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Impacts and damages of the European multi-year drought and heat event 2018 - 2022 on forests, a review

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Abstract. Drought and heat events are becoming more frequent in Europe due to human-induced climate change, affecting many aspects of human well-being and ecosystem functioning. However, the intensity of these drought and heat events is not spatially and temporally uniform. Understanding the spatial variability of drought impacts is important information for decision makers, supporting both planning and preparations to cope with the changing climatic conditions. Currently, data relating to the damage caused by extended drought episodes is scattered across languages and sources such as scientific publications, governmental reports and the media. In this review paper, we compiled data of damages caused by the drought and heat of 2018 until 2022 in forest ecosystems and relate it to large European data sets, providing support for decision making both on the regional and European levels. We partitioned data from 16 European countries to the following regions: Northern, Central, Alpine, and South. We focused on drought and heat damage to forests, and categorized them as (1) physiological (2) pest, and (3) fire damage. We were able to identify the following key trends: (1) Relative defoliation rates of broadleaves is higher than of conifers in every country with the exception of Czech Republic (2) the incidence of wood destroyed by insects is extremely high in Central Europe and Sweden (3) Although forest fires can be related to heat and drought, they are superimposed by other anthropogenic influences (4) In this period (2018-2022), forests in central Europe are particularly affected, while forests in the Northern and Alpine zones are less affected, and adaptations to heat and drought can still be observed in the Southern zone. (5) Although in several regions 2021 was an average year still high levels of damages were observed indicating strong legacy effects of 2018- 2020. We note that the inventory should be continuously updated as new data appear.

1 Introduction

1.1 General introduction

Global temperature rise due to the accumulation of anthropogenic greenhouse gases in the atmosphere, is causing extreme drought and heat events to become more likely and more extreme (Seneviratne et al., 2021). Even if we manage to stay below the e 2°C global warming threshold (relative to pre-industrial levels), in Europe one out of every two summer months is projected to be as warm or warmer than the summer of 2010, which has been one of the warmest across Europe to date (Suarez-Gutierrez et al., 2018). Neither of the recent spell of anomalously warm summers 2018, 2019, 2021, and 2022 has exceeded 2010 yet (Rousi et al., 2023). Extreme heat occurring under severe drought conditions can lead to even more devastating ecological and socio-economic impacts (Feller et al., 2017; Zscheischler et al. 2020; Bastos et al., 2021), such as economic losses (García-León et al., 2021), increased risk of wildfires (Ruffault et al., 2020), increased risk of crop loss (Toreti et al., 2019, Brás et al., 2021; Bento et al., 2021), and unprecedented forest mortality events (Schuldt et al., 2020). As such, the recent period of drought and heat between 2018-2022 is especially concerning as the possible beginning of a new climatic era in Europe.

Those hot and dry extremes are part of a long-term trend seen in Europe, making it a hot spot for heatwaves in comparison to other regions of the northern hemisphere midlatitudes over the last 42 years (Rousi et al., 2022). Central and southern Europe are affected by a longer-term drying trend, in line with expectations from theory and climate model simulations (Ionita et al.,

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2022). Consecutive multi-year meteorological summer droughts, such as those of 2018 to 2022 in central and western Europe, are characterized by two or more summers of lower than normal precipitation and higher than normal evaporative demand, resulting in a larger reduction of soil moisture content in the second year of the drought, and therefore to potentially more extreme drought impacts (Van Der Wiel et al., 2022). Worryingly, climate models project a strong increase of dry spells (Rousi et al., 2021) and multi-year droughts in western Europe in response to further global warming (Van Der Wiel et al., 2022). The current period of drought started with the summer of 2018, which was an extreme climatic season in Europe, characterized by concurrent heatwaves and droughts in large parts of the continent (Rousi et al., 2023).

1.2 Scope and aims

In this review we present the impacts documented in European forests during the years 2018-2022, some of the warmest and driest on record over Europe. We focus primarily on these ecosystems because they are not irrigated and thus the effects of climate extremes are clearest. Furthermore, in irrigated ecosystems, the irrigation infrastructure and capacities could vary considerably, adding a potential bias in the interpretation of results. Forests play a fundamental role in our livelihoods and supply the renewable raw material wood and other essential ecosystem services.

We partitioned the forest environment into four main geographical zones with district climatic and environmental conditions: (1) Northern Europe, (2) Central Europe, (3) Alpine zone, and (4) Southern Europe. The four geographical zones do not overlap in all cases with the international borders. Thus, since some of the sources (e.g. government reports) used for this review refer to political boundaries, we assigned those sources to only one geographical zone, which was the most suitable.

The insight of the exceptionally severe compound drought and heat event during the period 2018 - 2022 and its impacts are derived with an interdisciplinary study combining different sources that allow assessing the temporal and spatial heterogeneity impacts. We start with the description of the climatic conditions in 2018-2022, with focus on drought and heat. For Southern Europe, we also describe the year 2017 if necessary to give better context. Following, we focus on the drought and heat impacts on forests. We collected the different estimates of damages from research papers, reports and even media coverage when no better source was available. We focus our review on damage caused by drought and heat that induced (i) physiological stress, (ii) insect pests, and (iii) fire events, since the three impacts were the most dominant in our sources. Data collection was conducted as broadly as possible across Europe over months of work by a working-group in the ClimXtreme project with additional experts beyond the project contributing their expertise. Not all European countries were included due to language barriers or data scarcity.

