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Discussions

An Alpine Drought Impact Inventory to explore past droughts in a mountain region

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Abstract. Drought affects even mountain regions, despite a humid climate. Droughts' damaging character in the past and an increasing probability in future projections call for an understanding of drought impacts in the European Alpine region. The European Drought Impact Report Inventory (EDII) collects text reports on negative drought impacts. This study presents a considerably updated EDII focusing on the study region of the greater 'Alpine Space'. This first version release of an Alpine Drought Impact Inventory ($\mathrm{EDII_{ALPS}}$) classifies impact reports into categories covering various affected sectors and enables comparisons of the drought impact characteristics. We analyzed the distribution of reported impacts on the spatial, temporal and seasonal scale, and by drought type for soil-moisture and hydrological drought. For the spatial analysis, we compared the impact data located in the Alpine Space' to entire Europe. Further, we compared impact data between different climatic and altitudinal domains (Northern vs. Southern region, pre-Alpine vs. high-altitude region), and between the Alpine countries. Compared to entire Europe, in the Alpine Space agriculture and livestock farming impacts are even more frequently reported, especially in the Southern region. Public water supply is second most relevant sector, but overall less prominent compared to Europe, especially in spring when snowmelt mitigates water shortages. Impacts occurred mostly in summer and early autumn with a delay between those impacts initiated by soil-moisture and those by hydrological drought. The high-altitude region showed this effect the strongest. From 1975 to 2020, the number of archived reports increased, with substantially more impacts noted during the drought events of 1976, 2003, 2015 and 2018. Moreover, reported impacts diversified from agricultural dominance to multi-facetted impact types covering forestry, water quality, industry and so forth. Though $\mathrm{EDII_{ALPS}}$ is biased by reporting behaviour, the amount of more than 3200 compiled reports on negative drought impacts demonstrates the need to move from emergency actions to better preparedness. These may be guided by $\mathrm{EDII_{ALPS}}$' insights to regional patterns, seasons and drought types.

1 Introduction

Droughts are natural hazards, which can cause widespread and severe impacts on the environment and societies. Compared to other weather-related hazards, such as floods and storms, droughts are among the most damaging events in terms of affected people and economic costs (Wilhite, 2000a; UNISDR, 2009; UNDRR, 2019). The summer droughts of 2003, 2015 and 2018 have raised concerns about the vulnerability of the European water budget to climate change (Weingartner et al., 2007; Teuling, 2018), because these events have affected more than 17 % of the European population (Mastrotheodoros et al., 2020). Because of the humid mountain climate with an annual total precipitation between 400 to beyond 3000 mm/year (Isotta et al., 2014) and the four major European rivers Po, Rhone, Rhine, and Danube, the Alps are also called the "Water towers for Europe" (Viviroli et al., 2007). Nonetheless, past droughts caused severe impacts such as limited supply of water for drinking, irrigation and hydropower generation (Haslinger et al., 2019). The predicted increase of drought frequency, duration and extent stresses the relevance of systematic analysis of drought impacts and their cascading effects in mountainous areas. This is particularly relevant within the Mediterranean climate in the Southern parts of the Alpine regions, where recent drought events triggered water disputes and spread of multiple impacts (Yves et al., 2020). The need to understand the role of drought impacts in Europe's mountainous region is stressed by the fact that more than 170 million people live within the major river basins (Viviroli et al., 2007). Until now and to the best of our knowledge, only the expert paper by the "Water management in the Alp" platform (Water Management in the Alps Platform of the Alpine Convention, 2018) is a transnational study focusing on drought impacts in the Alpine region presenting experiences, approaches and common challenges for water management by stakeholders. This expert paper emphasizes the need to move from emergency to preparedness actions, essential for the Alpine-wide research on past drought and potential future impacts.

Drought builds up slowly and accumulates over time with cascading effects and the provoked impacts may linger for years after termination (Wilhite, 2000b). Compared to other disasters these characteristics brought up different drought definitions with the difficulties to determine the onset and termination of the phenomenon. A common approach is to define drought as a sustained period of below-normal water availability (Tallaksen and van Lanen, 2004) and classify the phenomenon into four types that generally occur in the following order (Wilhite and Glantz, 1985; van Loon et al., 2016): (1) Climate variability leads to precipitation deficit causing meteorological drought (D_M), the initiator for the other types. Meteorological drought combined with high potential evapotranspiration leads to (2) agricultural or soil moisture drought (D_{SM}). (3) Hydrological droughts (D_H) occur delayed, associated with the effects of temperature anomalies, precipitation shortfalls, and/or anthropogenic demand pressures on surface or subsurface water supply (e.g. streams, reservoirs, lakes or groundwater). (4) Socioeconomic drought (D_{SE}) is associated with an inadequate supply of some economic goods resulting from meteorological, agricultural, and hydrological droughts. In a mountain-to-foothill region this propagation may differ as hydrological processes vary from high to low elevations. The annual hydrological cycle may be more likely to be reset every year by winter snow, response and reaction times are fast, gradients steep and storages more local and diverse.

The different drought types generally lead to a wide range of impacts, making an impact assessment more difficult compared to other disasters. D_{M} is typically understood as the prime trigger. While D_{M} impacts in lowlands may often have compound causes with heat waves, e.g. excess mortality as a result of cardiovascular diseases, in cooler mountain regions such direct impacts are likely less relevant. Most direct drought impacts can be linked to either D_{SM} or D_{H}. For example, low soil moisture typical for D_{SM} initiates reduced vegetation health or crop quality, whereas low discharge and/or groundwater storage typical for D_{H} causes problems in *Public water supply* (Wilhite and Vanyarkho, 2000). Impacts not directly induced by D_{SM} or D_{H}, are also known as 2nd-level or indirect impacts (Wilhite and Vanyarkho, 2000), such as increased costs due to supplementary irrigation. In mountain regions economic sectors and priorities or activities may differ. These indirect impacts are the least tangible and often related to D_{SE}. In order to link drought impacts specifically to drought types, D_{SM} and D_{H} are the most evident types (Stagge et al., 2015). Despite the challenge to identify drought impacts, several efforts have been made predominantly focusing on the agricultural sector (Logar and van den Bergh, 2013; Poljanšek et al., 2019; Cammalleri et al., 2020), but not specifically on mountain regions or mountain-to-foothill transitions. Stahl et al. (2012) introduced the European Drought Impact Report Inventory (EDII) to widen the perspective to the broad scope of drought impacts including more sectors, such as *Public water supply*, *Tourims and recreation* and *Energy and industry*. The EDII defines drought impacts as negative consequences for environment, society or economy and classifies these into 15 sectoral categories with multiple subtypes. Blauhut et al. (2016) and Stahl et al. (2016) used these geo-referenced reports to compare sectoral differences across Europe, which demonstrates the value of this impact inventory. Stagge et al. (2015) and Bachmair et al. (2016) went even further and predicted impacts based on EDII.

This study builds up on the drought impact data collected and classified in the EDII, expanding it with the help of existing databases to develop an Alpine-specific drought impact inventory. The main objective is to survey, classify and systematically assess past drought impacts in the European Alpine region with the following leading questions:

- How do impacts differ in such a mountain-foreland region compared to the whole of Europe? Are there any spatial patterns within the Alpine Space driven by altitudinal or climatic conditions (high-altitude region, pre-Alpine region, Northern and Southern region)?
- Are there any trends of drought impact frequencies over different time ranges (e.g. seasons)?
- How are the drought types impacts distributed in the Alpine Space? Can we link the impacts' location to drought types of D_{SM} and D_{H}?

