaller stone and block falls.

In the course of assessing the potential danger, geologists often explore rock areas difficult to access from the air (helicopters). Therefore, helicopter fire-fighting operations could be combined with a simultaneous initial assessment of the hazard potential of gravitational natural hazards.

Recovery:

In the recovery phase, it is important to consult geologists explore potential rockfall hotspots after the fire event. In this way an assessment of the immediate dangers can be made. If additional infrastructure is exposed to new danger situations due to the loss of the protection forest over a large area (because the run-out lengths and energies of rockfalls have increased significantly), technical protection measures must be installed immediately. Depending on the space available and the potential energies appear, dams or rockfall nets should be established. In future, a simplified legal basis for expropriation should be created for the use of space. The dimensioning of measures primarily requires the determination of the expected block size / design event (in Austria e.g., according to ON24810).

If the forest fire results in the rather unlikely scenario of potentially collapse of larger rock masses, evacuations and, in extreme cases, resettlement will have to be considered more often in the future. At the same time, the establishment of technical protection measures should also be accompanied by forest biological protection measures. The integration and establishment of protection forests as "ecosystem-based risk reduction measures" is indispensable for areas that are increasingly affected over large areas. After forest fires have occurred, the opportunity should be taken to rejuvenate the stand - adapted to the risk situation. Hardwoods for the energy absorption of rockfall in combination with thick-barked coniferous woods with a high fire resistance would be a simple example of a postfire forest structure to be aimed at and at the same time the beginning of multi hazard prevention.

4. Conclusions

Wildfire events will not increase (per se) the rockfall risk, as a direct cascade effect. The wildfire event will affect the forest protection function, which allows to decrease the rockfall energy impact. Thus, the possible measures to apply are basically focused on response and recovery (through forest replantation or technical measures as rockfall nets), to recover these protection function which allows to increase the exposure and vulnerability.

5 Conclusions

Climate change will have a significant **influence on natural risks** analysed: Storms, Floods (flash floods), Wildfires, Avalanches, Landslides and Rockfalls. From the review carried out, it is possible to highlight some specific trend for each hazards:

- Wildfires: global average temperatures and droughts are expected to increase. The intensity and frequency of wildfires will therefore increase. The number of annual fire risk days and the potential of extreme wildfire events (EWE) increase
- Floods (flash floods): increase in the occurrence and intensity of floods in Europe.
- Storms: increase in the occurrence, duration and intensity of winter storms.
- Avalanches: increase in the frequency and magnitude of wet snow avalanche situations.
- Rockfalls: degradation of permafrost due to global warming will favour an increase in the frequency of rockfall above the permafrost limit.
- Landslides: the expected increase in torrential rainfall may lead to a higher frequency of landslides.

In general, an increase in hazard, exposure and vulnerability is expected.

In this context, it is worth of reminding that climate change and its impacts on the risks are affected by high level of uncertainty. This could have some important implications for DRM actions and policies, that should be addressed among other by maintaining flexibility, developing improvements even in absence of climate change, exploiting potential opportunities, and by being able to cope with a range of climate impacts.

From the risk management review, it is worth noting that the underlying idea or focus of most of them identifies as concern a change of mentality and approach to risk management.

The “new” approach proposed mainly consists in:

- a greater collaboration between stakeholders but also a more deepen engagement of the different actors in DRM, including the private sectors and political actors– in the different phases of the DRM cycle;
- a clearer chain of responsibility;
- an integrated and holistic approach of DRM and a better governance.

A further remark is that DRM needs a bigger and consistent economic support. For this reason, many projects work on risk transfer and insurance, in order to strengthen the link between risk transfer and risk reduction.

