Landslides
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Wildfire-induced geohydrological risk in the Alps

Abstract Wildfire-induced geohydrological risk in the central-eastern Alps is addressed by synthesizing publications in the Alps and a first inventory of fire-induced geohydrological processes, identifying future challenges, and proposing a procedure for indicator identification within an integrated fire management strategy for policymakers. Using representative data sets, findings are transferrable to other areas in the Alps. We discuss how wildfires, intensified by climate change, human activity, and urbanization, are altering mountain ecosystems and increasing the risk of geohydrological processes like erosion, and gravitational mass movements such as rockfalls, slides, and debris flows. Key terminology is clarified. Important settings of the Alps for wildfire occurrence and resulting geohydrological processes are summarized. The effects of wildfires in different geological settings in Austria, Northern Italy and Switzerland are described to help explain indicators for burn severity and for geohydrological processes during and following a wildfire event. The first inventory of post-wildfire geohydrological processes in the Alps is also presented. The importance of understanding the effects of wildfires in different geological settings in the Alps and proposed systematic documentation procedures for integrated fire management strategies is emphasised.

Keywords Alps · Wildfire · Geohydrological processes · Erosion · Rockfall · Landslide · Debris flow · Risk

Introduction

In the Alps, wildfires are a disturbance that can have cascading effects on slope and catchment characteristics and on vegetation, soil, and rock properties (Melzner et al. 2022). Soil becomes susceptible to erosion once vegetation is removed and/or burnt (Nyman et al. 2013). In mountainous regions like the Alps, this can also lead to increased runoff (Marxer et al. 1998). In severe cases, it can result in gravitational mass movements and debris flows (Esposito and Gariano 2025). Such effects alter the landscape, can increase geohazards locally, but can also lead to sedimentation in rivers and lakes, and impact water quality and aquatic life (Conedera et al. 2003). While wildfires have always been part of mountain ecosystems, the risk of wildfires and post-fire induced geohydrological processes have intensified due to climate change, human activity, and urbanization (Melzner et al. 2022).

The tectonic evolution of the Alps creates spatially varying geologic, topographic and geomorphological conditions. These variable conditions in geology and topography highly influence the occurrence of ecosystems at different elevations and have an impact on the evolution of a fire, its area and on fire-induced geohydrological processes. In addition, historical settlement development and landscape and vegetation structures that are associated with these spatially varying conditions (Melzner et al. 2022) also impact the spatial evolution and fire regime.

The Alp's geography, prevailing winds and vegetation, and the heat/thermals generated by a fire, also impact a fire's characteristics. This includes fire type (ground fire, surface fire, or crown fire),speed, intensity, duration, and height, in addition to the spatial pattern of spread (Melzner et al. 2022). Fires not only completely or partially destroy the vegetative cover, but they also have both an immediate and indirect effect on the protection function of forests. Geohydrological processes such as erosion, rockfall, shallow landslides and debris flows are likely to become more frequent as a result of the physical and chemical effects of fires on both the soil and rock mass structure (Melzner et al. 2019).

The impacts of fire on the landscape are relatively well known. They include changes in: (i) general geomorphological factors in fire-affected areas (e.g. Heel 2015; Regione Piemonte 2017; Melzner et al. 2019, 2022; Nyman et al. 2020; Roehner et al. 2020; Vega et al. 2020; Rengers et al. 2023), (ii) forest protection function against landslides and rockfalls (e.g. Maringer et al. 2016; Sass 2019; Gehring et al. 2019; Melzner et al. 2019, 2022), (iii) geotechnical properties of soils and rocks (e.g. Melzner et al. 2019; Sarro et al. 2021; Shtober-Zisu and Wittenberg 2021a, b; Peduto et al. 2022a, b), (iv) initiation processes of debris flows (e.g. Cannon 2001; Cannon et al. 2001, 2003a, b; Tillery and Rengers 2019; Alessio et al. 2021), (v) rill erosion (e.g. Galanter et al. 2018; Alessio et al. 2021), (vi) decay in root reinforcement and its impact on slope stability (e.g. González-Pérez et al. 2004; Jackson and Roering 2009; Schwarz et al. 2015; Cohen and Schwarz 2017; Vergani et al. 2017), (vii) the hydrogeological behaviour of mountain catchments (e.g. DeBano 2000; Conedera et al. 2003; Onda et al. 2008), (viii) hydraulic systems of tree species, tree mortality and tree line (e.g. Hofmann et al. 1998; Maringer et al. 2016; Baer et al. 2019), (ix) impact on forest carbon budget and floodplain organic carbon (e.g. Wohl et al. 2020; Loiselle et al. 2020), (x) fire and post-fire management strategies on the regeneration of forests in the Alps (e.g. Providoli et al. 2002; Regione Piemonte 2017; Conedera et al. 2017).

Most studies on the geohydrological impacts of wildfires have been from the USA, Mediterranean region and Australia (Kean et al. 2011; Nyman et al. 2011, 2015; Shakesby 2011; Tillery and Rengers 2019; Hoch et al. 2021; Sarro et al. 2021; Esposito et al. 2022; Rengers et al. 2024). In contrast, only a few publications have focused on wildfire-induced geohydrological processes in the Alps (Grabherr 1936, 1950; Providoli et al. 2002; Conedera et al. 2003; Sass et al.

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2010a, b; Heel 2015; Conedera and Pezzatti 2016; Maringer et al. 2016; Sass 2019; Gehring et al. 2019; Melzner et al. 2019, 2022; Tiranti et al. 2021; Müller et al. 2021; Mandrone et al. 2023). Furthermore, a framework synthesizing existing spatial and temporal data about post-fire processes and risk is lacking for the Alps.

This synthesis study addresses the multidisciplinary issue of wildfire-induced geohydrological risk in the Alps by (i) presenting characteristic conditions in the Alps impacting the spatial distribution of wildfires and geohydrological processes, ii) proposing a systematic procedure for documenting the identification of indicators for the estimation of post wildfire risks, and iii) identifying future challenges. Terminology is clarified (Table 1) and important settings of the Alps for wildfire and geohydrological processes summarised. Factors such as soil, rock and vegetation properties that influence geohydrological processes (i.e. rockfalls, slides, debris flows and erosion processes) during and after a wildfire event are discussed using four wildfire case studies. Key objectives are to highlight understanding of the impact of wildfires in the Alps, to publish a first inventory of fire-induced geohydrological processes and to contribute knowledge to aid effective integrated wildfire management and conservation efforts in mountainous regions facing the challenge of climate change.

Methods

Collection of data

While wildfire databases exist at national levels in the *Alps* (e.g., Austria, Switzerland, Slovenia, France, Italy), they are not fully harmonized and data are often not publicly available. Our study utilizes wildfire data from three countries (Fig. 1).

Switzerland has a nationwide forest fire database called Swissfire (www.swissfire.ch), which is a central component of the national forest fire strategy. It was developed in 2008 in a collaboration between the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Federal Office for the Environment and the country's 26 cantons (Pezzatti et al. 2019). The database can be considered complete for fires of ≤1 ha since about 2000. Since then, on average 106 forest fires have been reported annually, affecting an average area of 151.5 ha (Fig. 2 in Melzner et al. 2022). Since 2023, fires smaller than <1 ha have also systematically been recorded.

Austria has a nationwide Forest Fire Web GIS application (https://fire.boku.ac.at/firedb/en/), which was developed by the Institute of Silviculture, University of Natural Resources and Life Sciences (BOKU) as part of several projects (i.e. AFFRI, ALP_FFIRS, FIRIA) (Vacik et al. 2011; Müller et al. 2013, 2021). Since 2008, data are collected by interviewing communities and searching firefighter reports. The increasing volume of data necessitated a reorganisation of the recording process in 2012. An information portal enables interested parties to query forest fire events via an interactive map and to generate statistics or graphics.

In *northern Italy*, the *Autonomous Region of Friuli Venezia Giulia* has a regional fire data archive (A.R.D.I) system for the management of forest fire data. With A.R.D.I., the Regional Forestry Department manages the recording of descriptive (alphanumeric) information on forest fires, of geographic-cartographic information, such as the total perimeter of the burnt area (Total Geometry), the sub-areas identifying the wooded, unwooded or pasture areas (Specific Geometry) and the starting point of each fire. The geographical database of forest fires was set up by digitizing the forest fire news sheets (FNIBs) since 1990 in accordance with Regional Law no. 8/1977 by the competent Forestry Stations. In 2003, the FNIB data were digitized through the "Catasto degli incendi boschivi" (Forest Fire Cadastre) application and subsequently updated in 2009 with the A.R.D.I. application. Computer and spatial data have been made available since 2008 through the IRDAT portal https://irdat.regione.fvg.it/ and subsequently through the EAGLE FVG portal (https://eaglefvg.regione.fvg.it/eagle/main.aspx?configuration=guest).

Databases of *geohydrological processes* exist at national levels, but those of different countries in the Alps are, like those of wildfires, also not harmonized nor often publicly available. In Austria, for example, there are national-level databases from Geosphere Austria and Austrian Torrent and Avalanche Control, and databases from the nine federal state governments.

Based on the INSPIRE Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007, a European harmonized geodata infrastructure was established. INSPIRE aims to optimize the exchange, sharing, accessibility and use of interoperable spatial geodata and spatial data services at European level in order to provide the best possible support for decision-making in relation to policies (https://www.inspire.gv.at/) and measures that may have a direct or indirect impact on the environment.

Lastly, data on *fire-induced geohydrological processes* has to date not been systematically collected in the Alps and monitoring sites are yet to be installed. Observations of geohydrological processes were mainly made by wildfire experts (i.e. fire fighters, foresters) dealing with the management of the wildfire and its impacts on communities. More detailed data on geohydrological processes was collected in the field by geoscientists during a disaster or by interviewing wildfire experts (i.e. fire fighters, forest scientists) following the fire. In addition, detailed mapping using high resolution Lidar data together with photos taken during and after the fire provided additional data. Repeat site inspections at regular intervals together with any information on processes reported by habitants of affected sites completed the data collection (e.g. Table 2).