2 Methods

2.1 The study region and its specific characteristics

Our study region is the so-called "Alpine Space" introduced by the EU-funded programme of the same name (Fig. 1, Interreg -Alpine Space Programme 2014-2020). The Alpine Space covers the Alps and their foothills, as well as different climatic zones

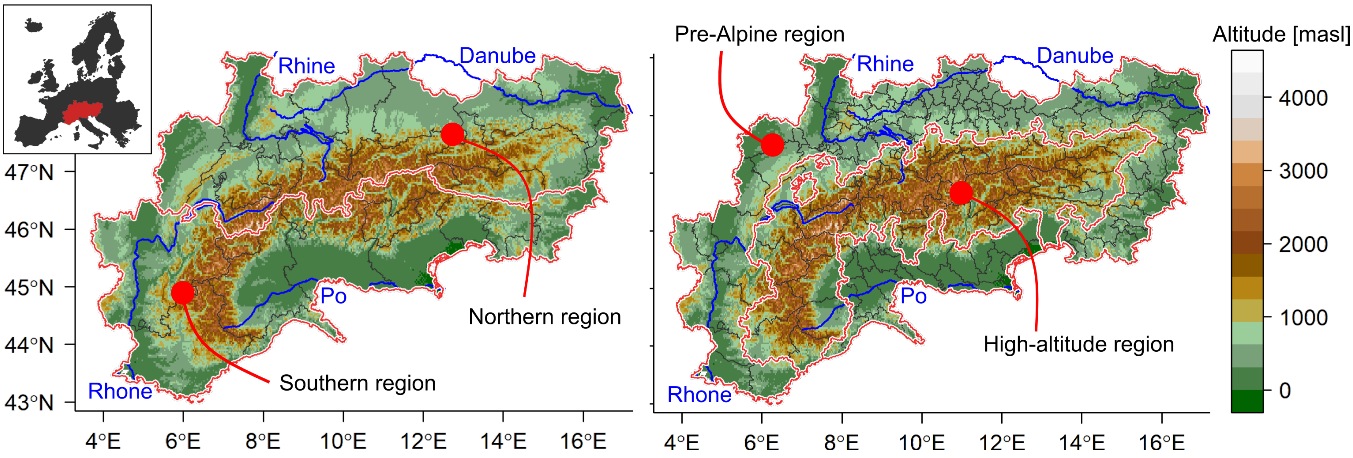

Figure 1. The “Alpine Space” study area within Europe for which the Alpine Drought Impact Inventory ($\text{EDII}_{\text{ALPS}}$) was developed, showing the major rivers draining the Alps and the paired subregions for the analysis: on the left the Northern and Southern region divided by grouped NUTS 2 regions, and on the right the pre-Alpine and high-altitude region divided by grouped NUTS 3 regions.

and therefore allows the consideration of water and resource flow and exchange typical to mountain regions. With the study region’s extent, we therefore include drought impacts not only at high altitudes, but also in downstream areas of the water-rich source regions (e.g. the river basins Po, Rhine, Danube etc.). We analyzed impact patterns within subregions of the Alpine Space and compared the Alpine Space with the pan-European region with the help of EDII (Stahl et al., 2016).

The Alpine Space boundary corresponds to the borders of NUTS regions. The Nomenclature of Units for Territorial Statistics (NUTS) is a spatial unit with levels 1, 2 and 3 used in the European Union to subdivide countries into major, middle in minor regions for statistical purposes (Eurostat). Using these NUTS regions, we grouped the Alpine Space into four domains in order to compare contrasting climatic and altitudinal conditions: (1) The “Northern region”, with all NUTS 2 (and thus including all NUTS 3) regions characterized by maritime climate versus (2) the “Southern region” with the other NUTS regions characterized by the Mediterranean in the South and Southwest and continental climate in the Southeast (Bouma, 2005). Haslinger et al. (2019) presented a strong North-South dipole along the Main Alpine Crest for dry and wet areas during the last 210 years. (3) The “high-altitude region” identified with NUTS 3 regions for which ≥ 30 % of the area are higher than 1000 masl versus (4) the “pre-Alpine region” covering all remaining NUTS 3 regions. For the altitudinal comparison, we chose the spatially higher resolved NUTS 3 regions, because altitudinal characteristics do present stronger the smaller the area. In the following the term “domains” includes these four subregions, the Alpine Space and Europe, and thus differs from smaller spatial units.

2.2 Collection and pre-processing of drought impacts’ data

We retrieved drought impact data from different sources located in the European Alpine countries considerably updating the latest version of the European Drought Impact Report Inventory EDII (Stahl et al., 2016). EDII itself archives text-based reports

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on drought impacts from different sources, most frequently from newspaper articles, web pages, scientific or governmental reports, databases and other information sources. We compiled impact data fulfilling the standards the EDII requires, e.g. impact description, reference, location and timing. Our collected impact data came from sources located in the different Alpine-countries: (1) A broad variety of Italian and (2) German text-reports, (3) the French platform Propluvia (Ministère de la Transition Écologique et Solidaire), (4) the Austrian chronicle of severe weather impacts “Unwetterchronik” (Zentralanstalt für Meteorologie und Geodynamik), (5) the Drought Management Center for Southeastern Europe (DMCSEE) covering Slovenia (Slovenian Environment Agency) and Slovenian text-reports, and (6) the media archive of the Swiss information platform Drought-CH (Zappa et al., 2014).

Complying with the EDII guidelines (www.geo.uio.no/edc/droughtdb/img/Guidelines_EDII_Webversion.pdf), these sources offered drought impact information as negative consequences of drought as text-based reports (Italian and German reports, Unwetterchronik, DMCSEE, Drought-CH). A typical recorded entry in relation to *Agriculture and livestock farming* is described in the following example: “In some regions in lower Austria the grain harvest was less than 50 %, especially for wheat and canola. [...] The first cut of grasslands summed up to only two thirds of the normal yield [...]. Higher costs for irrigation appeared. The federal state of lower Austria supported the farmers with 1.5 million euros for the so-called ‘Feeding stuff acquisition’ [...].” This report was published in August, 2003, by the Austrian centre for agricultural information. An exemplary summarized description related to a drought impact on management of livestock on higher-elevated pasture was published in October, 2018 by the Unwetterchronik: “Due to persisting drought some meadows in the district of Landeck could not be cut a second time [...]. There were losses between 60 to 100 %. [...] Due to fodder shortage the farmers had to buy additional hay or sell their animals. [...] In Oberland the alpine pasture farmers brought their cattle down to the valley earlier, as there was a lack of fodder and drinking water.” A typical example related to water supply is the following report published in July, 2015 by a regional Italian newspaper: “In Trento fountains were closed. At the Arco municipality drought conditions are severe with water use bans. The civil protection monitors the level of the Lago delle Piazze, where different sectoral water demands can quickly worsen the current conditions.” In contrast to the other sources, Propluvia offered mapped management strategies across France, classified by increasing warning levels dependent on the drought severity. For example, the warning level ‘reinforced alert’ means that in the mapped region bans on watering gardens/lawns, open spaces, golf courses, and washing the car at certain times are taking place. Further, the reduction of withdrawals for agricultural purposes less than or equal to 50 % and measures prohibiting valve operations and nautical activity are applied. This way, Propluvia provides information about negative drought impacts with specific measures for the society and economy that could be translated into EDII database entries.

We compiled data with available information for at least NUTS 2 regions and at least with the information on a given season or month of a year in which an impact started to occur. We then classified the impact data into 13 (out of 15) categories and to 96 subtypes related to the potentially most impacted sectors proposed by EDII: *Agriculture and livestock farming* (1), *Forestry* (2), *Freshwater aquaculture and fisheries* (3), *Energy and industry* (4), *Waterborne transportation* (5), *Tourims and recreation* (6), *Public water supply* (7), *Water quality* (8), *Freshwater ecosystems* (9), *Terrestrial ecosystems* (10), *Air quality* (13), *Human health and public safety* (14), and *Conflicts* (15). We excluded the EDIIs categories *Soil system* (11) and *Wildfires*

(12) as the link between drought, impact and management in these categories is often inconclusive and other databases, such as the Forest Fire Information system (EFFIS, 2020) are more comprehensive. The final categorization enabled the analysis of spatial distribution, temporal trends and differences by drought and impact type. The resulting dataset of this systematic collection and classification of impact data within the Alpine Space in its first version is: $\text{EDII}_{\text{ALPS}}$ V1.0 available from the FreiDok repository (doi: tbd, last update 8th of January, 2021).

The distributions of all reports impact categories from $\text{EDII}_{\text{ALPS}}$ were compared with those of entire Europe (EDII_{EU}). Within $\text{EDII}_{\text{ALPS}}$, we compared pre-Alpine and high-Alpine, Northern and Southern Alpine regions, as well as political units: countries (respectively the part of the country within the Alpine Space), and NUTS 2 and 3 regions (Fig. 1). Because the total numbers differ among these areas, we additionally focused on relative proportions ('fractions') of the 13 categories, i.e. information that is independent of the overall data availability.

For the investigation of temporal trends, we aggregated $\text{EDII}_{\text{ALPS}}$ data per year and compared the proportions of the most frequent impact categories for the drought events 1976, 2003, 2015 and 2018. For the seasonal analysis, we pre-processed impact data as follows: Within the data collection, each impact was assigned to a month or season, in which the impact started to occur. Most of the time, information about the end of an impact was unavailable. In this case we assumed that the impact only occurred in that month or season and not beyond. When a starting season is given for an impact, we assigned the season "spring" to the months March, April, May (MAM), "summer" to June, July, August (JJA), "autumn" to September, October, November (SON), and "winter" to December, January, February (DJF) for monthly impact data.