1.3 Occurrence of drought and heat in Europe during 2018-2022

Persistent above average temperatures and extreme deficits in precipitation characterized the summers during 2018-2022 (Fig 1) across Europe, one of the worst consecutive drought periods that occurred in the continent. The extreme climatic conditions were linked to strong atmospheric circulation anomalies with extended periods of blocking over Europe, especially in late spring and summer 2018. It was found that a persistent positive North Atlantic Oscillation (Drouard et al., 2019; Li et al.,

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2020) combined with a double jet stream configuration were present before the initiation of the heatwave (Rousi et al., 2023). The associated tripolar sea surface temperature anomaly pattern in the North Atlantic has previously been identified as a precursor for European heatwaves (Beobide-Arsuaga et al., 2023), such as the one of 2015 (Duchez et al., 2016), or for increased drought risk in central Europe via changes in the large-scale atmospheric circulation (Haarsma et al., 2015; Rousi et al., 2021; Ionita et al., 2022).

Using pattern climatology data for Europe and linking it with observations over the last 120 years, Hari et al. (2020) claim that the consecutive 2018-2019 drought was unprecedented during the last 250 years. Including 2020 in their analysis, Rakovec et al. (2020) found that the 2018-2020 drought was not only unprecedented in intensity, but what made it truly exceptional was its average near-surface air temperature anomaly of +2.8K above the pre-industrial period. From a spatial perspective, the authors found that approximately 35% of Europe was affected during the first two most severe years of the drought. Following the 2018-2020 extreme drought, 2021 marked a rather normal to wet year. However, persistent hot and dry conditions returned in spring and summer 2022, leading to similarly depleted soil water levels as in 2018 and regionally worse drought conditions (Fig 1). Here, we use the Standardized Precipitation Evapotranspiration Index (SPEI), which includes, in addition to precipitation, the effects of temperature and hence evapotranspiration. Throughout the summer of 2022, heat waves and exceptionally low rainfall led to very dry conditions in central Europe. Based on observed runoff anomalies, it was also highlighted that the 2022 European drought could have been the worst in 500 years (Schumacher et al., 2022). Many areas in Europe were subject to the strongest 500 hPa geopotential height anomalies since 1950 between May and July 2022 (Toreti et al. 2022a).

In the following sections, we take a closer look at the climatic situation during those five critical years in four European sub-regions (Britain/Scandinavia, Central, Alpine, and Southern zone of Europe). Table 1 lists the countries and regions present in this review. Countries were selected based on exposure to heat and drought during 2018-2022, but also based on data availability and language barriers.

Table 1: Four climate zones and the associated countries. Please note that France is found in the Central Zone, Italy in the Southern Zone, but both are also partially assigned in the Alpine zone.

Zone	Countries
Northern	Finland, Sweden, Norway, United Kingdom (UK), Ireland
Central	Poland, Czech Republic, Switzerland, Austria, Germany, Netherlands, Belgium, France
Alpine	Switzerland, Austria, Italy, France
Southern	Italy, Spain, Portugal

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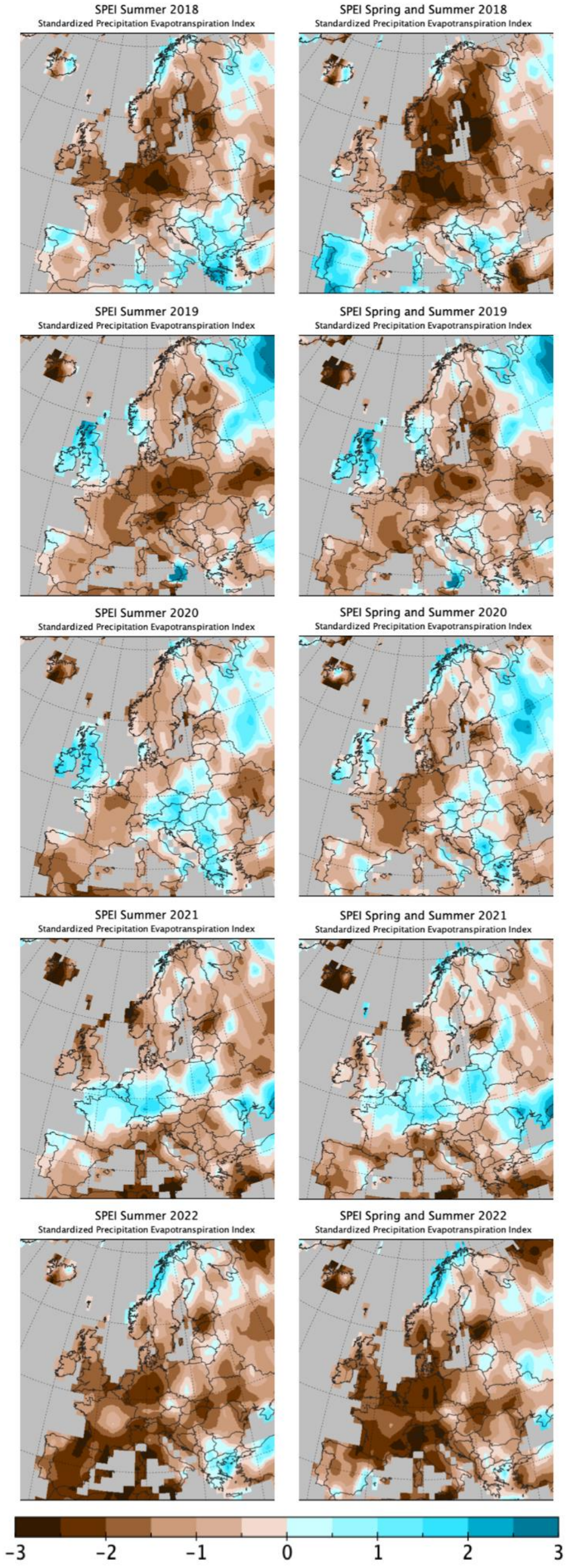

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Figure 1: SPEI for summer (June to August) and the entire growing season (May to August) during the 2018 (top row) to 2022 period (bottom row). Data was derived from the Global Drought Monitor, which offers near real-time information about drought conditions at global scale. Mean temperature was obtained from NOAA NCEP CPC and precipitation from GPCC (DWD).