Definition of indicators for burn severity of wildfires in the Alps

Determining the geohydrological hazard potential of an area that was burnt requires the development of a post-fire burn severity map and how the fire affected the functioning of ecosystems, including the soil, rock structure and geohydrology in the area (Parsons et al. 2010; Rengers et al. 2020). The Normalized Burn Ratio (NBR) index is a tool that allows burned areas to be mapped and for assessing the severity of fires (Keeley 2009). By leveraging satellite imagery, the NBR index calculates the difference between near-infrared (NIR) and shortwave infrared (SWIR) reflectance values, which are sensitive to vegetation health and soil conditions (Keeley 2009). Healthy, unburned vegetation reflects more in the NIR range and less in the SWIR range, while burned areas reflect less in NIR and more in SWIR. The NBR index produces a clear distinction between burned and unburned areas. A high NBR value indicates healthy vegetation while a low value indicates bare soil and recently burnt areas. In unburned areas the Normalized Burn Ratio (NBR) typically produces positive values,

Table 1 Terminology

Term	Meaning	Reference
Wildfire	Any uncontrolled fire that spreads rapidly across vegetation, including forests, grasslands, shrublands, and prairies	modified after Pezzatti et al. (2019)
Forest fire	Specific type of wildfire that occurs within forested areas. It involves the burning of trees and underbrush in a forest environment	modified after Pezzatti et al. (2019)
Event	The sum of the effects of one or more processes that are spatially, temporally and causally related and whose effects are noticeable because they go beyond the usual level and often are associated with damage	(Hübl 2016)
Fire effect	The physical, biological, and ecological impacts of fire on the environment	(Machlis et al. 2002)
Fire intensity	The amount of energy or heat released per unit time or area during the consumption of organic matter from fire	(Keeley 2009)
Burn severity	How the fire intensity affects the functioning of the ecosystem in the area that has been burnt and often varies within the affected area	(Keeley 2009)
Ground fire	Consumes the organic material beneath the surface litter ground, such as peat fire, such as peat fire	(Melzner et al. 2022)
Surface fire	Burns loose debris on the surface, which includes dead branches, leaves, and low vegetation	(Melzner et al. 2022)
Running fire	The fire front captures the burnt material on the ground surface and trees are only burnt in the lower area of the trunk (trunk base)	(Melzner et al. 2022)
Crown fire or consumption	Combustion of the twigs and needles or leaves of a tree during a fire	(Melzner et al. 2022)
Crown scorch	The browning of needles or leaves in the crown of a tree or shrub caused by heating to lethal temperature during a fire. Crown scorch may not be apparent for several weeks after a fire	(Popescu et al. 2022)
Protection forest	The term *protection forest* is used inconsistently and sometimes misleadingly both nationally and throughout the Alps. The main function of a protection forest is to protect people, goods and infrastructure from natural hazards	(Teich et al. 2022)
Geohydrological processes	includes gravitational mass movements, erosion processes and debris flows (see Figs. 1a and 1b**)**	Authors of this publication
Gravitational mass movements	Are driven by gravity and can be classified according to their failure mechanisms (falling, sliding, creeping, flowing, spreading) and involved material (rock, debris, soil) into different gravitational mass movement types. Depending on the ratio of water and entrained solid materials, some authors (e.g. Davies 1988) classify debris flows as gravitational mass movements or hydrological processes Fig. 1a and b	(Davies 1988; Hungr et al. 2014)
Erosion processes	Are characterized by a transport medium (i.e. water, wind) and can be distinguished into linear erosion processes (i.e. rill, gully) and areal erosion processes (denudation)	(Dikau et al. 2020)

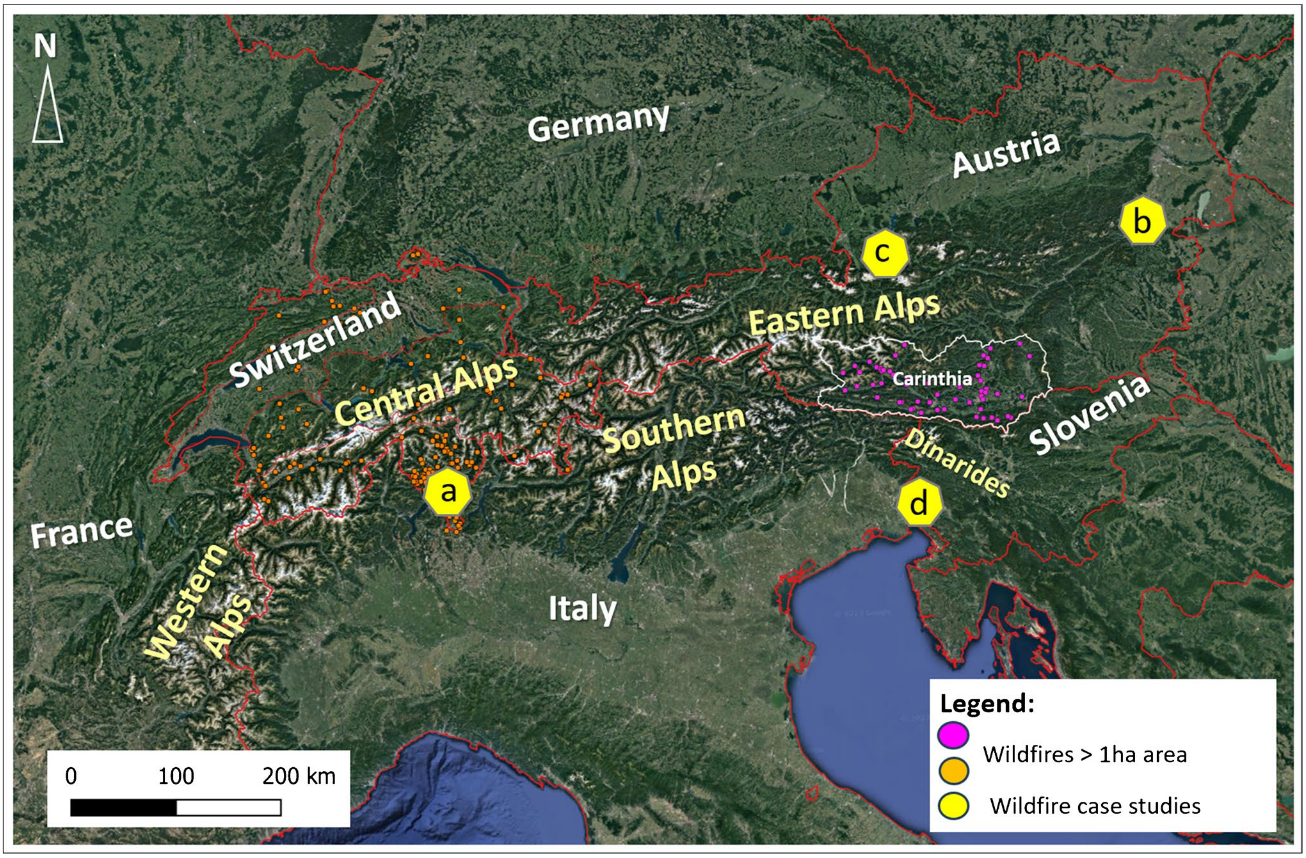

Fig. 1 Geographic Units of the Alps. Orange points are wildfires > 1 ha in Switzerland. Pink points are wildfires > 1 ha in Carinthia. (a–d) Correspond to the wildfire case studies: (a) Verdasio (Switzerland), (b) Hirschwang (Austria), (c) Hallstatt/Echern Valley (Austria), (d) Trieste (Italy/Slovenia) (Forest fire database in Switzerland and Austria: https://www.swissfire.ch, https://fire.boku.ac.at/firedb/en)

generally ranging from 0.2 to 0.7. NBR values close to zero areas are normally attributed to burned or unproductive vegetation (Key and Benson 2005). The Sentinel-2 satellite provides optical imagery with a spatial resolution of 20 m and can be downloaded on the Copernicus homepage (https://dataspace.copernicus.eu/). The difference between the pre-fire and post-fire NBR obtained from satellite images is used to calculate the *delta* NBR (dNBR or ΔNBR), which is used to estimate the burn severity. A higher value of dNBR indicates more severe damage, while areas with negative dNBR values may indicate regrowth following a fire (Keeley 2009).

Normalized Burn Ratio (NBR) and delta NBR (dNBR) were calculated in different areas the Alpine Region with varying characteristics (i.e. topography, geology, vegetation) to identify different burn severity using the NBR index. These results were compared and validated with field evidence.

To date, there is no standard for systematic field mapping of burn severity indicators and of wildfire induced geohydrological processes to aid effective wildfire management for the Alpine region (Melzner et al. 2019). As part of this study, a catalogue of indicators of burn severity for vegetation, soil and rock was developed based on the field experiences and interviews with experts (Table 2).

Alps

Geology and geography

The Alps are a mountain range with an arc form that is between 120 and 250 km wide and about 1000 km long (Fig. 1). The Southern Alps, Eastern Alps, Central Alps, and the Western Alps Arc are the four primary regions that comprise the Alps (Fig. 2). Distinct geological structures and a particular geomorphology are the result of paleogeographic features that occurred at different times during the Alpine tectonic history, and characterize each region (Schmid et al. 2004).