Different drought types may lead to different impacts, with D_{SM} typically related to impacts in agriculture and D_H typically related to impacts within a range of several water uses, such as the *Public water supply*. In this study, we focussed on the D_{SM} and D_H type. D_M often does not lead to impacts directly and D_{SE} is challenging to relate to specific impacts, as they are the least tangible. Additionally, impacts on agriculture and on various water uses are among the most relevant concerning drought (Stahl et al., 2016). To analyse timing, amount and the relevance of specific impacts, we re-grouped impact data to the D_{SM} or D_H type using the subtype category for assignment. For instance, within the category *Energy and industry* (4) subtypes are e.g. 'Reduced hydropower production' (4.1) and 'Impaired production' [...] (4.2) (Stahl et al., 2016). Regardless of the corresponding primary category, these subtypes were assigned to D_{SM} and/or D_H. For example, 'Reduced hydropower production' (4.1) is a result of low discharge and is therefore assigned to D_H, whereas 'reduced productivity of annual crop cultivation' (1.1) is a result of low soil moisture and therefore assigned to D_{SM}. Based on expert knowledge, four different people identified independently all 96 subtypes to D_{SM} and/or D_H. The newly grouped D_{SM} and D_H impacts were then analysed for seasonal occurrence in the different domains (entire Europe, Alpine Space, pre-Alpine and high-altitude region, Southern and Northern region). We calculated smoothed seasonal "impact regimes" as loess curves by local regression (Cleveland, 1979).

2.3 Hypothesis testing

The following hypotheses on spatial differences were tested: the distribution of impact categories reported for the Alpine Space differed from that of the entire European region, the high-altitude region from that of the pre-Alpine region, the Northern region from that of the Southern region. Additionally, we tested the hypothesis that the distribution of reported impact categories of

$\mathrm{EDII}_{\mathrm{ALPS}}$ differed between the Alpine countries and the NUTS 2 regions. We tested as well, if the distribution of impact categories differed for the years between 1975 and 2020. At last, we tested whether the distribution of impact categories reported differed for the season spring, summer, autumn and winter in the regions Europe, the Alpine Space, the pre-Alpine, high-altitude, Northern and Southern region.

For the statistical analyses, we used the compiled impact data as count data. We applied the *Pairwise Wilcoxon Rank Sum Test* to test whether the fraction of the counted data were significantly different. The test analysed if the central tendencies of the distributions between the groups differed (Cuzick, 1985). With the p-value ≤ 0.05, we rejected the null hypothesis that tendencies among the tested groups are the same and concluded a statistically significant difference between them. In addition, this test allowed us to identify which group(s) was (were) significantly different, if we tested more than two.

3 Results

3.1 Spatial differences across domains and countries

At the time of this study $\mathrm{EDII}_{\mathrm{EU}}$ comprised in total around 10,600 reported drought impacts for NUTS 2 and 3 regions. The first version of $\mathrm{EDII}_{\mathrm{ALPS}}$ summed up to more than 3,200 impacts. We observed substantial differences between the amounts of reported impacts across the domain (Fig. 2) with most reports located in the Northern and pre-Alpine region, followed by the Southern and high-altitude region. The *Pairwise Wilcoxon Rank Sum Test* depicted significant differences between the impact category distributions of the Alpine Space and Europe, but not between the other pairs (Table 1). Among the Alpine countries, the test identified Slovenia to be significantly different from Austria and Germany. At the smaller scale, several NUTS 2 regions located in Italy differed to NUTS 2 regions in Austria, Switzerland and Germany.

In addition to the test results, relative distributions provide further information. The $\mathrm{EDII}_{\mathrm{ALPS}}$ and $\mathrm{EDII}_{\mathrm{EU}}$ report the same two most frequent impact categories: *Agriculture and livestock farming* ($\mathrm{EDII}_{\mathrm{ALPS}}$: 48 %, $\mathrm{EDII}_{\mathrm{EU}}$: 31 %) and *Public water supply* ($\mathrm{EDII}_{\mathrm{ALPS}}$: 21 %, $\mathrm{EDII}_{\mathrm{EU}}$: 25 %). More than half of all reports on drought impacts belong to these two sectors in both regions. With 61 % this dominance is even stronger in the $\mathrm{EDII}_{\mathrm{ALPS}}$ ($\mathrm{EDII}_{\mathrm{EU}}$: 56 %). The fraction of reported impacts in *Agriculture and livestock farming* was clearly higher in all domains in the Alpine Space compared to the average of Europe. Especially, the Southern region presented almost 60 % of the reported impacts in this category, with more than half of all reports related to the subtypes ‘Reduced productivity of annual [...]’ (1.1) or ‘[...] permanent crop cultivation’ (1.2) and ‘Agricultural yield losses $\geq$ 30 % of normal production’ (1.3). This is related to 96 % of all impacts in *Agriculture and livestock farming* on country-level in Slovenia. The subtype ‘Reduced availability of irrigation water’ (1.4) was the most prominent in the high-altitude region. Impacts related to the second most important category *Public water supply* were less often reported in the Alpine Space compared to the average in Europe. In the Alpine Space, the high-altitude region depicted the highest fraction with 31 %, and on country-level France stood out with 39 %, both exceeding the European average. The most common subtype in this category was ‘Bans on domestic and public water use’ (7.3).

The third most frequent category in the $\mathrm{EDII}_{\mathrm{EU}}$ was clearly identified with *Freshwater ecosystems* (11 %). For the $\mathrm{EDII}_{\mathrm{ALPS}}$’ third rank, we identified *Forestry* (7 %) with a slightly higher fraction than *Freshwater ecosystems* (6 %). 17 % of all entries in the German part of the Alpine countries and 13 % of the Swiss entries related to *Freshwater ecosystems*, and thus, exceeded the European average. Most of these impacts were located at the Rhine river and most frequent with the subtype 'Increased mortality of aquatic species' (9.1). The $\mathrm{EDII}_{\mathrm{ALPS}}$' impacts on *Forestry* (7 %) were as well mostly located in the German (19 %) and Swiss (10 %) part of the Alpine Space. In the $\mathrm{EDII}_{\mathrm{EU}}$ the category *Forestry* is ranked 6th with a fraction of 5 %. In both the $\mathrm{EDII}_{\mathrm{EU}}$ and $\mathrm{EDII}_{\mathrm{ALPS}}$ we identified the same most relevant subtype 'Reduced tree growth and vitality' (2.1).

The $\mathrm{EDII}_{\mathrm{ALPS}}$ presented these four described categories *Agriculture and livestock farming*, *Public water supply*, *Freshwater ecosystems* and *Forestry* among the most important ones for the domains, but as well on the country-level with the following differences. As already mentioned, reports located in Slovenia were clearly dominated by the category *Agriculture and livestock farming* (96 %). More than 70 % of the impacts located in France (77 %) , Italy (78 %), and Austria (72 %) reported drought affecting *Agriculture and livestock farming* and *Public water supply* with switching relevance. Impacts located in Germany and Switzerland presented less dominance by these two categories, as *Forestry* and *Freshwater ecosystems* played as well a major role.

Regarding the other categories and subtypes, we observed smaller differences. Impacts related to *Waterborne transportation* presented the 5th highest fraction for both, the $\mathrm{EDII}_{\mathrm{EU}}$ (9 %) and $\mathrm{EDII}_{\mathrm{ALPS}}$ (5 %). The relevance was lower in the Alpine Space, but high in the French part with 14 % and in the high-altitude region with 7 % of all impacts related to this category. Whereas the impacts across entire Europe related most to the subtype 'Impaired navigability of streams (reduction of load [...])' (5.1), the majority of the impacts in the Alpine Space were not tangible to a specific subtype. They related to 'Others' (5.3), with a majority from the French database, Propluvia mapping 'measures prohibiting valve operation, nautical activity', which could not be clearly assigned to any subtype of the category *Waterborne transportation*. In the $\mathrm{EDII}_{\mathrm{EU}}$ and $\mathrm{EDII}_{\mathrm{ALPS}}$, the category *Water quality* presented a fraction of 7 % and 4 %, both with the most frequent subtype '(Temporary) *Water quality* deterioration / problems of surface waters [...]' (8.2). Thus, the frequency of this category was lower in the Alpine Space, and mostly located in Italy with 7 % meeting the fraction by the $\mathrm{EDII}_{\mathrm{EU}}$. The categories *Air quality*, *Freshwater aquaculture and fisheries*, *Tourims and recreation*, *Terrestrial ecosystems*, *Energy and industry*, *Human health and public safety* and *Conflicts* did not depict an obvious relevance in any of the analysed regions.