The challenges posed by climate change on risk management identified through the literature review have been also expressed and confirmed by the civil protection and emergency management stakeholders and risk managers interviewed. As seen, some common needs expressed by the stakeholders interviewed are in fact:

• to strengthen the collaboration between institutions at different levels and between offices of the same agency (not only during an emergency, but in all the phases of the risk management cycle) and innovating the approach of risk management from “protect all” to “live with”;

• to improve the forecasting and monitoring capacities and systems related to the hazards analysed, and so to improve early warning system;

• to get new real-time tools to manage an emergency and to support decisions (including new monitoring and risk assessment tools);

• to better understanding new risk scenarios and uncertainties and integrating climate change impact in risk analysis and mapping, but also to continue knowing and managing the actual exposure and vulnerabilities and improving civil protection plans;

• to rise risk awareness of the population, also by involving the population (for example in the civil protection planning process control plans) and by reinforcing communication, and reinforcing risk perception.

• to integrate territorial, urban planning, forest and agricultural policies in the DRR Framework (included forest protection) and developing legislative measure to facilitate land management.

These needs are referred to all the phases of the risk management cycle, but especially to prevention and preparedness, addressing and embracing the concept that by collaborating and working on prevention and preparedness, the emergency response could require less efforts.

The most important measures to respond to the **needs of emergency management bodies and risk managers to cope with the impact of climate** change have been linked with the risk factors identified per each natural hazard[20]. Some of them are reported below.

- Hazard Measures
    - Forest management: priority should be given to mixed and age-uneven forest formations. Especially species with root systems more resistant to the effects of wind (see Storms single risk analysis).
    - Monitoring: improve the forecasts of meteorological models and incorporate new monitoring systems that allow an effective response to a risk situation (see Floods and Rockfalls single risk analysis).
    - Promote forest structures and choose of species better adapted to climate change: climate change implies changes in weather. It is therefore necessary to identify and promote those forest structures (i.e., able to avoid high intensity fire behaviours) and species that are best adapted to climate change and which in turn help to reduce the hazard (see Wildfires single risk analysis).
    - Modelling: it is necessary to model the hazard in those areas most exposed and vulnerable. In this way we will be able to determine the future magnitude of the hazard (see Avalanches and Landslides single risk analysis).

[20] See Deliverable 2.1 *Report on data attributes for integrated risk assessment and planning of wildfires, floods, storms, avalanches, rockfalls, landslides and their interactions* .

- Exposure Measures
    - Risk assessment and mapping tools: detailed mapping (e.g., 1:5.000) is necessary to assess the level of exposure in the territory (see Storms and Landslides single risk analysis).
    - Spatial and urban planning: to integrate the most hazardous areas into spatial and urban planning so that guidelines can be established for the development of the territory and exposure to risk can be reduced to a minimum. For example, establish a zoning according to the degree of hazardousness: buildable area without protection, buildable area with protection and non-buildable area (see Floods, Avalanches and Rockfalls single risk analysis).
    - Early warning systems: due to the expected increase in the frequency and intensity of extreme events there is a need to develop effective early warning systems to reduce exposure and vulnerability to risk (see Wildfires single risk analysis).
    - Technical protection systems: the growth and expansion of activities in mountain areas leads us to think and plan carefully about protection systems to reduce vulnerability to risks (see Rockfalls single risk analysis).
    - Safety programs and awareness-raising measures: e.g., cutting-off roads to reduce exposure to risk. In situations where there is an increase in risk, it is necessary to carry out awareness-raising measures (greater communication/information to users) (see Rockfalls single risk analysis).

- Vulnerability Measures
    - Planning and training/drill measures: update civil protection plans to strengthen the response to future alert or emergency situations. Promote training (education, drills, etc.) in the population to know the protocol of action in case of alert or emergency (see Storms and Floods single risk analysis).
    - New operative tools: development of new tools that collect real-time information to facilitate a rapid and effective response to reduce vulnerability (see Wildfires single risk analysis).
    - Protection systems: review, strengthen and install risk protection systems taking into account future climate change trends in each region (see Avalanches and Rockfalls single risk analysis).
    - Mandatory insurance: promote insurance to help reduce the vulnerability of people and companies and facilitate subsequent recovery in the event of serious damage (see Landslides and Wildfires single risk analysis).