The tectonic units of the Alpine orogenic belt descend under the sediments of Miocene extensional basins of the Pannonian Basin System (Vienna Basin in the north and Styrian Basin in the south) marking the eastern boundary of the Alps, which generally runs north–south from Vienna to the south. Although the Alps and the Dinarides cannot be clearly distinguished geographically in the southeast, the Southalpine Unit is thrust southward along a Neogene thrust belt onto the northwest-vergent Dinaric fold and thrust belt (Schmid et al. 2004). The Po Basin, which is still a foreland

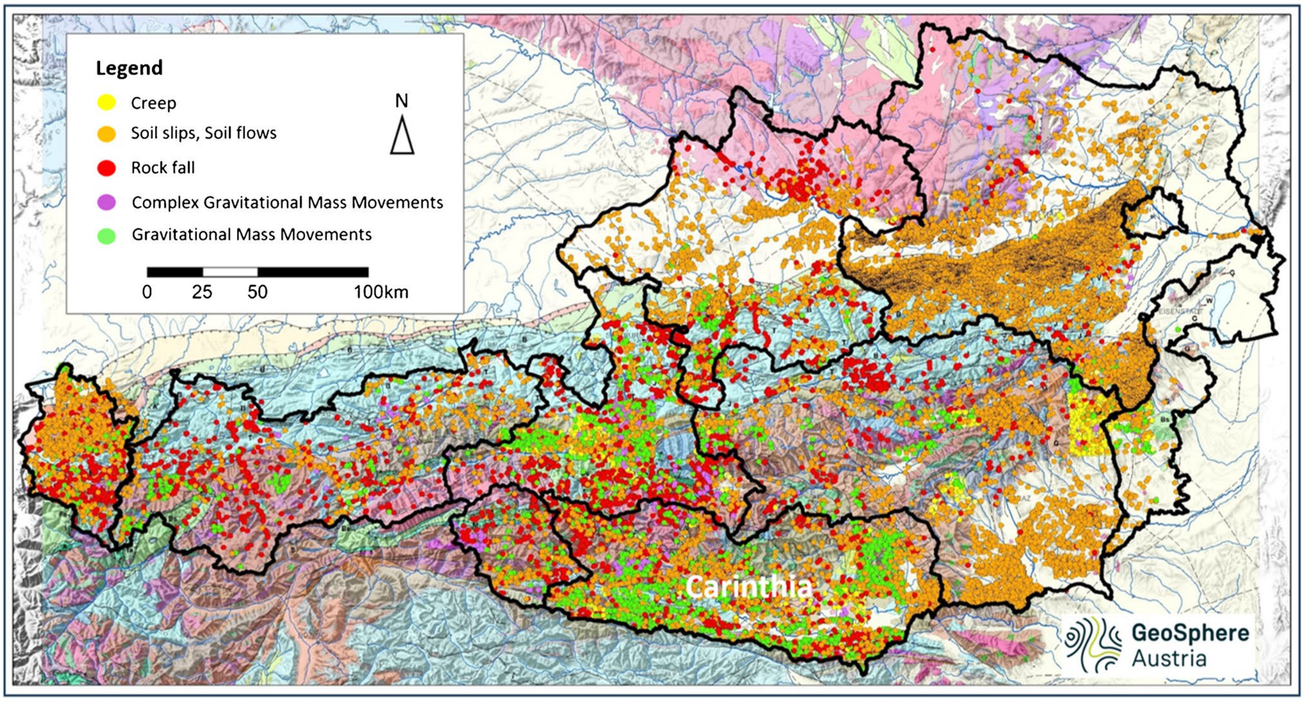

Fig. 2 Inventory map showing the spatial distribution of gravitational mass movements in Austria (GEORIOS inventory database, GeoSphere Austria data extraction date 12/2023 by N. Tilch; Geological map: Schmid et. al., 2004)

basin that is actively subsiding and absorbing sediments, is a representation of the southern foreland basin. The Provençal Mountains and the Po basin are next to the Western Alps arc. The latter is a group of mountain ranges that strike west–east and structurally represent the eastern extension of the Pyrenees (Froitzheim and Schmid 2009). The fill of the Cenozoic Rhone-Bresse Rift borders the Alps to the north of these mountains. Further north, the chain of the French and Swiss Jura Mountains separates from the frontal part of the Alps. The same tectonic processes that formed the Alpine orogenic belt also created this arc-shaped, west-to-north vergent mountain range. A large part of the Swiss Molasse Basin is located between the Alps and the Jura Mountains. It continues eastward across Austria and Bavaria to Vienna. Unlike the Po Basin, the northern foreland basin of the Alpine orogenic belt is uplifted and undergoing erosion. Due to its location atop the Alpine nappe pile, the western portion of the Swiss Molasse Basin, which is situated south of the Jura Mountains, is now known as a piggy basin (Froitzheim and Schmid 2009).

Spatial distribution of gravitational mass movement types

The heterogeneous geological and geomorphological setting in the Alps results in a high variability of processes (Figs. 2 and 3) and interrelationships between processes in which the output of one serves as the input for the next (i.e., a process chain). In general terms, the spatial occurrence of the different types of gravitational mass movements in the Alps includes the high mountain areas with the glacially over steepened U-shaped valleys that are predominantly characterized by deep seated gravitational slope deformations (DSGSD), rock slides and rock falls. The quaternary slope coverings, loose material or weathered debris of the valley fills are highly susceptible to soil slips, slides (translational and rotational) and secondary rockfalls (Agliardi et al. 2001; Crosta et al. 2013; Melzner et al. 2015). Furthermore, debris flows are common in the high mountain environments (Huebl and Nagl 2019; Hürlimann et al. 2019; Nagl et al. 2020). In the north of the Alps, the low mountain range landscapes are characterized by plateaus and comparatively gentle hills. In such lower elevation alpine regions, the susceptibility for gravitational mass movements can also be very high with moderate slope inclination but susceptible geological settings. Rock falls mainly occur along valleys with steep slopes where there are numerous rock outcrops (Melzner et al. 2019). The areas of the low mountain ranges, where there was no ice cover during the Pleistocene ice ages, are characterized by deep soil weathering (Tilch et al. 2009; Chifflard and Tilch 2012). These soils are highly susceptible to shallow landslides and soil flows (Tilch et al. 2014; Vecchiotti et al. 2016; Mergili et al. 2019). In the basin landscapes and wide valleys, which are drained by the main rivers (e.g. Danube) and their tributaries, in addition to earth flows and soil creep, sliding in solid or loose rock (translational or rotational slides) is the dominant process.

Wildfire occurrence in the Alps

Overview

The Southern and Central Alps high mountain regions of Switzerland account for most of the documented wildfire events between 2000 and 2022 with a fire-affected area larger than 1 ha (see Fig. 1 and

Table 2 Indicators of burn severity for vegetation, soil and rock (based on Parson et al., 2010, Melzner et al. 2019, 2023)

Burn severity	Vegetation	Soil	Rock
Low			
	Canopy and understory vegetation are not burned (likely appear in green color)	Ground cover: little or no change from pre-fire status- less than 50% consumption of litter, some char. Needles and leaves are mostly intact	Surface organic layers are not completely consumed and still recognizable
		Surface organic layers are not completely consumed and still recognizable	
		Ash color: ground surface may be black with recognizable fine fuels	
		Soil structure:	
		Roots are generally unchanged	Roots are generally unchanged
		Structural aggregate stability is not changed from its unburned condition	Rockmass structure is not changed from its unburned condition
		Ground surface may appear brown or black (lightly charred)	Rock color is unchanged
Moderate			
	Canopy and understory vegetation may be burned (brown color), but not all	up to 80% of the pre-fire ground cover (litter and grand fuel) is consumed, but incomplete; recognizable leaves and needles remain	
		Fine roots ($<0{,}25$cm φ)may be scorched but rarely completely consumed	
		Ash color: thin layer of black to gray ash with recognizable litter beneath it	
		Potential for recruitment of effective ground cover from scorched needles or leaves remaining in the canopy that will soon fall to the ground	
		Color of the burned site is often brown due to canopy needle and other vegetation scorch	
		Soil structure is generally unchanged, in talus slopes may cracks form	Rockmass structure is generally unchanged, sometimes forming of deep cracks in the rock
High			

Table 2 (continued)

Burn severity	Vegetation	Soil	Rock
	Canopy is dark brown or black (charring), understory vegetation is fully consumed	Nearly all of the pre-fire ground cover and surface organic matter (litter, duff, and fine roots) is consumed (more than 80%); all or most of litter and duff has been consumed	Roots in the rockmass structure are consumed
	Leafs and needles are consumed	Charring may be visible on large roots	Charring may be visible on large roots
		Fine root consumption or charred larger roots in the surface soil horizon	
		Prevailing color of the site is often black due to extensive charring	Color can differ depending on the rock type
		Bare soil and ash is exposed and susceptible to erosion, and aggregate structure may be less stable	Bare rock is exposed, rock disintegration
		Ash Color: white or gray (up to several centimeters in depth) indicates that considerable	Formation of thin flakes, shattering, spalling and exfoliation
		Ash depth: thick layer of powdery gray or white ash	
		Sometimes very large tree roots (> 8 cm diameter) are entirely burned extending from a charred stump hole	rock mass structure is disintegration
		Soil color: often gray, orange, or reddish at the ground surface where large fuels were concentrated and consumed	

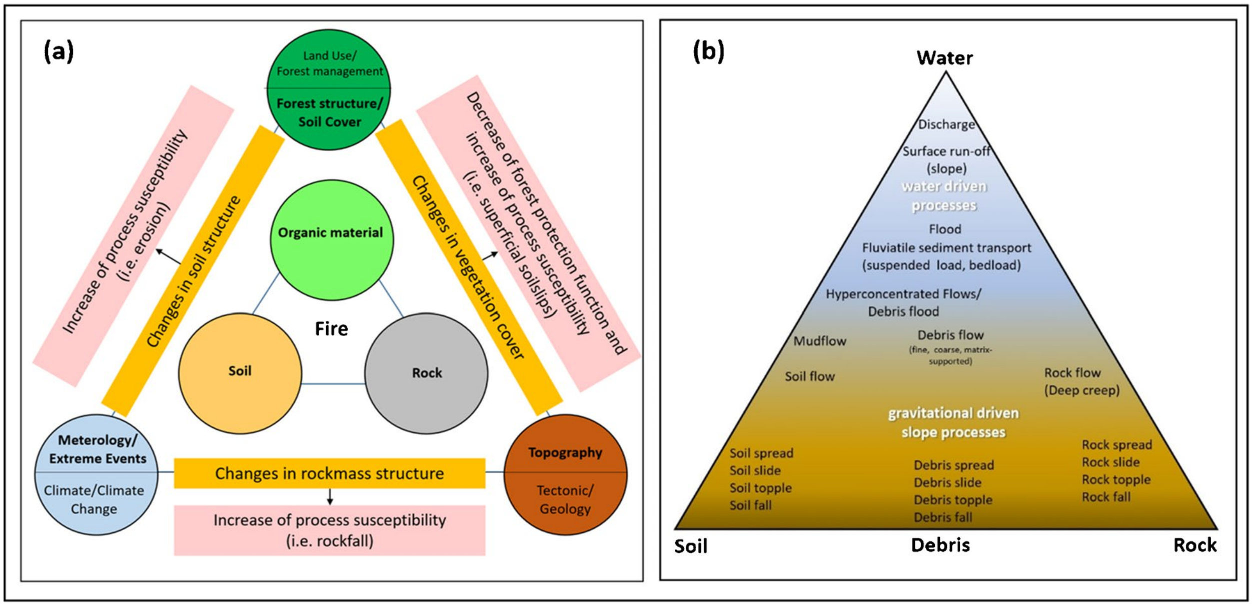

Fig. 3 The effects of wildfire on slopes and catchments (a). Predisposing factors on the occurrence of post-fire geohydrological processes (b). Classification of geohydrological processes (Fig. 3b was modified from Davies 1988)