1.4 Drought attribution

As alluded to in the general introduction, a longer-term drying trend is observed in central and southern Europe, backed up by climate model simulations that project these trends to continue. There is high confidence that both temperature increase and precipitation decrease has already led to increased aridity in the Mediterranean region (IPCC, 2021). There is less clear of a trend in western and central Europe (Germany, northern France, southern UK), which is not surprising given the fact that there is high confidence of decreased aridity in response to a mean precipitation increase in northern Europe (Scandinavia, Scotland, Ireland) (IPCC, 2021). Nonetheless, using summer SPEI trends between 1950-2018, Christidis and Stott (2021) found that there is an increased drought risk also in France and Germany, both in observations and CMIP6 models. Southeastern Europe is equally affected, with northern Poland being the exception. This is also confirmed when analyzing longer-term SPEI trends (1902-2020), where hotspots in terms of drying were found in Spain, Portugal, the southern part of France, Italy, the eastern part of Germany, the Czech Republic, Poland, Hungary, Slovenia, and Croatia, with the opposite trend in Norway (Ionita et al., 2021a). However, the same authors link those observations to changes in large-scale atmospheric circulation in the North Atlantic region (Ionita et al., 2022). Others have highlighted that the changes in the North Atlantic circulation may in turn be linked to the slowdown of the Atlantic Meridional Overturning Circulation (AMOC; Caesar et al., 2018). Hence the question remains to what extent the observed trends are directly (thermodynamically) or indirectly (dynamically) attributable to anthropogenic factors. There are two ways to address this question more broadly: (1) The paleo-climatic perspective and (2) longer-term climate model projections.

(1) Looking at reconstructions that are typical for summer conditions over the Czech Republic and neighbouring regions in Poland, Germany, Austria, Hungary and Slovakia, Büntgen et al. (2021) found that the most recent drought extremes between 2015 and 2018 are not only unprecedented during the period of proxy-target overlap, but also in the context of the past approximately 2,000 years. In other words, the most recent drought episode is beyond the variability seen in proxy data as far back as two millennia. These results are in contrast to findings by Ionita et al. (2021b), who claim that mega-droughts during the 15th and late 18th/early 19th century were longer and more severe compared to recent drought events. It is noteworthy, that both studies used summer scPDSI (self-calibrated Palmer-Drought Severity Index) data which are not entirely comparable with SPEI, but they should at least be consistent against one-another. For now, we can only conclude that either the location (central part of Europe in case of Ionita et al. (2021b)), the method (the latter based on the Old World Drought Atlas), and/or the spatial extent considered may be different. But what both results indicate is that it is difficult to draw definite conclusions from paleo-evidence.

(2) Climate model projections based on the latest CMIP6 assessment broadly confirm the trends that were found in observations. As shown in see *IPCC AR6*, the rainfall deficit is going to be most pronounced during the summer season (end

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of 21st century vs current conditions). While increased Winter and Spring precipitation may balance some of the summerly water deficit, this is unlikely to be the case in France and Germany (and certainly not in the Mediterranean region). Given that trends in evapotranspiration are already negative with regard to the annual mean, the trend is only going to be larger in summer (we note that annual mean rainfall changes are not very informative when it comes to drought attribution). In tandem with the rainfall deficit, it is very likely that meteorological drought conditions will occur much more often than they do now. In fact, it is highly unlikely that the current string of extreme drought years is an exception, rather than a harbinger of what will be the new normal soon. That said, these projections are valid only for transient warming conditions. As soon as we stop emitting carbon to the atmosphere, the planet is slowly transitioning from its current transient warming state, entering the equilibrium warming phase following an e-folding trajectory. Thermodynamically, the transient warming state is characterized by a maximized temperature contrast between land and ocean (land masses warming much faster than ocean waters), causing the water deficit over land to increase even more than it would under (hypothetical) uniform land and ocean warming conditions. Given that the water vapour supply from oceans is limited due to relatively cooler ocean SSTs, the relative humidity over many land areas decreases (Byrne and O'Gorman, 2013). While not relevant for the near future, it should be kept in mind that the current drying trend is unlikely to continue once the climate system is allowed to return to a new equilibrium state.

How do these two lines of evidence compare with actual attribution studies of individual extreme drought events? While it is generally straight-forward to attribute heat waves to anthropogenic climate change (e.g. Vogel et al. 2019; IPCC, 2021), the fact that the signal-to-noise ratio for drought events is still low, (despite attributable global warming of 1.2-1.3°C) leaves the attribution community in a limbo as far as robust results are concerned. For example, Van der Wiel et al. (2022) conclude that drought events like 2018-2020 are part of the realm of possibilities in the present-day climate, that is, a comparable event could have been expected to occur based on the average frequency or return period. Eventually the signal will emerge and it would be prepared and to have contingency plans at hand in order to be able to cope with the detrimental effects for biodiversity and human health.