3.2 Temporal trends and drought years

Before the year 1950 the $\mathrm{EDII}_{\mathrm{ALPS}}$ only contains a small number of reported impacts (n: 244), covering eight categories, dominated by *Agriculture and livestock farming* (n: 272) and followed by *Public water supply* (n: 23), *Energy and industry* (n: 16), *Forestry* (n: 13) and *Human health and public safety* (n: 11). In this early time-period most impacts were reported in Austria, Switzerland, Germany and France. The number of reported impacts increased substantially after 1975, and again after 2000 and 2010 (Fig. 3a). Only the last three years presented less impact reports. After 1975, the years 1976 (n: 120), 2003 (n: 401), 2015 (n: 463), and 2018 (n: 412) showed substantially more impacts than other years. The Pairwise Wilcoxon Rank Sum Test confirmed the years 2003, 2015 and 2018 to be significantly different from others. Thus, our impact data represents four specific drought years. Beside the increase of collected impacts over time, the diversification increased as well.

Table 1. Results of the *Pairwise Wilcoxon Rank Sum Test*.

Regions [1]	P-value[2]
Alpine Space vs. Europe	0.022*
Pre-Alpine region vs. Northern region	0.085
Northern vs. Southern region	0.097
Alpine countries (n = 5)	
Austria:Slovenia	0.010*
Switzerland:Slovenia	0.063
Germany:Slovenia	0.035*
Alpine NUTS 2 regions (n = 35)	
Provincia Autonoma di Bolzano/Bozen:Niederösterreich	0.115
Provincia Autonoma di Bolzano/Bozen:Ostschweiz	0.143
Provincia Autonoma di Trento:Ostschweiz	0.134
Provincia Autonoma di Bolzano/Bozen:Freiburg	0.031*
Provincia Autonoma di Trento:Freiburg	0.050*

[1] Pairs for regions with more than two subregions (n > 2) whose central tendencies differ with a p-value ≤ 0.15.

[2] marked with '*' for the significant p-value ≤ 0.05.

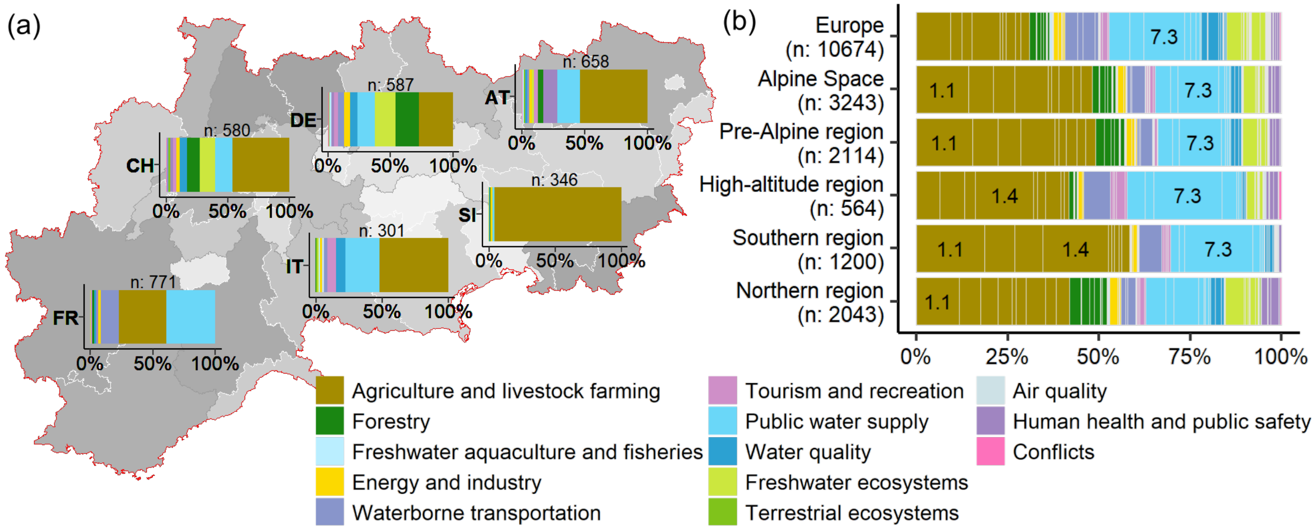

Figure 2. Reported impacts in 13 categories by region (n = total no. of reports per region). (a) Proportion of impact category per country. Darker grey shading relates to a higher count of reports per NUTS 2 region. (b) Proportion of impact categories for the regions. Subtypes with a proportion ≥ 10 % per region are labeled.

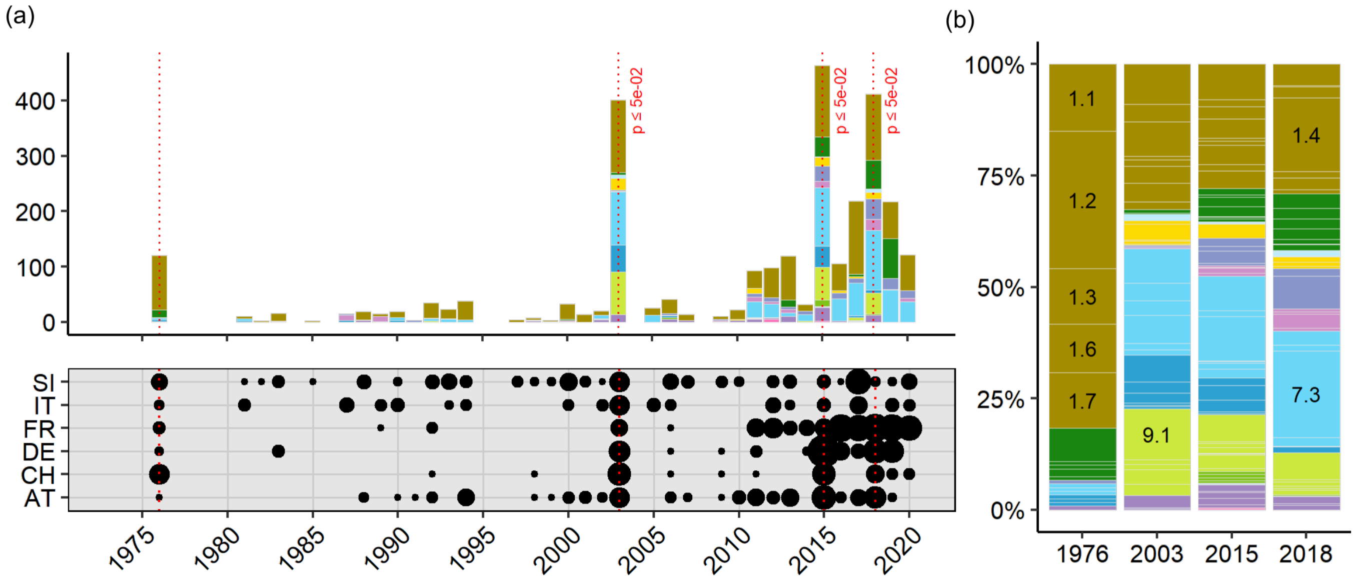

Figure 3. Reported impact categories between 1975 and 2020. (a) Counts of reports per year, outstanding years marked with red dotted lines. Counts of all reports per country and year. (c) Relation between sectors for these years. Subtypes with a proportion ≥ 10 % per region are labeled. Colours correspond to the legend of Fig. 2.

Comparing the drought events (Fig. 3b), the extreme relative dominance of the category *Agriculture and livestock farming* in 1976 (82 %) decreased substantially in the years 2003, 2015 and 2018 (33 %, 28 %, and 29 % respectively). In 1976, the second most reported impacts were for *Forestry* (12 %). The year 2003 showed high fractions for *Public water supply* (24 %) followed by *Freshwater ecosystems* (20 %) and *Water quality* (12 %), but still dominated by *Agriculture and livestock farming* (33 %). The most frequent subtypes during this drought event were 'Agricultural yield losses ≥ 30 % of normal production [...]' (1.3) and 'Increased mortality of aquatic species' (9.1). The categorial impact distribution of 2015 was comparable to the one of 2003 with the following alterations. In 2015, we observed more reports related to *Forestry* (8 %) and *Waterborne transportation* (6 %), but less to *Agriculture and livestock farming* (28 %), *Freshwater ecosystems* (13 %), *Water quality* (8 %) and *Energy and industry* (3 %). Further, the categories *Terrestrial ecosystems*, *Human health and public safety* and *Tourims and recreation* were represented with low relevance. In addition, no subtype presented the fraction ≥ 10 %. The general picture of the year 2018 was comparable as well. Impacts related to *Agriculture and livestock farming*, *Public water supply* and *Freshwater ecosystems* did not change their fractions remarkably between 2003 and 2015. Within these categories, the subtypes 'Reduced availability of irrigation water' (1.4) and 'Bans on domestic and public water use' (7.3) were more frequent in 2018 compared to 2015 and 2003. Furthermore, the year 2018 showed again higher fractions in *Forestry* (13 %), *Waterborne transportation* (9 %) and *Tourims and recreation* (5 %) and less in *Energy and industry* (3 %) and *Water quality* (1 %).