Table 3). Chestnut forests in valley floors and lower slope areas are primarily affected. In contrast, beech and coniferous forests in these locations were burned less frequently. On the higher slope regions of alpine valleys, coniferous woods, like spruce and pine are mainly affected. In the area of the northern flank of the Alps and in the flatter areas of the Central Plateau, there are few records of major forest fires in the database (www.swissfire.ch). This is mainly due to comparatively wetter climatic conditions and fewer contiguous forest areas (especially in the densely populated Central Alps) resulting from the different area-specific conditions (e.g. geology, geomorphology). The low mountain range (*Jura Mountains*), with an area > 300 km² and characterized by shallow soils (rendzina) with beech and spruces historically experienced more wildfires than the Central Alps in Switzerland (Melzner et al. 2022). There are two main fire seasons in Switzerland: spring (March to April) and summer (July to August). In recent years, there have also been more winter wildfires, because of less snow in 2016 to 2017 and 2021 to 2022. The increased number of summer thunderstorms and droughts in recent years has also led to an increase in the number of documented lightning-caused wildfires (Pezzatti et al. 2019; Moris et al. 2020).

The federal state of Carinthia (Austria) (Fig. 1) is the second most densely forested province in Austria. It contains sixty percent of the country's forest. It stretches from the subcontinental inner Alps where spruce, larch, and fir occur to the eastern and southern intermediate Alps (spruce, fir, and beech on limestone) and to the Klagenfurt Basin and southern foothills of the Alps. In the latter area, an Illyrian climate (climate characterised by mild, wet winters and hot, dry summers, but with stronger continental influences) exists, in which beech-fir-spruce forests with thermophilic species such as hop hornbeam and manna ash naturally occur. Currently, about two-thirds of Carinthia's forest area are covered by coniferous forests, more than half of which have a largely near-natural tree species composition (www.bfw.ac.at/waldzahlen). The spatial distribution of documented wildfire events between 1993 and 2023 shows that events with a fire-affected area > 1 ha were mainly recorded in settlement areas in the *main valleys (Drau, Gail, and Gurk)* and in the *Villacher and Klagenfurter Basin* and *Karawanken* (https://fire.boku.ac.at/firedb/en/). Carinthia's fire season is between February and September, with a peak occurring in spring (March to May). All recorded wildfires were anthropogenic in origin with no lightning-induced wildfires being documented. There is also no discernible increase in the occurrence of wildfires in winter.

In the Regione Autonoma Friuli Venezia Giulia (Northern Italy) the region "Karst" is characterized by limestone covered by black pines (Fig. 1). It is often subject to wildfires that show a high degree of variability in wildfire susceptibility between successive years, for example for 2004 and 2014, and again for 2023 (https://eaglefvg.regione.fvg.it/eagle/main.aspx?configuration=guest). In 2021, the average fire surface area was 2.5 ha, in 2022 it was 12.8 ha and in 2023 only 0.25 ha. Furthermore, in 2023 no wildfire exceeded 2 ha. Each fire started small but, if not stopped in time, grew to a large extent. Therefore, the smaller the area of each individual fire, the more effective the system's response. As an example, 33 wildfires were recorded in 2023 with a total fire-affected area of 8.3 ha, of which only 3.7 ha were in forest areas. More than half the fires were caused by arson (55%) and only 18% were of natural origin (lightning). The remaining percentage was attributable in all cases to the human factor for culpable or unknown causes (unpublished reports by Canciani et al. 2022, Canciani et al. 2023).

Wildfire event case studies

Event 1 (Fig. 1) occurred between March 23rd and March 30th, 2022 on the south to southeast exposed slopes of the *Pianasc in Verdasio (Ticino/Switzerland)*. The terraced slopes have an average

Table 3 Overview of the spatial distribution of wildfires (with extension > 1 ha) in Switzerland

Geographic unit	Paleogeographic Unit (derived from)	Tectonic Units	Lithology/Chronostratigraphic	Topographic/geomorphologic characteristics	Wildfires > 10 ha [a]
Jura Mountains	European continental margin	- Internal Folded Jura - External Folded Jura	Limestone, marl, clay, anhydrite/gypsum (Mesozoic to Paleogene)	Central mountain range, karst phenomena	13
Molasse Basin	Northern Alpine forleland basin	- Autochthonous Northern Alpine foreland - Subalpine Molasse	Sandstone, "nagelfluh", siltstone, marl (Ceneozoic)	Hilly Landscape, the altitude differences are significantly greater than in the Bavarian and Austrian foothills of the Alps	9
Central Alps	- European continental margin - Alpine Tethys (Penninic) Ocean and continental fragments therein	- Helvetic nappes - Ultrahelvetic n - Subpenninic nappes - Penninic nappes	- Orthogneiss, paragneis, amphibolite (Cambrian to Permian) - Calcareous and marly sediments and metasediments (Permian to Paleogene) - Ophiolites, carbonaceous and siliziclastic metasediments (Jurassic-Paleogene)	Steep Alpine relief	142
Southern Alps	Adriatic continental margin	- Southalpine Unit	- granite, orthogneiss, paragneiss, amphibolite (Cambrian to Permian) - carbonaceous and siliziclastic sediments and metasediments (Permian to Paleogene)	Steep Alpine relief	70
Po Basin	Southern Alpine foreland basin	- Po Basin	Sediments (Ceneozoic)	Montane environment to plain	4

inclination of about 45° and are made of crystalline rocks such as paragneiss, amphibolite and pegmatite gneiss (Upper Austroalpine Unit) covered mainly with chestnut and beech forest. The wildfire was triggered probably by a short circuit on the railway tracks in the lower slope and spread rapidly up the slope (Figs. 4a and b, 5a, 8a) affecting an area of about 90 ha. The dominant fire type was surface fire with small-scale crown fires in gullies or other topographic depth contours and ground fire.

Event 2 (Fig. 1) occurred in the period October 25th to November 6th, 2021 on the southwest exposed slopes of the *Mittagstein/Feichtaberg in Hirschwang (Lower Austria/Austria)*. The slopes have an average inclination of about 35 to 50° and are made of carbonatic rocks such as limestone and dolomite (Upper Austroalpine Unit) covered with spruce, black pine and beech forest (Figs. 5b, 8b). The area is considered to be a spring protection forest owned by the City of Vienna. The fire was most likely initiated by a campfire and spread extremely rapidly and affected about 115 ha. The dominant fire type was surface fire, within small-scale topographic depth contours (i.e. gullies) predominantly crown fires occurred.

Event 3 (Fig. 1) occurred in the period August 21^{rst} to August 28th, 2018 on the southwest exposed rockwalls of a glacially over steepened Alpine trough valley in the *Echern Valley (Upper Austria/Austria)*. The valley is characterized by almost vertical rock walls several hundred metres high, which are mainly made of Mesozoic limestone (Dachstein formation) (Figs. 4c and d, 5c, 8c). Due to the upward blowing valley wind only the trees in the vertical rockwall were burned by the wildfire. The protection forest below the rockwall was affected in only very small parts by burning trees falling from the rockwall. Unusual low wind conditions and rainfall prevented the spread of the fire towards the village of Hallstatt. The dominant fire type in the rockwalls was crown fire, on top of the rockwall mainly surface and ground fire.

Event 4 (Fig. 1) occurred in the period July 19th to July 26th, 2022 in the border area of Italy and Slovenia affecting parts of the provinces of *Trieste and Gorizia (Italy)* and a large area in Slovenia (mainly the provinces of Nova Gorica/Sezana) (Fig. 5d). The affected area was estimated of approximately 4000 ha is situated in the karst region, which is characterised by moderately until steep

Fig. 4 Impact of topography and local wind systems on the characteristics of wildfires in crystalline rocks in the Southern Alps (a, b) and in carbonate rocks in the Northern Calcareous Alps (c, b). For vertical rock faces (c, d) fire effects are less pronounced, as the residence time of fire and the duration of heating is less than in moderately and steeply sloping terrain (Source: a and b by Pompieri Locarno; c and d by G. Schubert and S. Melzner)