Despite the difficulties to reconcile the existing lines of evidence, there are a few drought attribution studies that have been trying to quantify the role of humans. A prominent rapid event attribution of the intense 2022 drought in central and western Europe showed that human-induced climate change made the root zone soil moisture drought about 3-4 times more likely, and the surface soil moisture drought about 5-6 times more likely (Schumacher et al., 2022). They concluded that, while the magnitude of historical trends vary between different observation-based soil moisture products, all agree that the dry conditions observed in 2022 would have been less likely to occur at the beginning of the 20th century. One study on the 2015 European summer drought concluded that the attribution results depend on the methodology used (Hauser et al., 2015). Only when using the largest possible forcing difference in CMIP5 models were they able to detect a human influence for an increased likelihood of Central European droughts. García-Herrera et al. (2019) analyzed the drought that affected France and western Germany from July 2016 to June 2017, stating that recent trends, including those in human-induced higher temperature, have exacerbated the severity of the drought event. Finally, Philipp et al. (2020) investigated the hydrological drought of 2018, stating that the trend is driven by strong trends in temperature and global radiation rather than a trend in precipitation, resulting in an overall

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trend in potential evapotranspiration. Given that these trends are confirmed in climate model simulations, they conclude that the observed trend in agricultural drought can at least in part be attributed to human-induced climate change.

We conclude by pointing out that extreme drought is closely linked with extreme heat, which in turn increases heat-related mortality and morbidity as highlighted by Watts et al. (2020). Vicedo-Cabrera et al. (2021) found that up to 30% of heat-related deaths globally in the last 30 years can be attributed to anthropogenic climate change. Mitchell et al. (2016) found an increased risk of heat-related mortality during the intense 2003 summer heat wave in Central Paris by ~70% and by ~20% in London, both attributable to human factors having exacerbated the likelihood for such heat episodes.

2. Meteorological conditions

2.1. Drought and heat in Scandinavia and the British Isles 2018 -2022

Southern **Finland** experienced similar problems as Sweden did. For example, in central Finland, the all-time lowest groundwater table levels were measured in small and shallow aquifers (Veijalainen et al., 2019). Further, the summer of 2018 saw uncommonly large algal blooms and the death of fish and mussels, as well as a large impact on agriculture productivity, with 14-57% lower yields for most cereals.

Sweden experienced prior to 2018 two rather dry years in 2016 and 2017. Especially in southern Sweden, streamflow was 28% below normal and many regions issued local water use restrictions (Geological Survey of Sweden, 2017). This drought continued and culminated in 2018 (Swedish Board of Agriculture, 2019), which ultimately led to the most serious wildfires in modern times of Sweden (Teutschbein et al., 2022). In this context, Fires like those in 2018 were made approximately 10% more likely in Sweden under current climate conditions compared to pre-industrial climate (Krikken et al., 2021). Drought conditions were easing in the following years, with the return of slightly drier conditions in 2022.

Norway has also experienced periods of drought in the years 2018-2022. In the spring and summer of 2018 temperatures were up to 4.7 degrees above normal levels. Precipitation for the months between May and September 2018 was between 18 and 46 % of the average precipitation level for the years 1991-2020 (Norwegian Center for climate services, 2023). The summer of 2018 was the longest consecutive drought period in the past five years, but 2021 and 2022 were also dry with 83 and 84 % of average annual precipitation, the driest month for the country as a whole being August 2021 (Norwegian Center for climate services, 2023). This leads to a reduction in groundwater levels down to 75% of the average levels in most of southeastern Norway below the treeline in August 2018 and August 2022, causing problems for agriculture production in the region (NVE, 2023). As predicted by climate models, precipitation is becoming more concentrated, leading to periods of floods (early spring, certain days in summer) followed by periods of drought (late spring to summer) (Hanssen-Bauer et al., 2017).

In 2018, most parts of the **United Kingdom (UK)** suffered a combined heatwave and drought (Holman et al. 2021). In some parts of the UK protracted dry spell extended into late 2018 and 2019 (Turner et al. 2021). Nonetheless, humid weather conditions in the period from June 2019 to February 2020 led to strongly differing water resources conditions in the UK, causing substantial and even harmful flood events (Sefton et al. 2021). The year 2020 was also hot with a dry spring but a wet summer (Kendon et al. 2021) and the year 2021 continued this trend with temperature and rainfall reaching slightly below the long-term average (Metoffice 2021). The year 2022 was the first with an annual average temperature across the UK exceeding 10°C for the first time, while the UK's total rainfall accumulation has remained persistently below average (Metoffice 2022, Royal Meteorological Society 2023). At Coningsby, Lincolnshire, a temperature above 40°C was recorded for the first time in weather record history of the UK (Metoffice 2022).

2.2 Drought and heat in Central Europe 2018 - 2022

Due to its geographical location and the unfavourable hydrological conditions resulting from it, **Poland** has small water resources and occupies one of the last places in Europe in terms of water resources (Ministry of Climate and Environment, 2023, SUSZA 2023). The relative scarcity of water resources, in relation to Europe, is pronounced by almost 40% of arable and forestland in Poland is permanently threatened by drought (Polish Supreme Chamber of Control, 2021). Drought in Polish agriculture typically occurred every five years, whereas in the last years it has covered significant areas of the country almost every year - in 2015, 2016, 2018, 2019, and 2020. In 2018, the soil drought was severe with regions having more than 50 days of no plant-available water shortage (Wielkopolska and Kujawy Region; Wawrzoniak et al. 2019). In recent years, soil droughts have been observed also in large parts of forested areas (Lech et al. 2021).