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3.3 Seasonal patterns

All reported drought impacts occurred mostly in summer, followed by either spring (Southern region) or autumn (all other domains), and fewest in winter (Fig. 4). Significant seasonal differences were found in Europe and in the pre-Alpine and high-altitude region in the Alpne Space (Table 2), always presenting the winter significantly differing from the summer. We identified low p-values for the summer differing from spring, but not between summer and autumn.

Although the seasonality of $\text{EDII}_{\text{ALPS}}$ and EDII_{EU} is rather similar for the domains, some categories show differences. Impacts related to *Agriculture and livestock farming* occurred in all seasons in $\text{EDII}_{\text{ALPS}}$ and it is the dominating category throughout the year excluding winter. *Agriculture and livestock farming* in the entire EDII_{EU} on the other hand dominates only during summer and *Public water supply* is the most dominant category at other times of the year (Fig. 4a,b). Regarding *Agriculture and livestock farming*, we observed most of these impacts in the summer in all subdomains as well, with a strong increase before and a decrease after the summer months. The pre-Alpine and Southern region show a clear increase of impacts in March and April (Fig.4c,f), and the high-altitude region has substantially higher counts in September and October (Fig. 4d). In the Alpine Space, the spring and summer impacts in this category related most to the subtype 'Reduced productivity of [...] crop cultivation' (1.1, 1.2), whereas the impacts in autumn related most to 'Reduced availability of irrigation water' (1.4). The $\text{EDII}_{\text{ALPS}}$ reported impacts in *Public water supply* were less frequent compared to the ones by the EDII_{EU}, and especially in the first months of the year till May. The high-altitude region shows the most different pattern compared to Europe (Fig. 4b,d). The monthly sums of this category do not increase in spring, but start to accumulate from May to August, and were less but still frequently reported in autumn. Especially in November and December, the reported impacts showed the same fractions as those related to *Agriculture and livestock farming*. In the $\text{EDII}_{\text{ALPS}}$ the most frequent subtype 'Bans on domestic and public water use' (7.3) dominated this category, wheres in the EDII_{EU}, the subtypes 'Local [...] and region-wide water supply shortage / problems' (7.1, 7.2) were as well prominent.

The $\text{EDII}_{\text{ALPS}}$' category *Freshwater ecosystems* reported most impacts in summer and autumn and almost none in spring and winter, with reports mostly located in the Northern region respectively pre-Alpine region (Fig. 4c,e). The EDII_{EU} presented as well most counted reports in the summer months, but the fractions of this category spread more equally across the seasons. Further, we identified most impacts related to *Forestry* to occur in summer for both, in the Alpine Space and in Europe. Within the sub-regions of the Alpine Space, we observed the fraction of *Forestry* impacts in relative terms to be varying. We depicted the lowest relative fractions in autumn, which is due to higher counts in spring and summer especially in the Northern region (Fig. 4e) and higher counts in winter in the high-altitude region (Fig. 4d). In the Alpine Space and in Europe, we found most frequent reports in *Waterborne transportation* from high summer to early September and with highest seasonal fraction in autumn (Fig 4a,b). Impacts related to *Tourims and recreation* differed in their seasonal distribution between the domains. In the Alpine Space, these impacts were mostly winter impacts with a majority located in the high-altitude and Southern region (Fig. 4a,d,f). Additionally, the high-altitude region showed higher fractions in spring for this category. Though the pre-Alpine and Northern region reported most impacts in summer, similar to Europe, these records are few compared to the more frequent categories, such as *Agriculture and livestock farming* and *Public water supply*. We also found a few impacts on *Air quality* in

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Table 2. Results by the *Pairwise Wilcoxon Rank Sum Test*.

Regions	Seasons[1]	P-value[2]
Europe	Summer:Winter	0.043*
Alpine Space	Summer:Spring	0.117
	Summer:Winter	0.083
Pre-Alpine region	Summer:Spring	0.109
	Summer:Winter	0.028*
High-altitude region	-	-
Northern region	Summer:Spring	0.067
	Summer:Winter	0.020*
Southern region	-	-

[1] seasonal pairs whose central tendencies differ with a p-value ≤ 0.15.
[2] marked with '*' for the significant p-value ≤ 0.05.

the $\text{EDII}_{\text{ALPS}}$ and EDII_{EU}. In the Alpine Space, this category together with *Tourims and recreation* were the only ones reported most in autumn (*Air quality*) and winter (*Tourims and recreation*).

3.4 Impacts related to drought types

We re-grouped 42 out of 96 subtypes by their related drought type D_{SM} and D_H (Fig. 5a). Twelve subtypes were classified as D_{SM} impacts with most of them from the categories *Forestry* and *Agriculture and livestock farming*. Further, we classified 32 subtypes as D_H impacts with a majority from the categories *Water quality*, *Public water supply*, and *Freshwater ecosystems*. Two subtypes were classified into both, the D_{SM} group and the D_H group: 'Lack of feed/water for livestock' (1.7) and 'Lack of feed/water for wildlife' (10.8), as low soil moisture as well as low discharge and/or groundwater storage are appropriate drivers. For 54 subtypes neither D_{SM} nor D_H was considered a clear trigger. They were classified into a group of indirect impacts that include impacts less tangible to specific drought conditions and strongly dependent on market situations, management and governance aspects. We found most of these ambiguous subtypes in the categories *Energy and industry*, *Human health and public safety*, *Air quality*, *Conflicts*, *Freshwater ecosystems* and the subtype 'Increased costs/economic losses' in several categories (all assignments are presented in Table S1).

With this classification scheme, the fraction of D_{SM} and D_H impacts differ clearly per domain (Fig 5). In the Alpine Space 36 % of all impacts were assigned to D_{SM} and 43 % to D_H. In Europe, D_{SM} impacts were less (22 %) and D_H impacts (56 %) more frequent (Fig. 5a,b). In the pre-Alpine region, 38 % of the impacts were assigned to D_{SM} and 42 % to D_H %. In the high-altitude region, we assigned less impacts to D_{SM} (23 %) and more to D_H (56 %) (Fig. 5c,d). The Northern and Southern region compared differed less with 35 % and 37 % assigned to D_{SM} and 40 % and 49 % assigned to D_H (Fig. 5e,f). The Southern region shows the greatest fraction of combined D_{SM} and D_H impacts (86 %) among all domains.