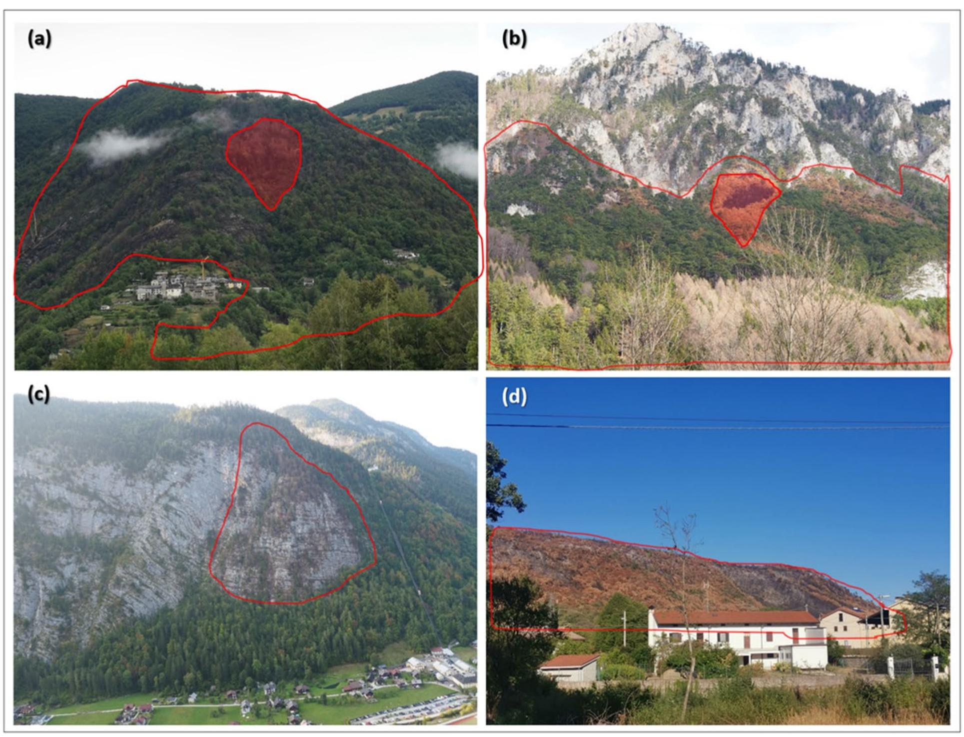

Fig. 5 Wildfire affected areas (red lines) with varying burn severities; high vegetation burn severity (filled red polygons) in topographic concavities/gullies. (a) Verdasio, (b) Hirschwang, (c) Hallstatt/Echern Valley, and (d) Trieste (Photos by S. Melzner)

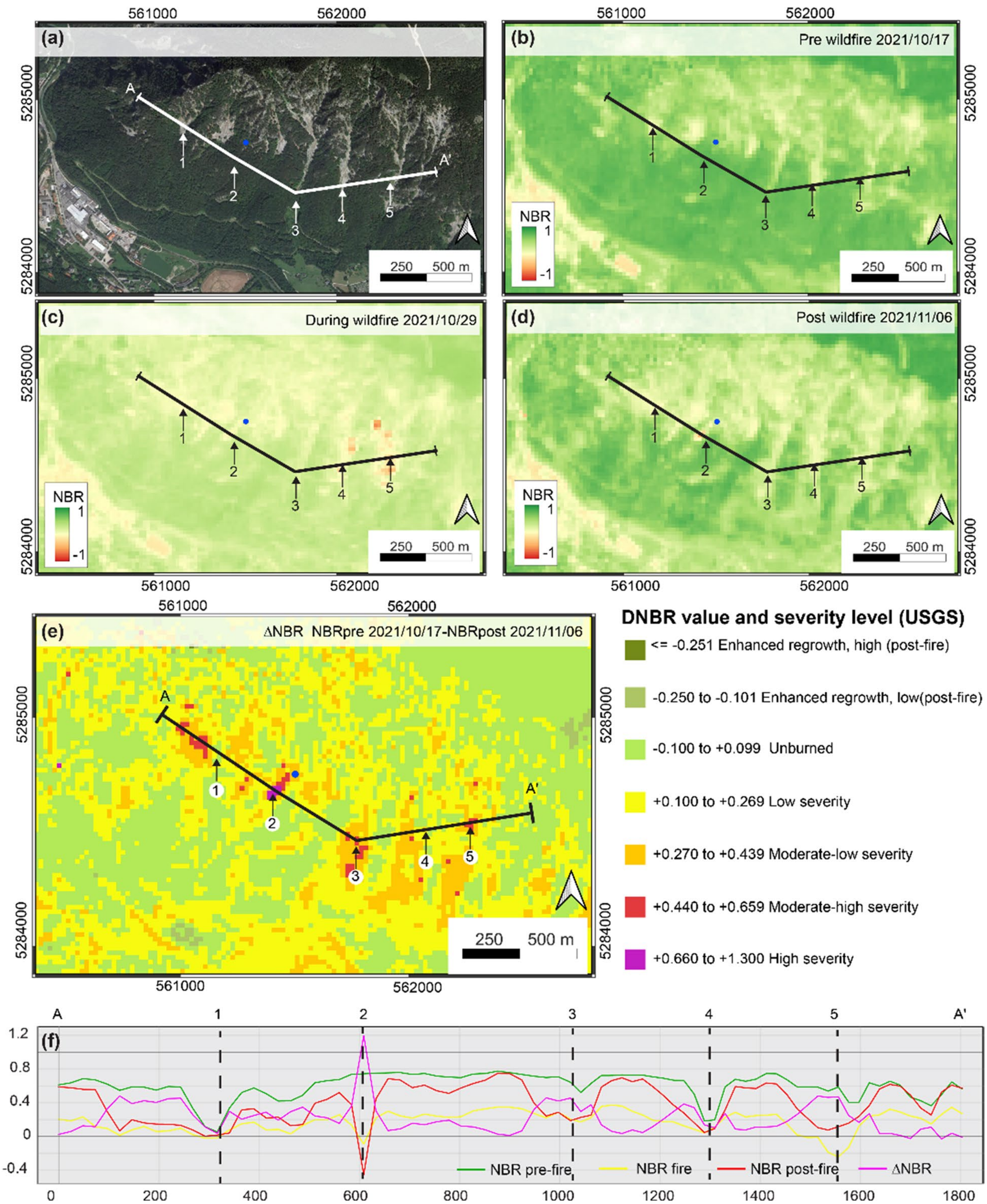

Fig. 6 Determination of wildfire affected area and burn severity with satellite image analysis. for the Study site Hirschwang. (a)–(d) Normalized Burn Ratio (NBR) obtained from band 8 (NIR) and 12 (SWIR) Sentinel-2 images with 20 m spatial resolution. (e) Differential NBR (ΔNBR) classified according to the severity level proposed by USGS (Keeley 2009). (f) Spatial profile of the indices, features are related to the points depicted on the map

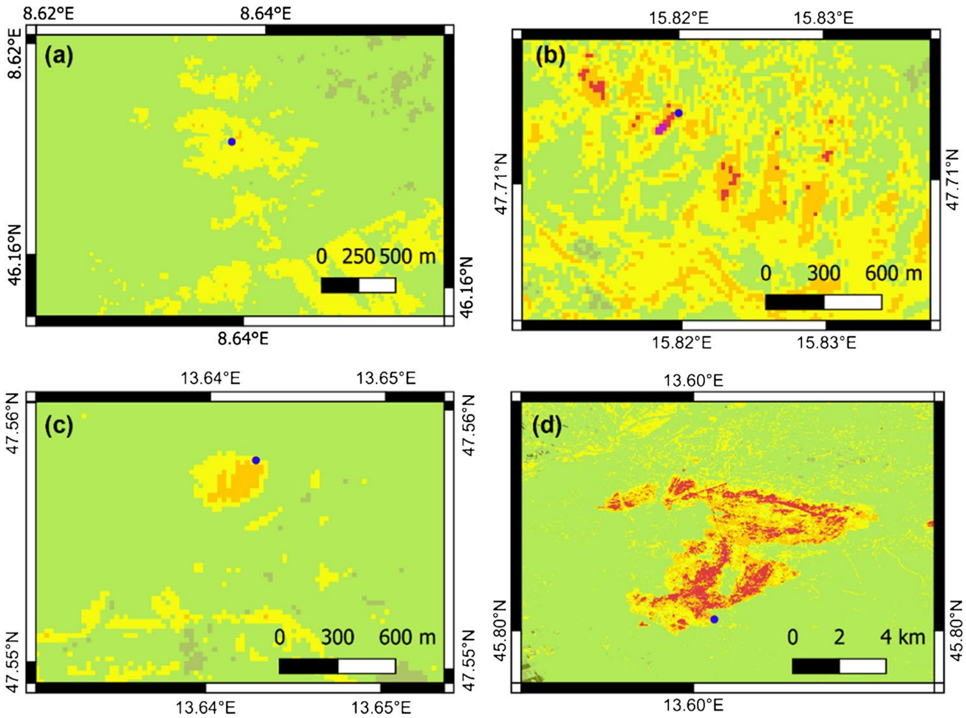

Fig. 7 Comparison of burn severity levels in the different wildfire case studies. Differential NBR (ΔNBR) classified according to the severity level proposed by USGS (Keeley 2009) see legend in Fig. 6). (a) Verdasio, (b) Hirschwang, (c) Hallstatt/Echern Valley, and (d) Trieste

Fig. 8 Indicators for high vegetation burn severity. (a) Verdasio — undamaged herbaceous vegetation in the area of paths due to fire thermal and flame skipping. (b) Hirschwang — in the area of gullies, the "chimney effect" creates a crown fire (right trees) compared to thermally impaired trees (left trees). (c) Hallstatt/Echern Valley — the vertical rock walls, the anabatic winds and patchy vegetation pattern caused an upward jumping of the fire resulting in a spotty burn severity pattern, and (d) Trieste — in the area of gulleys the winds create crown fires (Photos by S. Melzner)

Fig. 9 Indicators for soil burn severity. (a) Verdasio — high soil burn severity in the area of gullies. (b) Hirschwang — crack development in the scree, ash and needles cover the terrain with a "sealing effect" reducing the infiltration capacity. (c) Hallstatt/Echern Valley — low burn severity on relatively wet talus slope covered by a thin soil layer, and (d) Trieste — thin soil cover was burned completely during the fire (Photos by S. Melzner)

slopes build up mainly by carbonatic rocks such as limestones and dolomites covered by black pine (Fig. 5d and 8d). The dominant fire types were ground and crown fires.