The severe drought event of 2018 was centred over southwest **Germany**, Benelux and northeast **France**, the centre of the 2019 drought was further east, with eastern Germany and neighbouring countries most affected. The severity of the 2019 summer drought was not exceptional in itself, but the fact that it was a second consecutive drought year led to a worse water deficit than 2015 in many parts of Germany and France. Also, the spatial extent of the 2019 drought exceeded that of previous years. Using GRACE data, Boergens et al. (2020) found drought conditions were most severe in the western part of Germany in autumn 2018, while drought conditions were most severe in eastern Germany and Poland in summer 2019. Germany and France (with exception of southern Germany) experienced continued drought conditions till late summer 2020. Summer 2021 brought a relief in terms of precipitation, leading to severe flooding in central Europe (Mohr et al., 2023). The summer of 2022 saw a return to extreme drought conditions in Germany and France. These dry conditions were related to persistent lack of precipitation combined with early heatwaves in May and June. Overall, the spatial extent of drought affected area in Germany reached almost 40% in 2022, followed by 2019 (30%), 2018 (19%) and 2020 (16%).

2.3 Drought and heat in the Alpine regions of Europe 2018 - 2022

In **Switzerland**, 2018 included the fourth warmest spring (March, April, May) and the third warmest summer (June, July, August) since the start of the instrumental measurements in 1864 (Bader et al., 2019). While summer 2018 received only 70% of the long-term mean precipitation (1981–2010), winter rainfall (or snowfall for that matter) was above normal, which helped alleviate the worst impacts especially from a hydrological perspective. Between 2019 and 2021, frequent heat episodes occurred during summer, but mean precipitation during winter was about normal. This changed in winter 2021/2022, when

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anomalously warm and dry conditions persisted especially in Southern Switzerland and Northern **Italy**. Summer 2022 saw record-breaking temperatures. July 2022 was one of the hottest since measurements began in 1864, beating some of the records set only four years earlier. The heat was accompanied by low rainfall, which led to record low levels for many lakes in Eastern and Central Switzerland.

Austria with its alpine topography is generally considered as a water-rich country with freshwater resources that exceed the demand even in relatively dry years. However, Austria did experience exceptional heat and drought episodes in recent years, particularly in 2018 and 2022, raising concerns about water availability (Stelzl et al., 2021). One factor is a significant decline in observed snow depth in the wider Alpine region, which is required to balance the increased evaporative demand in summer (Matiu et al., 2021). While the summer of 2019 was less dry in Austria, it tied for warmest summer on record together with 2003 (since at least 250 years). Summer 2022 was the 4th warmest in recorded history right after a rather dry and mild winter, while several heavy rainfall events occurred, they barely alleviate drought conditions due to the high runoff.

2.4 Drought and heat in the Southern Europe region 2018 - 2022

Italy was affected by the 2018 drought to a lesser extent. For instance, there were no significant soil moisture anomalies and forest disturbance during 2018 in Italy (in Senf and Seidl, 2021a, see Fig. 1). Drought conditions persisted during the 2021 and 2022 summer (Toreti et al., 2022a). The rainfall deficit during winter 2021 to 2022 exacerbated drought conditions across the peninsula (Toreti et al., 2022b; Bonaldo et al., 2023). The winter 2022/2023 continued to be rather dry (Toreti et al., 2023).
In Spain, in the 2020/2021 water year precipitation was 5% below the normal value. Between the start of the next hydrological year on 1 October 2021 to the next reporting date on 8 March 2022, the national average value of accumulated rainfall has been 38.2% below the normal value (BOE, 2022). As of 8 March 2022, the peninsular water reserve stood at 40.5%, significantly lower than the average for the last 5 years (52.5%) and the average for the last 10 years (60.8%). The water reservoir network in Spain was conceived to sustain demand during dry years using the reserves from prior wet years. The succession of years with below average precipitation experienced in the region since the 2012/2013 water year, with the sole exception of 2017/2018, led to low to depleted water reserves compounding with the extremely persistent hydrological and meteorological drought conditions the years 2012-2022 (BOE, 2022). The hydrological year 2021/2022 ended as one of the three driest years on record, with 25% less precipitation than average and water reservoirs levels at around 35%, the lowest in 27 years (Greenpeace, 2022).
The last 20 years have been particularly dry in mainland **Portugal**, with 6 of the 10 driest years occurring after 2000, including 2017-2018, 2019 and 2021/2022. The average value of the amount of precipitation in the hydrological year 2021/2022 (488.3 mm), shows a precipitation deficit of -393.8 mm, compared to the normal accumulated precipitation 1971-2000. Compared to previous years of drought, 2021/2022 it is the 3rd driest hydrological year after 2004/05 and 1944/1945, always presenting a sharp deficit in relation to the average value throughout the year (APA, 2023).
Regarding the period 2018 to 2020, Portugal was affected by drought to a lesser extent, and mostly in the southern part of the country as depicted in Fig. 1. This reflects on water storage, with monthly storage deviations from the average in the last

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hydrological years showing that in 2019/2020 the hydrological drought was more severe with five of the eleven hydrographic basins in Portugal always maintaining negative deviations throughout the year. The 2020/21 hydrological year ended with only four watersheds with below-average storage levels (APA, 2023).