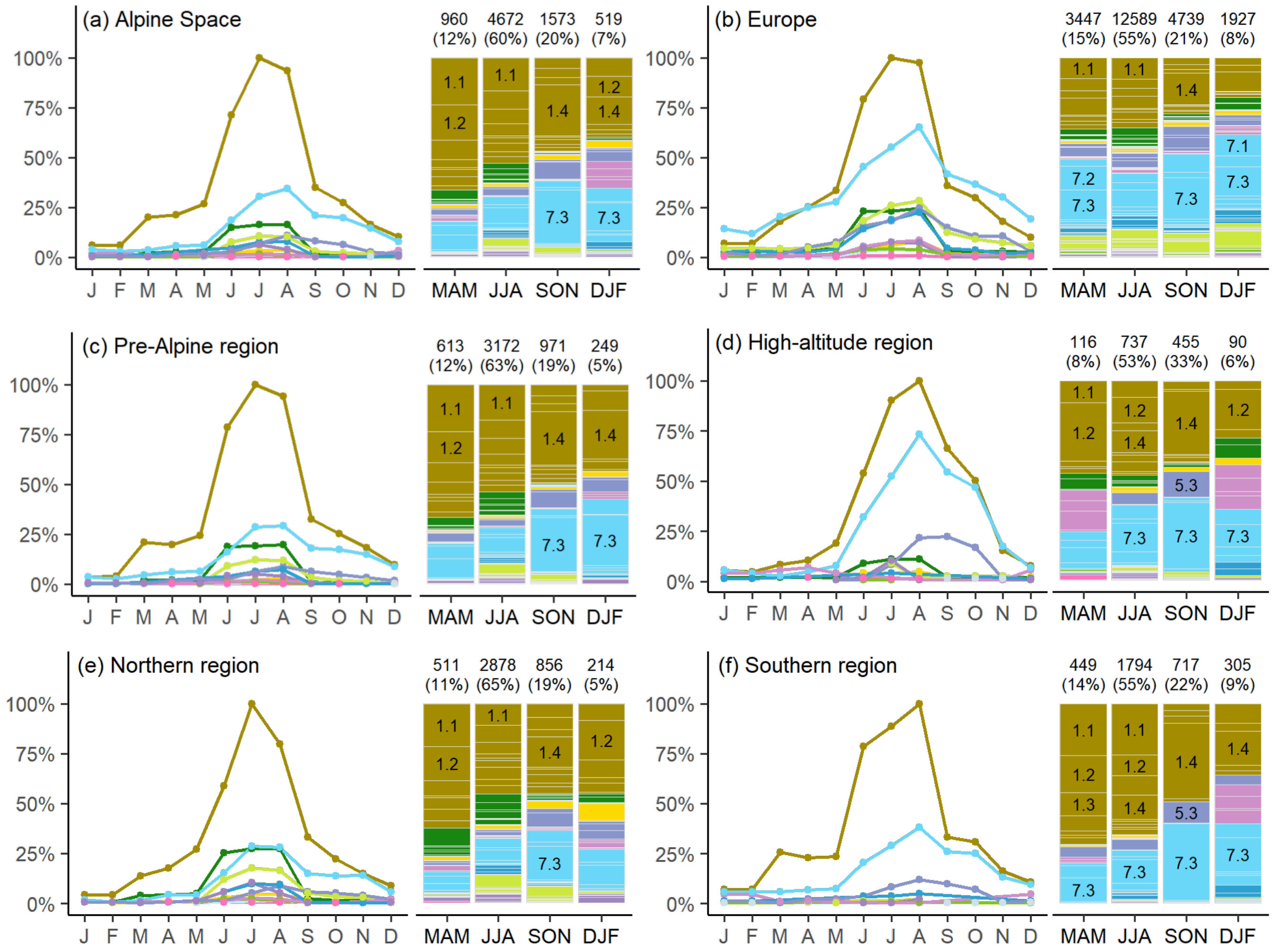

Figure 4. Annual distribution of reported impact categories aggregated per month (line diagrams) and season (bar plots) for (a) Alpine Space, (b) Europe, (c) pre-Alpine region, (d) high-altitude region, (e) Northern region, (f) Southern region. Monthly values are related to frequency of the month with most impacts. Total counts of each season are given on top of the bars, the proportion in brackets relates to the amount of impacts assigned to the season. Subtypes with a proportion ≥ 10 % per season are labeled. Colours correspond to the legend of Fig. 2.

In the D_H impact group, the most frequent subtypes are 'Bans on domestic water use' (7.3), 'Local water supply shortage/problems' (7.1), 'Reduced availability of irrigation water' (1.4), 'Regional shortage of feed/water for livestock' (1.7), and 'Increased mortality of aquatic species' (9.1). We found the largest proportional differences between the pre-Alpine and high-altitude region among the subtypes 'Reduced availability of irrigation water' (1.4), and 'Bans on domestic and public water use' (7.3). Accordingly, we observed a shift among these subtypes between the Northern and Southern region, but additionally for the subtype 'Increased mortality of aquatic species' (9.1). Both differences confirm the previous results. In the D_{SM} impact group, the most frequent reports are in the category *Agriculture and livestock farming* and about the subtypes ‘Reduced productivity of annual crop cultivation’ (1.1), ‘Reduced productivity of permanent crop cultivation ‘(1.2), ‘Agricultural yield losses $\geq$ 30 %’ (1.3) and ‘Regional shortage of feed/water for livestock’ (1.7). The different fractions for these subtypes depended on the domain. The Southern region reported the largest relative fraction of impacts about ‘Reduced productivity of annual crop cultivation’ (1.1), ‘Reduced productivity of permanent crop cultivation’ (1.2), ‘Agricultural yield losses $\geq$ 30’ (1.3). Within the D_{SM} impacts, *Forestry* impacts were substantially less frequent and non-existent in the Southern region.

The annual regime curves of the D_{SM} and D_H impacts are based on monthly reported impact sums. For all domains most D_{SM} and D_H impacts occurred in summer and early autumn as already shown in the previous results. In case of D_{SM} impacts, the high occurrence peaks were driven by ‘Reduced productivity of annual crop cultivation’ (1.1). Regarding the D_H impacts, the high peaks correspond to ‘Local water supply shortage / problems’ (7.1) in the Northern region and to ‘Bans on domestic and public water use’ (7.3) in all other domains.

According to the total counts of the grouped impacts by drought types, the Alpine Space has a higher D_{SM} impact peak occurring earlier in the year (June-July) than the D_H impact peak (July-August) (Fig. 5a). In addition, the increase and decrease of the D_H curve happens later in the year than that of the D_{SM} curve. Thus, between March and July D_{SM} impacts show higher fractions, while between September and December D_H impacts show higher fractions. The $EDII_{EU}$ contrasts these results (Fig. 5b), as the records across Europe depicted the higher peak of D_H impacts in the same summer months as the D_{SM} impact peak. Within the $EDII_{ALPS}$ the delayed D_H peak and the higher fractions of D_H impacts between September and December is confirmed by all subdomains (Fig. 5c,d,e,f). The most different pattern was found for the high-altitude region with the latest onset of the D_H impact curve and a delayed peak between August and September (Fig. 5d). Furthermore, this was the only domain within the Alpine Space with a higher D_H impact peak, and subsequently, the highest fractions between July and December.

4 Discussion

4.1 Drought impacts across the European Alpine region

Although the Alpine Convention has started to raise the topic, drought impacts in different regions of the Alpine and pre-Alpine area have not yet been formally compared. Assembling the $EDII_{ALPS}$, an inventory of drought impact reports, now enabled a first overview and some regional comparisons. Any collection of drought impact data is a challenging task because of the difficulties related to a clear definition of a drought impact’s onset and termination for multifaceted causes (Bachmair et al., 2015). The chosen data sources proved to be suitable, as impacts were clearly linked to the droughts occurrence as the cause for the collected impact report. Some impacts can be measured and are therefore easier to collect and hence more consistent through time and space (e.g., the agriculture yield losses), but most of them are hard to quantify (Logar and van den Bergh, 2013). For most of the impacts no continuous data is available, for which the text-reports proved to be a suitable surrogate and are worthwhile to collect (Bachmair et al., 2016; Hayes et al., 2012). Nonetheless, not all impacts are reported or only locally, in which case the compiled information in $EDII_{ALPS}$ V1.0 may still have gaps. Despite these barriers, the amount of impact