Results

Burn severity indicators in selected areas in the Alps

Normalized Burn Ratio (NBR) and delta NBR (dNBR)

An example of the NBR and dNBR for the "Hirschwang" wildfire (event 2, the largest wildfire in Austria to date) is shown in Fig. 6. The results of the NBR index (Fig. 6b, c and d) show that the high values indicating healthy vegetation (green colour) are mainly on the forested slopes while low values indicating recently burnt areas (orange and red colour Fig. 6c and d) are in the valley floor and topographic gullies (point 3 in the profile). Non-burnt areas and bare soil/rock are attributed to values close to zero (yellow colour in Fig. 6b, c and d), which are in the valley floors and rockwalls (point 1 and 4 in the profile). Very low NBR values on the satellite image during the fire (Fig. 6c) represent the burning fire. In the post fire image (Fig. 6d) these pixels appear as non-vegetated ground (points 3 and 5 along the profile). Figure 6e shows the dNBR classified according to the burn severity levels proposed by the USGS (Keeley 2009a). Low severity pixels (yellow colour) are present as well in areas which are not burned by the fire. High severity pixels (purple colour) are only recognizable in one topographic gully, which was mapped in the field (see Figs. 5b and 8b). A profile along the slope shows more clearly the differences in dNBR and NBR pre-fire, during fire and post-fire. A large difference (point 2 along the profile) is visible only in the before mentioned area of "high burn severity", which could be as well mapped in the field as "crown fire affected area". The dominant fire type in the Hirschwang wildfire was "surface and running fires", which are recognizable as "moderate-low severity" on the dNBR image.

Figure 7 shows the comparison of dNBR classified according to the burn severity levels proposed by the USGS for all four case study wildfire events (refer to legend in Fig. 6). In all four wildfire events, areas are well delineated as "low burn severity" (yellow colour) which were not affected by the wildfires. These areas are either located in the valley floor (e.g. concrete) or bare rock, for example as in the case of "Verdasio" (event 1) as well the opposite vegetated valley slopes. The dNBR results in the wildfire affected areas show for "Verdasio" along southward dipping slopes mostly "low burn severity" (yellow colour), for the rest of the wildfire affected area on the ridge and eastward dipping slopes "unburned" status (green colour). The wildfire "Trieste" (event 4) shows mainly "moderate high burn severity" (red colour) to "moderate low burn severity" (orange colour). As mentioned above, the "Hirschwang" wildfire (event 2) shows "moderate low burn severity" (orange colour), "moderate high burn severity" (red colour) and "high burn severity" (purple colour) in topographic concavities (= gullies). As in the "Verdasio" wildfire (event 1), areas in "Hirschwang" are indicated as "unburned" (green colour) but which were affected by the wildfire.

Fig. 10 Indicators for rock burn severity and rockfalls occurrence. (a) Verdasio — rockfall boulders detached during the wildfire are often easily identifiable by their black colour on one site. (b) Hirschwang — thermal shock-induced cracking and spalling on carbonate rocks. (c) Hallstatt/Echern Valley — rockfalls triggered during the fire reached the houses. (c) Trieste — rockfall source are triggered during the fire (Photo a by M. Conedera; photos b–d by S. Melzner)

Field evidence for burn severity indicators

The field surveys and expert interviews showed that burn severity indicators are recognizable in the field by the degree of burning of the tree vegetation, degree of burning of the litter, ash colour (the whiter the more intense the fire) and quantity of ash on the ground (Table 2 and Figs. 8 and 9). Typically for the Alpine relief, single slopes show small-scale topographic changes that have significant impacts on the wind systems. This results in spatially variable temperatures and duration time of wildfires (Figs. 3a and 4). Furthermore, more fuels typically caused longer fire residence time, which may result in greater impacts on the ground conditions.

The *effect of fire on the forest and ground vegetation* very much depends on the fire type and fire intensity (Table 1 for definitions). Ground fires burn the underground material slowly (smouldering fires), which in the field is recognized by holes in the surface (Fig. 9c). In running fires, the fire front captures the burnt material on the ground surface and trees are only burnt in the lower part of the trunk (trunk base). These field indicators were recognized on equally inclined slopes in wildfire case 1 and 3 (Fig. 9a). Crown fires are characterised by large flame heights that reached tree crowns and/or burn entire trees (Fig. 8b and d, 9a and d). Depending on age or stage of development and bark characteristics (e.g. bark type), trees may survive the burns. Intense wildfires or crown fires mainly developed in the Alps on slopes with small-scale topographic changes in the form of gullies, where the chimney effect causes rapid changes in fire behaviour and thermal spread. In such cases, entire tree crowns experienced lethal damage, even if the flames have only acted at the base of the trunk (Fig. 8b), the thermal-induced damage in the lower parts of the tree crowns. In "Verdasio" (case study 1), the influence of small-scale topographic changes on fire behaviour also resulted in undamaged herbaceous vegetation in the area of paths due to fire thermal and flame skipping (Fig. 7a). Wildfires in steep Alpine valleys such as the "Hallstatt/Echern Valley" (case study 2) showed an upward jumping of the fire resulting in a spotty fire and vegetation damage pattern due to the vertical rockwalls (Figs. 4c and d, 5c, 8c) and the anabatic winds and patchy vegetation pattern.

In all four wildfire events common *effects of fire on soil* are the surface color change (due to char, ash cover), the loss of soil structure due to consumption of soil organic matter and the consumption of fine roots in the surface soil horizon (Fig. 9) and the development of linear structures. *Changes on rock* were recognised in the field mainly by cracks in the rock or by the formation of exfoliation fissures (Fig. 10). Field findings in wildfire case study 2 to 4 in carbonate rocks showed cracking and spalling on rocks. In wildfire case study 1, which is built up by in crystalline rocks, this spalling of rocks was not recognised. For the vertical rock faces (Fig. 4c and d, 5c, 8c), fire effects were less pronounced on the rocks, as the residence time of fire and the duration of heating is less than in moderately sloping terrain.

Inventory of fire-induced geohydrological processes in the Alps

Table 4 shows the inventory of fire-induced geohydrological processes in the Alps. It indicates that wildfires in carbonate area

Table 4 Inventory of fire-induced geohydrological processes in the central-eastern Alps

Case study wildfire	Location	Area size [ha]	Year	Month	Day/Hour	Time period	Geohydrological processes	References
1	Verdasio (CH)	90	2022	March	23rd/1.00pm	23rd-30th 9.00pm	Rockfalls (0,015 m^3) during fire, initial scarp and rill erosion	Interview with WSL fire expert, Field mapping S. Melzner, Melzner et al. (2022)
2	Hirschwang (A)	60	2021	October	25th	25.10.-	Rockfalls, denudation No information about size	www.brandaus.at, Field mapping S. Melzner,
3	Hallstatt/Echern Valley (A)	3	2018	August	21/9am	21- 28th (8 days)	Rockfalls (0,01 m^3), rill erosion	Field mapping S. Melzner, Melzner et al. (2019)
4	Trieste and Gorizia (Trieste/Italy) and Nova Gorica/ Sezana (Slovenia) (I/Slo)	4200	2022	June		20th-	Rockfalls (< 0,002 m^3)	Field mapping S. Melzner ReportIn-cendi20212022.pdf, https://eaglefvg.regione.fvg.it/eagle/main.aspx?configuration=guest
5	Pollegio (CH)	30	2018	September	24th	24.9-x	Rockfall poential No information about size	Interview with WSL fire expert Melzner et al. (2022)
6	Mesocco (CH)	119	2016	December	27th	27.12.-x	Rockfalls, close up national road No information about size	Interview with WSL fire expert Krättli (2017)
7	Ronco s/Ascona (CH)	x	1997	x	x	x	Debris flow (3500 m^3)	Interview with WSL fire expert Melzner et al. (2022)
8	Visp (CH)	130	2011	April	26th	26.4- xx	Rill and gully erosion, Superficial, soil slips, debris flow No information about size	Interview with WSL fire expert Melzner et al. (2022)
9	Val Resia (I)		2022	July	xx	x	Rockfalls reaching road No information about size	Interview fire fighter
10	Windische Höhe (A)		2013	August	x	x	Rockfall No information about size	Interview fire fighter
11	Oberdrauburg (A)	75	2015	April/May	x	21.4. –3.5	Rockfall No information about size	Interview fire fighter
12	Tscheppaschlucht (A)		2019	x	x	x	Rockfall No information about size	Interview fire fighter
13	Steinfeld (A)	73	2002	February	6th/12.00	6.2-x	Potential for rockfall, rill erosion No information about size	Archive Federal State Government of Carinthia
14	Leuk (CH)	300	2003	August	13th/19.50	13.8.–5.9	rill erosion, landslides, rockfall potential No information about size	Wohlgemuth et al., 2010
15	Riederhorn (CH)		2023	Juli	17th	17.7.-xx	rill erosion, rockfall potential No information about size	Kanton Wallis (CH)

settings predominantly triggered rockfalls while, wildfires in crystalline rocks were associated with a greater variety of processes (Fig. 3) following a chronological sequence of geohydrological processes both during and after a wildfire (Fig. 12). For most fire induced geohydrological processes, quantitative data on volume and size of the geohydrological processes and triggering events were not recorded by the wildfire experts. For the recent wildfires described in the "Wildfire event case studies" section, there is little experience of the temporal development of future susceptibility of geohydrological processes already available other than from wildfires that occurred a long time ago (see Table 4 for details).

In all four wildfire events, a similar temporal development of the fire-induced geohydrological hazard potential was recognizable (Fig. 1, 10, 12, Table 4). In the "Hallstatt/Echern Valley (case 3)", the direct effect of the fire caused "primary" rockfall from the vertical rock walls or indirectly "secondary" rockfall was remobilised due to falling trees during the wildfire. Some of the rockfalls boulders triggered during the wildfire were of small size (< 0.01 m^3) and some of the boulders reached the settlement area (Fig. 10c). On top of the rockwall, the organic cover of the slope debris was nearly completely burnt, which enabled more secondary rockfalls the following months by the remobilisation of scree and boulders of the exposed slope debris or the burnt litter and humus layer due to surface runoff. In "Verdasio" (case 1), a rockfall ~ 0.015 m^3 was mobilized during the fire by a tree throw and the boulder was stopped by a chestnut tree trunk in the middle of the slope (Fig. 10a). Landslide scars and rill erosion were recognizable directly above the houses. In "Hirschwang" (case 2), rockfalls occurred during the fire, which almost injured fire fighters. No information of the size was recorded by the fire fighters. In some areas, very superficial denudation and rill erosion was recognized one year later. In the Trieste area (wildfire 4) only very small rockfalls < 0.002 m^3 occurred during the wildfire (Fig. 10d) not endangering any settlements. Due to lack of well-developed rendzinas only minor erosion processes in fine scree was recognizable.