3. Damages to forests

3.1 Introduction

Drought and heat are significant environmental factors that can have harmful impacts on forest ecosystems. Drought events compounding with heat waves can fundamentally transform the composition, structure, and biogeography of forested ecosystems (Allen et al. 2010, 2015). Overall, its consequences on forests can be summarized in three major impacts (i) physiological stress, (ii) insect outbreaks, and (iii) forest fires (e.g. Brodribb et al. 2020, Seidl et al. 2020, Mezei et al. 2022, Salomon et al. 2022). From 1950 to 2019, observations of natural disturbances in European forests increased, with wind being the most important factor (46% of total damage), followed by fire (24%) and bark beetles (17%), although the latter's contribution to total damage has doubled in the last 20 years (Pattaca et al. 2022).

One of the primary impacts of heat and drought on forests is increased tree mortality (Allen et al. 2010, Anderegg et al. 2013, George et al. 2022). Trees are highly sensitive to water stress, and prolonged periods of high temperatures and low precipitation can cause trees to experience water deficits, leading to physiological stress and ultimately death. In general, trees under drought and heat stress experience carbon starvation and have risk for embolism, which causes a failure in water transport (Allen et al., 2015, Schuldt et al. 2016). Such physiological stress can lead to mortality but also to more milder consequences such as crown defoliation (Figure 2), early leaf shedding or death of branches that reduces the vitality and growth of the trees (Schuldt et al. 2016). The reduced water availability can also strongly affect the carbon cycle by limiting photosynthesis and nutrient uptake and lead to decreased growth rates and reduced carbon storage in forests. Heat and drought can also disrupt forest ecosystem dynamics and alter community composition (Hicks et al. 2018), as tree species differ in their vulnerability to drought stress, leading to shifts in species abundance and distribution (Morin et al. 2018). These changes can also have cascading effects on other organisms that depend on forest ecosystems, such as wildlife, insects, and microorganisms (Liebhold et al. 2017).

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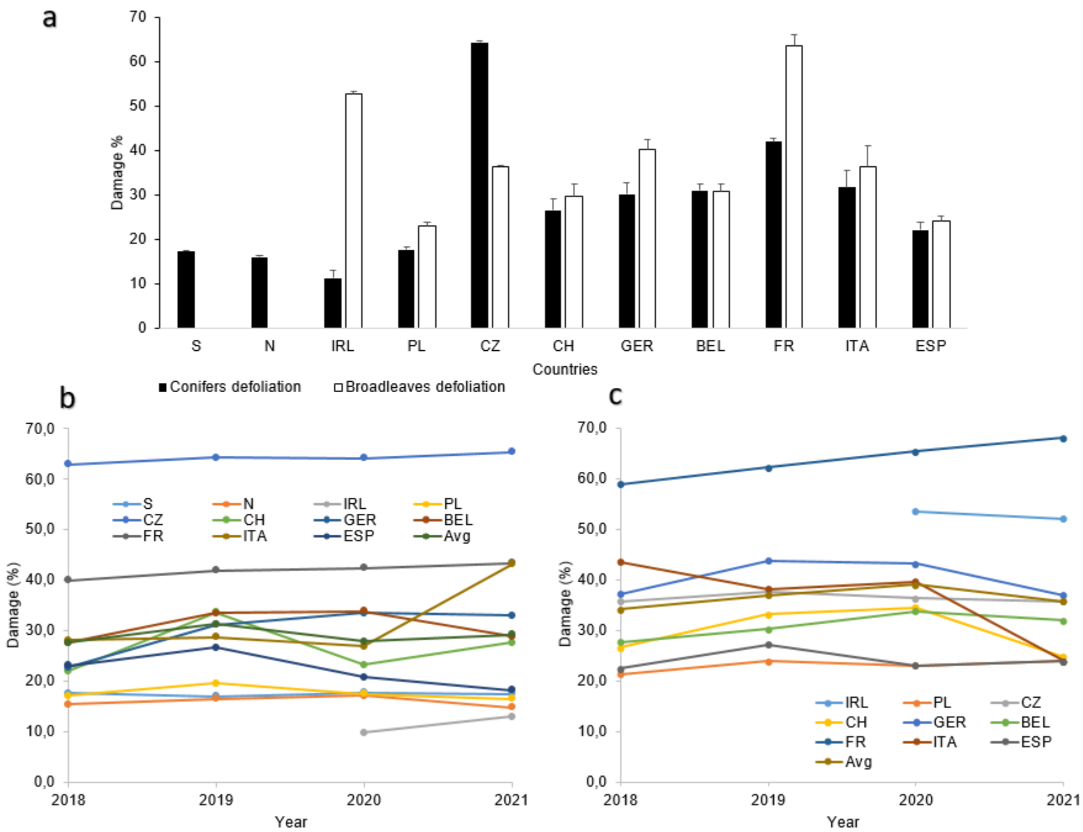

Figure 2: Crown defoliation in percent (moderate to severe defoliation); data from ICP-forests (2022). Mean rel. damage (2018-2022) of conifers and broadleaves (a), rel. damage during the period 2018-2022 of broadleaves (b), and conifers (c).