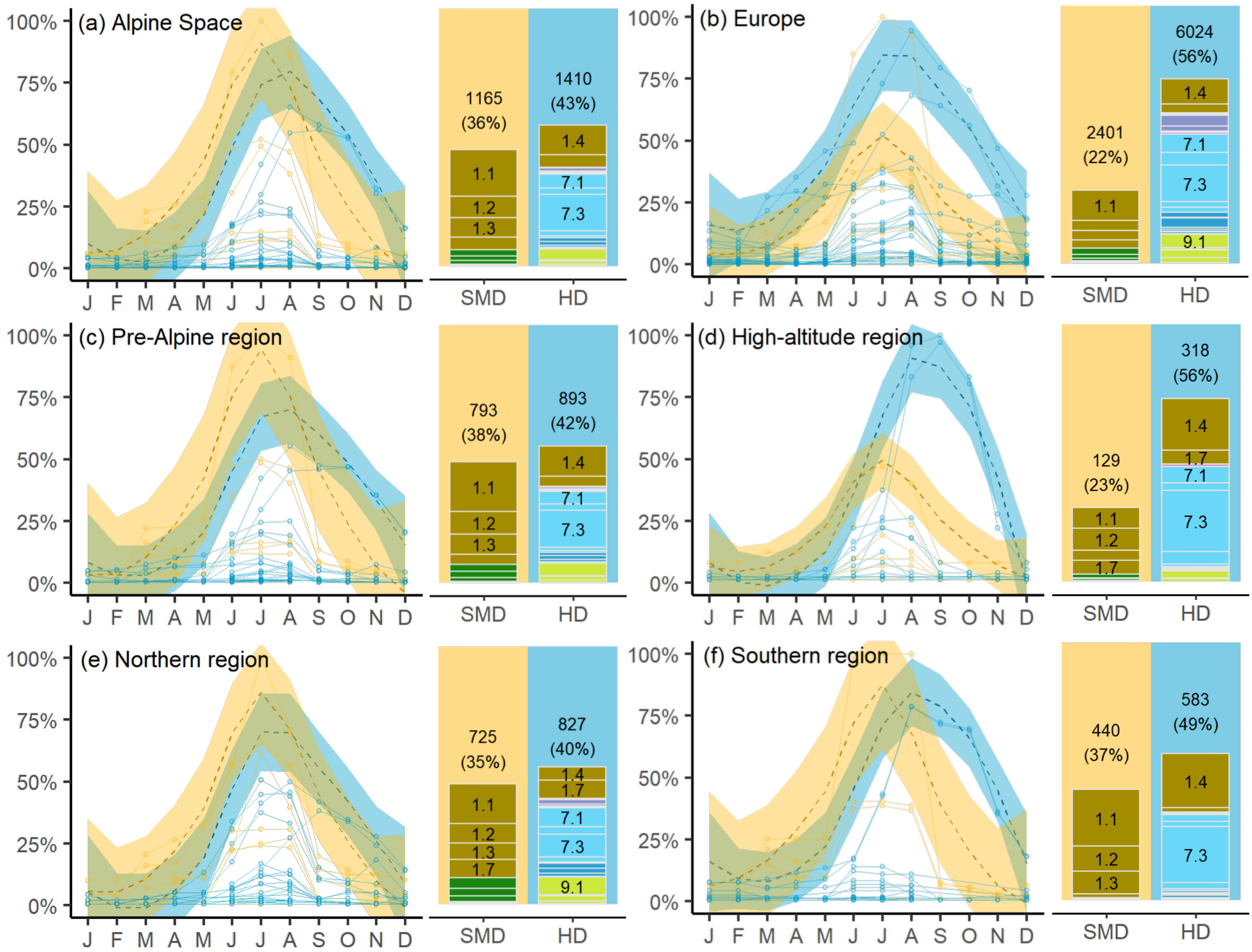

Figure 5. Impact subtypes assigned to D_{SM} (yellow) or D_H types (blue). D_{SM} and D_H impacts aggregated per month (line diagram) and drought type (bar plot) for (a) Alpine Space, (b) Europe, (c) pre-Alpine region, (d) high-altitude region, (e) Northern region, (f) Southern region. Seasonal regimes for D_{SM} (yellow lines) and D_H impacts (blue lines) are loess curves with standard errors (dotted line with coloured shape). Monthly values are related to frequency of the month with most impacts. Total counts of D_{SM} and D_H impacts are given on top of the bars, the proportion in brackets relates to the amount of impacts assigned to the season. Subtypes with a proportion ≥ 5 % are labeled. The colours of the subtypes correspond to the legend of Fig. 2.

345 data we collected within the Alpine Space (n: 3243) demonstrates that drought impacts have been present in the European Alpine region. Despite the humid mountain climate, 30 % of all impact data across Europe is located in our study region. Subsequently, this study confirms the relevance to understand the role of drought as well in the European Alpine region and

not only in low-altitude areas. We analysed the impact data differences between the Alpine Space and Europe, as well as for the paired domains (pre-Alpine and high-Alpine, Northern and Southern region) and for political units (countries, and NUTS 2 and 3 regions).

Similar to all of Europe, most reported impacts in the Alpine Space fell into the category *Agriculture and livestock farming*, specifically to the subtype 'Reduced productivity of annual crop cultivation' (1.1). In contrast to the Northern region, the Southern region is known for less precipitation and higher air temperatures due to the Mediterranean climate. Even though the region adapted partly to the climatic conditions with permanent irrigation systems (Yves et al., 2020), we found substantially more impacts related to *Agriculture and livestock farming*. Haslinger and Blöschl (2017) showed that drought frequencies were higher in the Southern region and hence also the exposure for impacts. Relatively, even more impacts in *Agriculture and livestock farming* were reported for the Alpine Space than for entire Europe. It should be kept in mind that the 'Alpine Space' includes not only the mountains but large foothill and foreland areas as well. Besides urban areas such as Vienna, Milan or Zurich, the Alpine Space is known for its agricultural crop production in lower elevation areas and for mountain pastures for beef and dairy production typical in higher elevated areas (Jäger et al., 2020). Subsequently, in this region *Agriculture and livestock farming* is among the most relevant economic sectors (Flury et al., 2013). This dependence potentially affects the vulnerability and hence drove the number of reported impacts we compiled compared to the whole of Europe with less economic dependency on the agricultural sector.

The second most impact category in the Alpine Space relates to *Public water supply*. Relatively however, it is less relevant compared to Europe, confirming the typical association that the European Alpine region is a water-rich Water Tower (Viviroli et al., 2007). Nonetheless, the amount of reports for the subtype 'Bans on domestic and public water use' (7.3) emphasizes the need to develop management strategies. Specifically, for periods of particular high water demand compared to its actual availability, e.g. periods with high demand for supplementary irrigation or for high touristic uses. The fraction of impacts related to *Public water supply* was highest in the high-altitude region, but it was not high in absolute number. Whether upstream headwater areas have to deal with impacted water supply, or less access to stored water compared to allocated water to lower (downstream) areas will have to be studied further to fully explain this result.

Impacts classified into the category *Freshwater ecosystems* were less reported and it may be concluded that they might be less relevant in the Alpine Space compared to Europe. However, in the Northern region the categories fraction was higher, mainly driven by reports from Switzerland and Germany exceeding the European average. Most of these reports were located along the river Rhine and associated with high water temperatures and less oxygen saturation in the year 2003. Drought impacts on *Forestry* were more relevant in the $\mathrm{EDII}_{\mathrm{ALPS}}$. This category ranked 3rd compared to 6th in the $\mathrm{EDII}_{\mathrm{EU}}$. Most of these impacts were located in Germany and Switzerland. The majority of German reports originated from governmental reports by national and regional agencies, such as the ressort of forest science by the federal state Baden-Wurttemberg or Bavaria that regularly publish articles about the forest conditions in Southern Germany. We found similar reports in Switzerland, but not in the other Alpine countries. Thus, $\mathrm{EDII}_{\mathrm{ALPS}}$ likely still misses *Forestry* impacts in other regions. The drought impact categories *Waterborne transportation* and *Water quality* appear to be less relevant in the Alpine Space compared to Europe. Reasons may include *Waterborne transportation* to take place in the lowlands and *Water quality* benefitting from less pollution and environmental degradation. Other impact categories did not show substantial differences.

4.2 Drought events and temporal impact trends

Reported impacts suggest a diversification over the main drought years from 1976, 2003, 2015 to 2018, confirming observations in earlier studies with the EDII$_{\mathrm{EU}}$ (Stahl et al., 2016). The impacts of the drought in 1976 differed substantially from the others, as more than 80 % of all impacts related to *Agriculture and livestock farming*, followed by *Forestry*. The other major drought events of the years 2003, 2015 and 2018 depicted a more comparable picture. A remarkable difference of the impacts in 2003 to the more recent events were the high fractions of the category *Freshwater ecosystems* and *Water quality*. According to the previous section, these impacts correspond to the river Rhine in Northern Switzerland and Southwest Germany. Blauhut et al. (2015) associated this increase with the new EU Water Framework Directive, which raised the topic's attention. In 2003, the high water temperatures and low oxygen levels were firstly reported as impacts in the category *Water quality*, but finally led to the great fish dieback, reflected by the subtype 'Increased mortality of aquatic species' (9.1) of the category *Freshwater ecosystems*. The years 2015 and 2018 showed substantially increasing reports related to *Forestry*. These impacts might be the response to the sequence of persistent dry and warm periods in-between, which accumulate in dry soils and subsequently soil-moisture drought. The fractions increase of *Forestry* impacts likely reflect the persistent character of soil-moisture drought accumulating longer than one year and thus depict delayed impacts. Trotsiuk et al. (2020) showed substantially stronger negative trends by the species Fagus sylvatica and Picea abies of forest productivity in Switzerland for the year 2018 compared to 2003. Though, they did not analyze the year 2015, the results for 2018 likely correspond to accumulated effects. Ogle et al. (2000) predicted higher tree mortality following severe droughts and McDowell et al. (2010) suggested the drought-induced lower, but more continuous mortality of tree species occurring delayed due to several interdependent physiological mechanisms. We observed a similar but less prominent pattern for the category *Waterborne transportation* between the years 2003 and 2018 that might correspond to a longer lasting hydrological drought, with less discharge and/or groundwater storage over the years.

Over the whole time period, the number of collected drought impacts increased, especially after 2000 and 2010. This trend is influenced by (1) general reporting behaviour changes with digitization and online media availability (regardless of the sources, such as scientific or newspaper articles or governmental reports), (2) accessibility to drought reports in the recent past being easier than to historic information (3) awareness of the drought hazard having increased along with climate change. For the most recent droughts, reports are yet to be published. Thus, the decreasing number of reports for the last five years is likely a delayed effect of publishing and collecting such text-based impact information. Nevertheless, we presented significant different values for the years 2003, 2015 and 2018, which correspond well to the major drought events after 2000. Additionally, 1976 depicts substantially more impact data, in a time where digitalization and the accessibility to online articles had been very different compared to the last 20 years. Thus, we expect our time trend to be biased and with 70 % of all reports located in the Northern region mostly oriented on the maritime climate. Droughts in the Southern region, might have been too local to

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affect the general development. However, the EDII$_{\text{ALPS}}$ as a whole still depicted the major events and the tendency of increased impacts.