Field observations in August 2024 (Fig. 11) showed that in the "Hallstatt/Echern Valley" (case 3) several rockfalls occurred, the last of which was recorded by a habitant without size information on June 29th, 2024 (Fig. 11a). In the area above the steep rockwall (Fig. 11b and c), recent rockfall boulders and denudation processes are still visible. Fallen trees have mobilised blocks and there is potential for future secondary rockfall in some areas. In "Hirschwang" in the upper slopes in the crown fire affected areas, sowing soil plants has been effective against erosion processes (Fig. 11d). Denudation processes are visible in some lower slope areas (Fig. 11e) and several rockfalls of small size < 0,1 m^3 occurred in the western part of the affected areas and in the upper slopes (Fig. 11f). Surface run-off and initial rill erosion is only recognizable in a few areas in the upper slopes.

Discussion

Wildfires in the Alps behave differently than those on flat or moderate slopes such as might be seen in the Mediterranean region or Australia, largely because of their topography affecting local wind systems and vegetation patterns. For example, they tend to be smaller, with the largest wildfire in Austria in "Hirschwang" only covering an area of about 115 ha. Further, the topography of the high mountains has a significant impact on the wind systems (i.e., Foehn wind, mountain winds and valley winds) and thus the occurrence of wildfire types (crown, surface and ground fire), and on fire intensity and burn severity. Greater fuel loads typically cause longer fire residence time, which may result in greater impacts on the ground conditions (burn severity indicators) (Melzner et al. 2022). It can vary significantly on a single slope and is an important factor for the timing of the fire-induced geohydrological susceptibility and hazard potential.

A wildfire not only intensifies the predisposing and triggering factors of geohydrological processes but also reduces the protective functions of mountain forests (Fig. 12). A fire creates tree stand dynamics, thus the changes in the structure, composition, and function of a forest over time, in the affected forests, which depends very much on the intensity of the fire and on the tree species. In the case of protection forests, if trees are severely damaged or completely burnt, it may lead to a temporary protection deficit against potential geohydrological hazards; being mainly rockfall, soil flows, shallow landslides, erosion and snow avalanches. This "critical window for the protective forest" effect can also extend over several decades after a wildfire, depending on the forest type and fire intensity, especially if all trees of the old stand have died and forest regeneration has not yet occurred, or trees are not yet mature. Pre-fire vegetation density (including ground fuels, litter, and duff) is a key factor to consider when mapping burn severity levels (Parsons et al. 2010).

The analysis of satellite imagery showed that it is very difficult to use NBR and dNBR for mapping the extent (area) of the wildfire-affected area. This is mainly because ground and running fires can't be easily detected with this method. Research findings in the USA showed that dNBR thresholds used to determine the cutoffs for unburned, low, moderate, and high severity need to be adjusted from site to site based on post-fire field observations to account for the area settings (Fallon et al. 2024).

The field observations and interviews with habitants in the vicinity of fire affected areas showed that there is a temporal pattern of geohydrological processes both during and after a fire. In the first months after a fire, affected areas are particularly vulnerable not only to raindrop erosion (splash erosion), but also to surface runoff, denudation and linear rill and gully erosion (e.g. Melzner et al. 2022). For example, in the Ronco s/Ascona (Switzerland) wildfire in March 1997, a 200-year flood and debris flow event were caused the following August on the fire-affected forest catchment by a 10-year precipitation event. The resultant debris flow of 3500 m^3 affected the village. This was also the case of the wildfire in Visp (Switzerland) in 2011, where a debris flow originated in the fire-affected area in 2018 (see Fig. 6 in Melzner et al. 2022). Studies in the semi-arid southwestern USA showed that wildfires are commonly followed by runoff-generated debris flows in the first year following the fire (Rengers et al. 2020). Years after the fire, the mass-wasting response to a long-duration rainstorm with high rainfall intensity peaks, was often shallow landsliding rather than runoff-generated debris flows (Rengers et al. 2020).

In other examples of wildfires in the Alps such as in Pollegio (Switzerland) in 2018, parts of a residential area were evacuated due to a high rockfall hazard (Melzner et al. 2022). In the case of the major fire in Mesocco (Switzerland) in 2016, a national road was closed due to rockfall hazard during the fire (Krättli 2017). A large wildfire in Leuk (Switzerland) in 2003 caused rill erosion one year after the fire

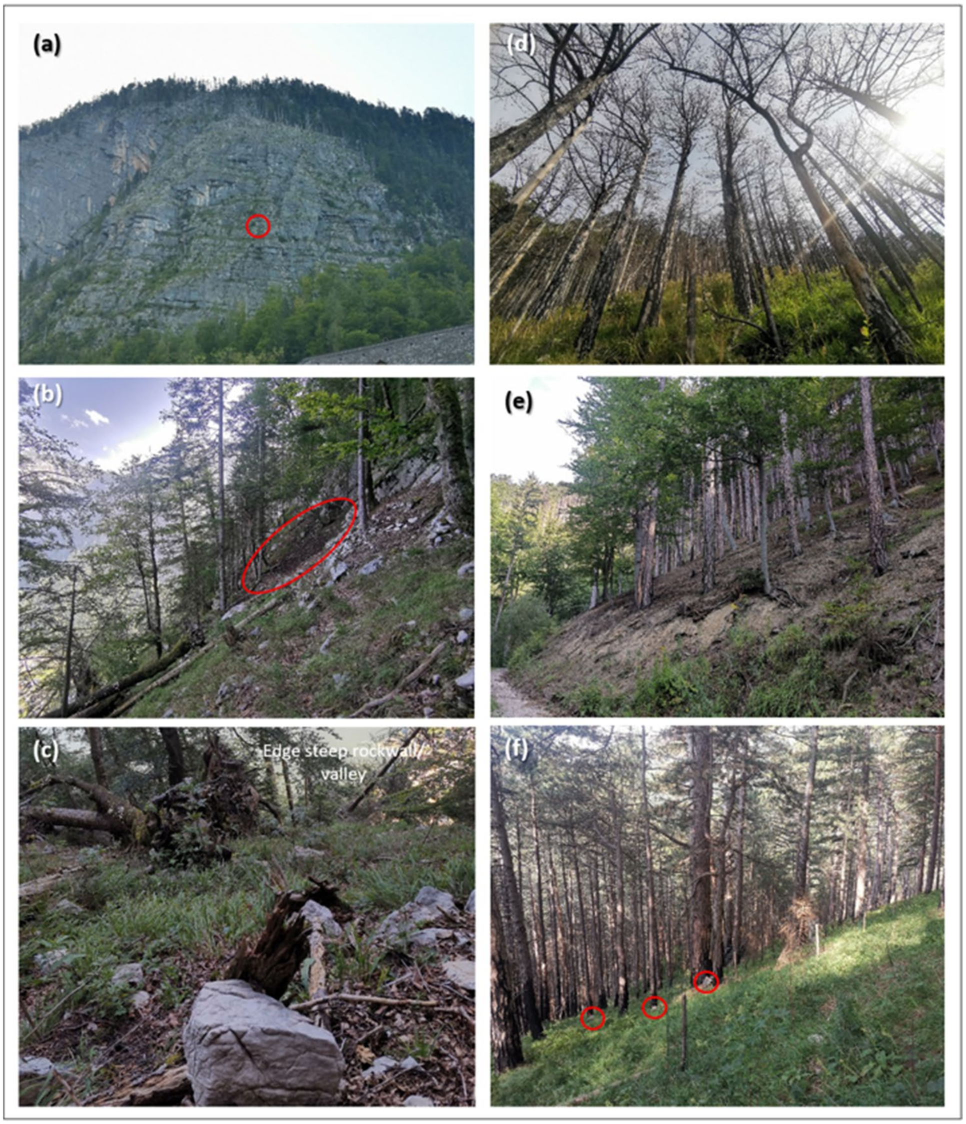

Fig. 11 Post wildfire geohydrological processes in August 2024 in the Hallstatt/Echern Valley (a–c) and Hirschwang (d–f). (a) rockfall release area from rockfall event on June 29th at 6 pm. (b) Denudation in the area above the rockfall. (c) Rockfall boulder from the rock outcrops above and falling trees triggering secondary rockfalls. (d) Crown fire affected area in the upper slope with seeded ground vegetation. (e) Run fire affected areas and trees (black marks) in the lower slopes with denudation processes. (f) Recent rockfall boulders stopped by run fire affected trees (Photos by S. Melzner)

(Wohlgemuth et al. 2005). In Lurnfeld (Austria) in 2015, a large wildfire caused rockfalls and rill erosion processes (Melzner et al. 2022).

Fire also has different effects in different lithologies or starts at different temperatures (Sarro et al. 2021; Peduto et al. 2022a, b). Thermal shock-induced cracking in rock occurs when the thermally induced stress is so great that the rock material is unable to adapt quickly enough to accommodate the required deformation (Melzner et al. 2019, 2022; Shtober-Zisu and Wittenberg 2021a, b). To date however, the effects of fire on hydro-geo-mechanical properties of different lithologies are mainly based on laboratory studies (Peduto et al. 2022b). As yet, there are no studies in the alpine high mountains that deal with collection of quantitatively data on the impact of fire during a wildfire and/or the long-term observation and monitoring of the geohydrological consequences (Melzner et al. 2019, 2022).