At the same time, other processes like outbreaks of forest pests can co-occur and follow to droughts. In the resistance of coniferous trees against bark beetles, the release of resin plays a pivotal role (Morcillo et al. 2019). Yet, resin is highly costly to produce and strongly linked to tree vigour as well as water availability (Zas et al. 2020). However, not only drought-induced host-weakening determines beetle outbreaks. Dry and warm conditions generally increase also the vitality and reproduction of poikilotherm insects with consequent shorter generation times, higher fecundity and survival rates (Jactel et al. 2019, Pettit et al. 2020). It should be noted that heatwaves also could negatively affect some insect pest species or pathogens by imposing heat stress (Sire et al. 2022).

Table 2: Damaged wood (m³) by insect pests in Europe. Roundwood production, mean of 2010 – 2014 (data from EUROSTAT 2016). Wood data derived from different sources (Wulff and Roberge 2020, Öhrn et al., 2021, ICP 2022, DESTATIS 2023, Waldschutz 2023, WSL 2023, BFW 2020, 2023, Czech Statistical Office). For the other countries data was not available.

Mean	2018	2019	2020	2021	2022

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S	70659800	3500000	7000000	8000000	8000000	
CZ	15597000	13059000	22780000	26243000	18289000	
CH	4710200	831108	1489151	1213866	607891	631778
A	17805400	5210000	4690000	2610000	1970000	3750000
GER	5409220	11300000	31700000	43300000	41100000	26600000
BEL	5539330	500000	100000	1000000	300000	
FR	5313720	1000000	4000000	5000000	9000000	

Forest fires can be facilitated by dry and hot conditions (e.g. Kirchmeier-Young et al. 2019). Heat and dry conditions can create favourable conditions for wildfires to spread, and drought-stressed trees are more susceptible to ignition and can burn more readily. Although wildfires have decreased on a global scale, and across Europe in recent decades (Grünig et al. 2023), during the last years, several regions (*inter alia* Central Europe) are likely to face larger and more frequent forest fires (Feurdean et al. 2020, Milanovic et al. 2020). A study investigating storm and fire disturbances in Europe from 1986 to 2016 identifies storms and fires as the most important abiotic disturbances in the recent past with wind (i.e. storms) mainly dominating in central and western Europe and fire in the southern part of the continent (Senf and Seidl 2021b). While in 2018 fire was likely only responsible for about 3 % of area disturbed in northern and central Europe in 2018 (Senf and Seidl, 2021a), there is strong evidence that wildfire will increase in a warmer and drier environment (Seidl et al. 2017). This increase can facilitate deforestation, loss of habitat, soil erosion, and long-term changes in forest structure and composition that can have severe environmental, economic and social consequences (Leverkus et al. 2019).

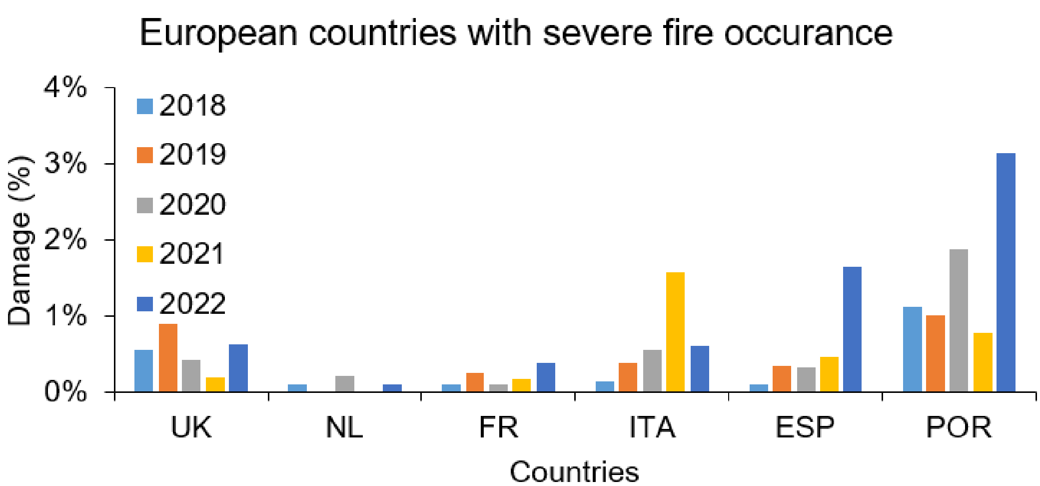

Figure 3: Burnt area in selected European countries. Italy and Portugal had large fires in 2017. All data from EFFIS (2023). The burnt areas in the other countries were less than 0.3% of the forest area.

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The forest damage caused by drought lead to significant socioeconomic consequences in European forest ecosystems (Lindner et al 2010) as forest owners, logging companies, and other stakeholders in the forestry sector experience significant losses due to a reduction in volume and quality of timber (e.g. Brecka et al. 2018, Davies et al. 2020, Knoke et al. 2021). Further impacts to local economies and communities can occur, since the forestry sector is an important employer in many rural areas of Europe, for about 3.6 million people (EU-27, Eurostat 2023). Furthermore, the value of forest areas is likely to decrease, if economically valuable tree species decline (Hanewinkel et al. 2012), and the cultural and recreational qualities of forests can suffer (Winkel et al. 2022). Finally, drought can have consequences particularly for biodiversity, since forests provide habitat for a wide range of plant and animal species, and drought can disrupt these ecosystems (Krumm et al. 2020, Vicente-Serrano et al. 2020).