4.3 Seasonal patterns and delayed impacts

Summer and early autumn are the seasons with most drought impacts in all domains regardless of impact category or drought type. This confirms the expectation that drought impacts occur especially in summer. Additionally stressed by evapotranspiration, this season has the highest water demands, and hence, higher potential water shortages occur despite a mostly balanced annual precipitation in the Northern and Western parts of the Alpine Space (Kruse et al., 2010). In early autumn natural soil and catchment water storages are depleted. This low flow season, known from low elevated regions (Laaha and Blöschl, 2006), also leads to drought impact occurrences. The statistical tests provided proof for the summer season differs significantly from winter, but not from autumn.

Summer and often early autumn impact dominance most clearly shown for the impact categories *Agriculture and livestock farming* and *Public water supply*. We indeed observed higher fractions of autumn impacts in the high-altitude region mostly related to *Public water supply*, followed by 'Reduced availability of irrigation water' (1.4). The relevance supports the expectation that water supply depends not only on direct precipitation, but also on natural water storages feeding springs used for drinking water. Reservoirs are likely managed differently across the Alpine Space, depending on the reservoir location and purpose. Hence, clarifying upstream-downstream dependencies would be a prerequisite to understand in more detail, why and where impacts have happened. Regarding the Alpine Space, autumn does not differ significantly from summer, thus highlighting the importance of this season for the European Alpine region.

Although we presented least winter impacts, this season should not be neglected. Several studies showed winter as an essential part of the droughts development, and suggested the delayed effects by summer and autumn accumulating in winter and winter as the early driver for upcoming impacts in the following seasons (van Loon et al., 2010; Livneh and Badger, 2020). Our compiled winter impacts differed slightly by their composition. The fraction of impacts related to *Agriculture and livestock farming* decreased (especially in the high-altitude and Southern region) with the last crop harvests in autumn. The impacts in the categories *Public water supply* and *Waterborne transportation* are also less in winter but with comparable relative portions as in autumn. In contrast, impacts on *Tourims and recreation* peak in winter, driven by the high-altitude region (all impacts from the southern region in this category were as well located in the high-altitude region). In the EDII$_{\text{ALPS}}$ most impacts in this category reported limited snow availability and snow production, both threatening ski tourism. Several studies raise the topics attention, as the problem is real and should not be ignored in management of tourism in mountain regions (Abegg et al., 2007; Gilaberte-Búrdalo et al., 2014; Spandre et al., 2019).

In almost all domains, more than 10 % of all impacts occurred in spring. In the Alpine Space, the Southern region reported the most impacts in spring, which could relate to the Mediterranean climate that is in general warmer and drier also in the early stage of the year and hence the vegetation season starts earlier. A corresponding example published in April, 2020 by an Italian newspaper is summarized as follows: "In the Brescian area, emergency irrigation was carried out on wheat, barley and fodder, but also on freshly sown corn. [...] In some cases the seedlings begin to dry out. Maize is also suffering: sowing took place between the end of March and the first days of April, but the lack of rainfall is compromising growth [...]. In some cases, farmers preferred to postpone sowing. Wherever possible, emergency irrigation is used [...]". The constitution of the $\text{EDII}_{\text{ALPS}}$' spring impacts differed from that of the EDII_{EU}. We found substantially less impacts related to *Public water supply*. In mountain regions, the precipitation in winter does not evaporate as quickly as in lower elevated regions and soil moisture may replenish. In higher elevations, it is first stored as snow and will not replenish the water storages, both soils and artificial reservoirs, before all snow is melted around July - or even later if glacier melt is used for filling. Both processes likely mitigate water shortages in spring in mountain areas, leading to less hydrological drought impacts related to low discharge and groundwater storage. Furthermore, we found a higher fraction of *Forestry* impacts occurring in the Northern region. Delayed summer and autumn effects could persist over winter, especially in winters with temperatures cold enough to hinder precipitation to function as soil water, as it is stored in snow (van Loon et al., 2010). This could lead to dry soil and vegetation more vulnerable to drought. Additionally, most plants reduce their water intake during the cold season, to be less prone to frosts (Theocharis et al., 2012). Thus, cold winters high up do not prevent drought impacts in spring, what we likely observed with the *Forestry* impacts in the Northern region. The high fraction of impacts related to *Tourims and recreation* in the high-altitude region is mostly due to ski tourism lasting into spring.

The $\text{EDII}_{\text{ALPS}}$ reveals several delayed effects between impact categories. A delayed start and termination of hydrological drought impacts in all domains confirmed the expectation that drought types occur in a particular order, which is not as clear in the EDII_{EU}. Further, higher total counts of hydrological drought impacts compared to soil-moisture drought impacts in all domains underlines the effect that drought impact frequencies increase over time. Both effects were shown to be strongest in the high-altitude region. In the high-altitude region, snow accumulation in winter and in general lower air temperatures lead to better water availability in spring and early summer and subsequently, as shown by our results, less impacts (smallest fractions of impacts in spring and summer). Further, this typical mountain hydrology likely delays the hydrological drought impacts, as water released by snowmelt leads to longer water availability of natural storages typical for upstream areas. This effect could be found in all domains of the $\text{EDII}_{\text{ALPS}}$, but not in the EDII_{EU}. However, the high-altitude region experienced relatively the most hydrological drought impacts later in the year, showing the regions dependency on water and the need for management strategies also in upstream areas.

5 Conclusions

The presented $\text{EDII}_{\text{ALPS}}$ constitutes the first comparative view of drought impacts across the European Alpine region. Most of the $\text{EDII}_{\text{ALPS}}$' recent data stem from newspaper articles, web pages, governmental reports and scientific articles and specialty databases with a majority reporting drought impacts on *Agriculture and livestock farming* and *Public water supply*. Between the sources covering the Alpine countries the focus varied: Comparable to EDII, the Unwetterchronik, Drought-CH as well as the text-report collection for Germany and Italy offered varied information about the droughts impacts. In contrast to these more broad databases, the bulletins from DMCSEE and the Slovenian text-reports were more focussed on impacts related to agriculture and the French "Propluvia" informed on water restrictions in drought periods. The resulting report based impact

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data collection EDII$_{\mathrm{ALPS}}$ is therefore shaped by national priorities and societal effects. Our statistical tests confirmed this spatial heterogeneity. Nonetheless, we should consider the national focus as valued information, because this likely depicts the current major challenges on the national scale in drought management, but further efforts might focus on complementing them. Despite this differences, EDII$_{\mathrm{ALPS}}$ depicts plausible patterns in altitudinal and climatic subregions in the Alpine Space and may serve as an example how international collaboration can customize existing databases such as the EDII with a moderate effort to make them useful in regions that have previously not really been a focus.

Our study presented the European Alpine region vulnerable to drought, despite the water-rich character. We compiled a great amount of impacts mostly related to agriculture and livestock farming followed by public water supply. These affected sectors are firmly established in the region, wherefore adaption and management strategies are essential for the future climate regimes. Apart from the most relevant sectors, we found a surprising diversity of impacts covering a wide range of environmental, economic and societal effects that confirm the multifaceted character of drought in the Alpine Space. This growing diversity over time is likely due to the increasing complexity of the socio-economy in the Alpine Space with various sectors exposed and/or vulnerable to drought. In addition, the number of impacts increased substantially over time.

Key characteristics of drought impacts in the region are that impacts mostly occur in summer and early autumn regardless of region, climatic condition or altitude. Typical to EDII$_{\mathrm{ALPS}}$ are also some winter impacts related to ski tourism while spring impacts occur mostly in the southern region. The regions' specific snow accumulation in winter likely mitigates water shortages through snowmelt contributions in spring and early summer. Further, we could prove the possibility to link impacts to hydrological drought and soil-moisture drought in order to analyse drought specifics in different hydrological and climatic conditions. For the mountainous regions, we could demonstrate the delayed effect between impacts caused by soil-moisture drought and hydrological drought, especially for the higher elevated region. All these seasonal effects of water redistribution and demand are essential to understand the hazard potential in different climatic and altitudinal zones for which our study presents a good starting point. Despite some biases in the current database, the amount of impacts we compiled in the EDII$_{\mathrm{ALPS}}$ should raise awareness. Future climate predictions with increased drought severity, less snow and shift in precipitation patterns, suggest the European Alpine region will be vulnerable to drought impacts. This has to be taken into account for drought risk and management assessments.

Data availability. We plan to publish the EDII$_{\mathrm{ALPS}}$ data with a DOI.

Author contributions. Ruth Stephan, Mathilde Erfurt and Kerstin Stahl, designed the research. All co-authors provided data. Ruth Stephan moderated all EDII$_{\mathrm{ALPS}}$ entries, carried out the analysis and created the graphs, maps and tables in the manuscript. Ruth Stephan prepared the manuscript with contributions from Mathilde Erfurt and reviews from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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