Finally, some general conclusions can be drawn from the **multi-risk analysis**:

- The risk of wildfires has an obvious effect and influence on the other natural risks (Storms, Floods, Avalanches, Landslides, Rockfalls). This incidence enhances the negative effects on the risk territories.
- Other natural risks (e.g., storms or avalanches) can also increase the risk of wildfires. Storms and avalanches are two natural phenomena with the capacity to destroy large forest areas and generate dead fuel that can facilitate the ignition and spread of wildfires.

- Multi-risk situations imply a response to a previous emergency situation (e.g., wildfires, storms with intense winds, etc.) that has affected/modified a risk in the territory. This major impact implies an increase in the frequency and intensity of other natural hazards. Therefore, there is a new scenario with a more unstable and hazardous terrain where the risk has increased.
- On that sense, the measures envisaged are response measures to a previous emergency situation and are aimed at preventing future risk situations that could be aggravated if the affected areas are not properly managed. The idea is that a territory affected by an extreme event (wildfires, extreme avalanches, intense storms, flash floods, etc.) should be reinforced and protected in order to minimise and reduce the risk of other possible natural hazards.
- This reinforcement and protection need to be implemented through concrete measures that allow organise the actions on the terrain and the stakeholders involved. Therefore, action and implementation of measures on the terrain affected must be as quickly as possible. To this end, it is necessary to develop protocols and measures of action for each particular case.

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Annex I

CIVIL PROTECTION & EMERGENCY MANAGEMENT STAKEHOLDERS]

This interview is focused on natural hazards (including forest fires) so we must exclude manmade hazards (technological hazards like accidents in chemical factories or during transportation involving dangerous goods).

DATA OF THE INTERVIEW		**Num**		**Date**		**Partner**	
Name				Email			
Position							
Organization/Service							
Main duties							

EXTREME EVENT EXPERIENCED
1. What is the biggest single and/or multi natural hazard situation you have ever experienced in your professional career as a part of the emergency response system? (e.g. e.g. Gloria storm in Catalonia).
2. *Regarding the event, please describe shortly this event in terms of:* • Site and date • Hazards / multi-hazard involved and potential interactions and cascade effects • Predictability (and level of uncertainty) and return period of the event • Causes of the event (meteo, seismic,…)” • Spatial and temporal scale • Dynamics (physical evolution) of the event
3. *Describe the main points of the emergency management and its post emergency management of this extreme event in terms of:* • Data and tools used (for monitoring-forecasting / communication / coordination / rescue and assistance / data collecting and updating / risk scenarios knowledge and static data) • Territorial levels and authorities activated and typology of actions • Means and resources used • Main direct and indirect damages • Risks in the aftermath
4. *Taking a back analysis:* What are the main points of weakness that the emergency management system had? (in general: communication within institutions, communication/coordination between institutions, communication with population, data and information availability, decision-making process, information discrimination schemes, resources management, Standard Operating Procedures, civil protection plan,..)
5. What are the best practices that the civil protection system used during this event?

CLIMATE CHANGE (CC) RELATED SCENARIOS
Taking into account the extreme event described and considering this event able to represent a hypothetical CC scenario: 1. What will be the main changes and challenges of the civil protection system in order to face this/these CC scenario/s?
2. Would you have new needs in this scenario in terms of operational management? (e.g. new decision-making scenarios, faster decisions, new decision-making schemes, new perspectives like focus more in psico-social aspects, more resources, new prevention approaches, new planning approaches or tools…)
3. Would you have new needs in this scenario in terms of operational tools? (e.g. better communicating tools, new or better forecasting tools, monitoring tools, nowcasting, geographical information and tools, DSS tools (e.g. multicriteria modelling systems)
4. Would you have new needs in this scenario in terms of data integration? (e.g. new platforms, new outcomes, new tools, faster tools, improved visualization tools, redundant systems, background information, information from other institutions like municipalities or agencies…)
5. How the balance between prevention-preparedness-response efforts/actions could be improved? How their interactions and balances should change or improve to face these new scenarios? Through which actions?
6. What should be improved in the prevention and preparedness phases by the civil protection system in order to have a more effective and efficient emergency management and response system? (e.g. more detailed risk scenarios, civil protection plans...)
7. Could you identify a possible trigger effect pattern in this situation?
8. What is the role of the population preparedness for facing this CC scenario?