There have been many international studies that have looked at the effects of ash deposition on the formation of water repellent layers and the impact of water runoff and erosion processes, and rates (e.g. Bodí et al. 2011). While many studies suggest that ash temporarily reduces infiltration by either plugging soil pores (Marxer et al. 1998a) or forming a surface crust (Onda et al. 2008), other studies suggest that ash, and in particular the black carbon produced by light to moderate fires, may increase infiltration by storing precipitation and protecting the underlying soil from sealing (Wittenberg and Shtober-Zisu 2023). Ash layers may also protect the burnt soil from the impact of raindrops and associated splash erosion (Melzner et al. 2019). Studies in the Alps have shown that ash predominantly causes a sealing effect that reduces infiltration and increases and accelerates surface runoff (Marxer et al. 1998; Conedera et al. 2003).

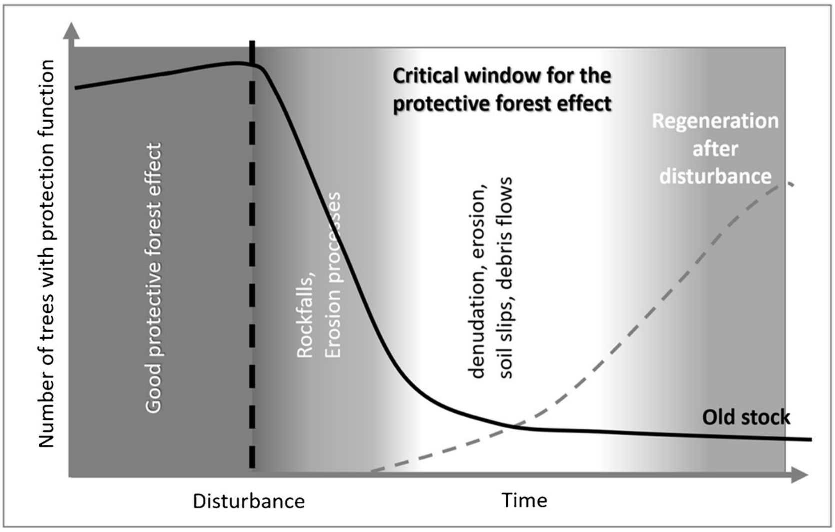

Fig. 12 Critical time window for the protective effect of the forest against geohydrological natural hazards (modified after Melzner et al. 2022)

With respect to the completeness of the wildfire databases, the Southern and Central Alps high mountain regions in Switzerland accounted for most of the documented wildfire events. The Swiss dataset can be considered complete for fires affecting an area ≥ 1 ha since 2000, and incomplete for wildfires < 1 ha. Besides climatic reasons (accumulation of fuel), the higher number of wildfires in the south of Switzerland could also be related to the fact that the Swiss Federal Institute for Forest, Snow and Landscape Research WSL fire experts in Switzerland have their institute in that region. For example, rockfall and landslide hazard research publications have shown that the permanent presence of experts in a region has an influence on the completeness and representativeness of process data sets (Melzner et al. 2020, 2023). The spatial distribution of wildfires in Carinthia (Austria) indicates that larger man-induced wildfires were predominantly documented from the main valleys. In contrast to Swissfire, the Austrian wildfire database also contains data of wildfires affecting areas < 1 ha. However like the Swiss situation, the rockfall and landslide research showed that small-scale processes and those that have not caused any damage are often not recognized nor documented by habitants or local authorities (Melzner et al. 2020, 2023). The Italian/Slovenian wildfire case showed that the "karst" region is often subject to wildfires, which are initiated along the railroads and can effect very large areas in both countries.

Conclusion

The steep topography of the Alps has a significant impact on the wind systems (i.e., Foehn wind, mountain winds and valley winds) and the occurrence of types of wildfire, as well as on the fire intensity and burn severity (Figs. 3a and 4). The heterogeneous tectonic and geological settings have a significant influence on the occurrence of ecosystems at different elevations, wildfires and geohydrological processes. Thus it is essential to develop assessment strategies involving a variety of different methods (Table 5), which are suitable to be applied in different geological settings.

In comparison with other countries and regions such as Colorado and California in the USA, in the Alps there are no long-term observations linking the effects of wildfires with the occurrence of geohydrological processes in fire-affected areas. Our study and its results thus represent the first such inventory.

Evaluation of the wildfire events revealed that the timing of fire-induced geohydrological processes was similar in all cases: during a wildfire the dominant processes are rockfalls and rill erosion processes, and to some extent, initial scarps of landslides were recognizable. Depending on the fire intensity and burn severity, the critical window of reduced mountain forest protection may last up to several years resulting in increased susceptibility to landslides and debris flows.

Recommendations for future research arising from our findings include:

- Development of new methods or further adaptation of existing techniques (e.g. NBR and dNBR) for the rapid detection of the extent of wildfire-affected areas that are suitable for alpine topographic, heterogenic geologic and vegetation settings.
- Systematic documentation of burn severity indicators and geohydrological processes (type, numbers, size, date of occurrence) before, during and after a wildfire event, and their integration into national fire databases. Development and evaluation of techniques to quantify the effect of wildfires in steep Alpine topography in different geological settings.
- Verification, understanding, and possibly quantification of the impact of fires on rock and soil surfaces to improve prediction of fire-induced geohydrological processes (of a certain size and time of occurrence) and associated hazard and risk levels.
- Monitoring of long-term effects of fire and other climatic extremes on future rockfall, landslide, debris flow and erosion (of a certain size and time of occurrence).

Table 5 Overview about a selection of methods to determine burn severity (vegetation, soil, rock) and identification of geohydrological processes

	Method/technique (examples)	Purpose	Reference (examples)
Vegetation			
	Field mapping	Changes in vegetation properties due to fire impact	(Wittenberg and Malkinson 2009; Parsons et al. 2010; Wittenberg 2012; Melzner et al. 2019, 2022)
	Analysis of satellite imagery	Delineation of burned area, assess characteristics of active fires, post-fire ecological effect	(Keeley 2009; Fallon et al. 2024)
	Photos from the opposite slope	Qualitative comparison of forest cover before and after a wildfire	Melzner et al. 2019
Soil			
	Field mapping	Char depth and ash, organic matter loss, altered soil colour and structure, and reduced infiltration capacity)	(DeBano 2000b; Melzner et al. 2019, 2022; Peduto et al. 2022a, b); Fallon et al. 2024)
	Analysis of satellite imagery	Burned area reflective classification (BARC)	(Fallon et al. 2024)
	Terrestrial LIDAR	Microtopography, soil cover changes	(Rengers et al. 2016, 2020, 2021)
	Line-point intercept method	Monitoring changes in ground cover and understory canopy	(McGuire et al. 2024)
	Minidisk tension infiltrometers	Estimation of soil surface field saturated hydraulic conductivity (Ks)	(Wall 2021; McGuire et al. 2024)
Rock			
	Field mapping	Changes in rock properties (Color, structure, etc.)	(Shtober-Zisu et al. 2018; Melzner et al. 2019, 2022; Sarro et al. 2021; Shtober-Zisu and Wittenberg 2021c; Peduto et al. 2022a, c)
	Terrestrial LIDAR	Evaluation of the changes in the rockwall	(Sarro et al. 2021; Melzner and Schiller 2022)
	Regular samples of intact rock heated in an oven	Evaluation of the changes in the chemical, physical and mechanical properties of rocks, forming of cracks density due to sudden thermal shock	(Sarro et al. 2021; Shtober-Zisu and Wittenberg 2021b; Peduto et al. 2022d)
Processes			
	Interviews with experts, local habitants	Information on the location and temporal occurrence	(Sass et al. 2010a; Melzner et al. 2019, 2020, 2022, 2023); Rengers and McGuire 2021; Sarro et al. 2021)
	Geological and Geomorphological mapping	Different types of gravitational movements such as rockfalls, landslides, flows etc	(McGuire et al. 2024)
	Terrestrial LIDAR	Erosion and deposition pattern, Rockfall and landslide location and magnitude, Sediment transport	(Rengers et al. 2016, 2020); Rengers and McGuire 2021)
	Geophones, pressure transducers and Time lapse cameras	Monitored of (debris) flows in watersheds	(McGuire et al. 2024)
	Monitoring barrier	Systematic measurements of velocity profiles in real-scale debris flows	(Nagl et al. 2020, 2022, 2024)

- Harmonization of forest/wildfire databases across the Alps and development of common access agreements and standards for data usage. The Autonomous Region Friuli Venezia Giulia (Italy) is an example of a public service that makes forest fire data available to the public by allowing GIS data and reports to be freely downloaded.
- Understanding of the fire ecology of alpine tree species and their post-fire resilience (i.e., root decay processes after stand replacing fires, seed versus bud bank regeneration, etc.).
- Susceptibility analysis referring to different aspects such as burn severity, soil/rock/vegetation types, climatic conditions with respect to the quality of the process inventory.
- Definition of standards and tools for fire-related data collection, management, sharing and distribution.

Experiences from landslide research have shown that information reported in different archives have enabled the compilation of extensive landslide inventories and catalogues. Recent publications in rockfall research (Melzner et al. 2020, 2023) have also shown that the data collection strategy that is used has a significant impact on the statistical representativeness of both the process and event data and its subsequent application. Thus, similar approaches are needed for wildfires and any resulting changes in geohydrological processes. This must be considered if data are to be used for hazard and risk assessments or forecasting of future fire regimes and trends. Systematic interdisciplinary experiences exchanged among Alpine countries at workshops (e.g. 1st and 2nd Alpine Workshop on fire-induced geohydrological processes in mountainous areas), in collaborative projects and in data collection, storing, and sharing are thus essential for defining and developing an Alpine post-wildfire management strategy.

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Author contribution

SM: Conceptualization and coordination, field work, selection of data sets, table/figure drafting and preparation of all figures, remote sensing analyse interpretation, manuscript writing. DP: Writing and editing manuscript. FF: Remote sensing analysis, preparation of remote sensing figures and editing of the manuscript. JH: Editing manuscript. CP: Editing manuscript and English proof reading.

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