OBSERVATIONS / COMMENTS
In case the interviewed wants to add some further comment, suggestion, observation, about the overall interview or about some specific point, whether it's related to the gap between the current situation and the convenient/desirable situation or the gap between the current situation and future situations facing CC scenarios. *The interviewer may also express his or her opinion about the interview, about these issues or about the interviewed.*

[RISK MANAGERS]

DATA OF THE INTERVIEW		Num		Date		Partner	
Name				Email			
Position							
Main duties							

CLIMATE CHANGE RELATED SCENARIOS
1. What is the **biggest single and/or multi natural hazard situation you have ever experienced** in your professional career as a part of the risk management system? (e.g. e.g. Gloria storm in Catalonia?)
2. What are the **territorial vulnerabilities** that have increased the impacts and damages and that have affected the emergency management?
3. What are the **best practices developed** in the territory (in terms of risk assessment, mapping and planning tools, risk governance and policy, risk culture and communication, technical measures) that have **mitigated** the **impacts** and **damages** and that have favored the emergency management?
4. *Taking into account the* ***extreme event described*** *and considering this event as a proxy of a hypothetical CC scenario:* What will be the **main changes** and **challenges** of risk managers in order to face this CC scenario?
5. Would you have **new needs** in this scenario in terms of **risk assessment** tools? (in terms of risk knowledge and comprehension)
6. Would you have **new needs** in this scenario in terms of **risk management** (in prevention)?
7. What should be **improved / modified** in the **prevention phase** by risk managers and other stakeholders in order to integrate this CC scenario in the disaster risk reduction measures?
8. What could you **provide to the civil protection** system in order to have a more effective and **efficient** emergency management and response system?
9. How could the balance between **prevention-preparedness-response** efforts/actions be improved? How should their interactions and balances change or improve to face these new scenarios? Through which actions?

OBSERVATIONS / COMMENTS
In case the interviewed wants to add some further comment, suggestion, observation, about the overall interview or about some specific point, whether it's related to the gap between the current situation and the convenient/desirable situation or the gap between the current situation and future situations facing CC scenarios. *The interviewer may also express his or her opinion about the interview, about these issues or about the interviewed.*

Annex II

WORKPACKAGE 3. Impacts of Climate Change projections on multi-hazard risk management. **Task 3.2.** Integration of Climate Change scenarios into multi-hazard risk assessment and planning. Each partner has to identify and describe the single/multi-risk scenarios and re-evaluate the risk factors, identifying new Emergency Bodies (Civil Protection, etc.) and Risk Managers requirements.	
SINGLE RISK **(Wildfires, Storms, Floods, Avalanches, Landslides, Rockfalls)**	
Question	1. How does Climate Change modify the factors and components of Risk and the needs of the Emergency Bodies (Civil Protection, etc.) and Risk Managers? Please, search the existing literature on how Climate Change affects risk factors and components and describe them.
Describe the new risk scenario/s foreseen.	
Hazard	**1. Factors.** 1.1. **2. Measures/Actions-New requirements/Stakeholders.** 2.1.
Exposure	**1. Factors.** 1.1. **2. Measures/Actions-New requirements/Stakeholders.** 2.1.
Vulnerability	**1. Factors.** a. **2. Measures/Actions-New requirements/Stakeholders.** a.

WORKPACKAGE 3. Impacts of Climate Change projections on multi-hazard risk management. **Task 3.2.** Integration of Climate Change scenarios into multi-hazard risk assessment and planning. Each partner has to identify and describe the single/multi-risk scenarios and re-evaluate the risk factors, identifying new Emergency Bodies (Civil Protection, etc.) and Risk Managers requirements.	
MULTI-RISK	
Question	**1. Please define/explain your multi-risk scenario(s).** **2. The multi-risk scenario(s) you will consider are simultaneously, cascadingly or cumulatively over time?** **3. What measures or actions do you propose to manage this multi-risk interaction?** **4. Conclusions.**