The projected increase in frequency and intensity of heat and drought events (Spinoni et al. 2018) will likely increase forest damage. The drought of 2018 alone was likely the largest source of severe forest disturbances in Europe in over 170 years (Senf and Seidl, 2021a). Forest disturbances during 2018 have increased 5 fold in large parts of Europe as compared with the average levels of the past three decades, and disturbances remained above average also in 2019 and 2020 (Senf et al., 2021). However, there are opportunities to limit this damage, which are dependent on how well we understand the damage that has already occurred. Below we present the collection of damage to forest ecosystems for the years 2018-2022.

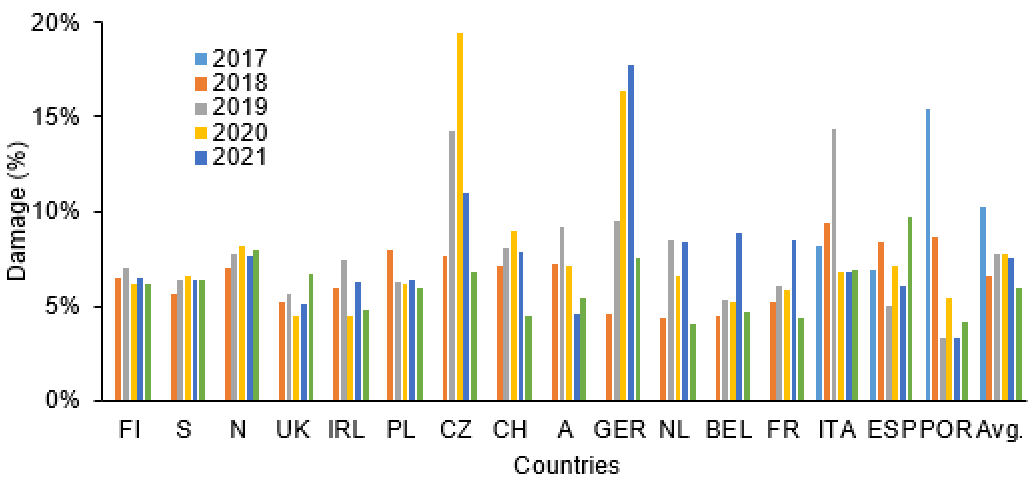

Figure 4: Relative tree cover loss; data from GlobalForestWatch. For Southern Europe (Ita, E, Por) also 2017 is included.

2.2 Damages to forests in Northern Europe and the British Isles

The total forested area of **Finland** is 26 million ha (EFFIS: 24.1 million ha), of which 20 million ha is suitable for forest production. Forest damage in Finland directly coming from the drought were highest in 2018 21,700 ha) and have been decreasing since then, with an increase in 2023; 2019: 15,800 Ha, 2020: 14,000 ha, 2021: 12,000 ha and 2022: 19,100 ha (Nuorteva, 2019; Nuorteva et al., 2022a, 2022b; Melin et al., 2022, Terhonen et al., 2023).

The areas influenced by drought and bark beetles were localized and, on annual scale, quite small when compared to, for example, snow and moose based damages (Nuorteva, 2019; Nuorteva et al., 2022a, 2022b; Melin et al., 2022, Terhohen et al., 2023). In Finland, the bark beetle population was slightly growing between 2018-2020 and the damages increased from 12,600 ha to 21,400 ha, but slightly declinedin 2021 to 20,800 ha and in 2022 to 18,000 ha. In 2021, the bark beetle damages were slightly lower than in 2020, but in 2022 the Finnish Forest Centre received reports of more damages than usual from more northern areas (South Karelia and North Savo). The reported salvage logging due to insect outbreaks was 3,400 ha by November 2022, which is three times more than in 2021 (Metsäkeskus, 2022). Overall, beetle damage in Finland has been increasing during the last decade, and in the future, the risk of more intense damages is rising (Neuvonen, 2020). It should be mentioned that the storm damages to forest in Finland have also increased from 2018 to 2020: from 249,000 ha to 307,100 ha (excluding year 2019 steadily increased). The efficiency of collecting the downed trees influences the bark beetle spread and outbreaks sincethey provide prime habitat for the beetle population to grow (Hroššo et al., 2020).

The number of forest fires in Finland in 2018 was the second highest recorded, but approximately only 1,200 ha of forest was damaged (Lehtonen and Venäläinen, 2020). In 2019 the area in Finland destroyed by forest fires was roughly 500 ha, in 2020/2021 slightly over 1,000 ha burned and in 2022 only a bit over 265 ha of forest was burned (Aalto and Venäläinen, 2021; Melin et al., 2022, Terhonen et al., 2023). Kosenius et al. (2014) estimated the economical losses of forest fires in Northern Karelia and the Republic of Karelia for the years 2009 to 2012. They took into account the direct and indirect costs when preparing estimates for the total costs. Venäläinen et al. (2016) used the estimates made by Kosenius et al. (2014) to derive a median estimate for forest fire costs in Finland: 6660 €/ha (estimate ranged from 5381 €/ha in 2009 to 8810 €/ha in 2012). Using the Swedish forest fire costs estimates of Venäläinen et al. (2016) for Finland, between 2018-2021 these caused roughly 25 million € of total damages.

In **Sweden**, about 90 million m^3 are felled every year (UNECE 2022) and the total forested area is 30 million ha (EFFIS 2023). Physiological damage expressed as crown defoliation was between 17.1 and 17.8% in conifers in the years 2018-2021 (data for the year 2022 and for broadleaved trees was not applicable; Michel et al. 2022). In Sweden during 2018, bark beetles damaged 3–4 million m^3 spruce, 7 million m^3 in 2019, and 8 million m^3 in 2020 and 2021, thus over than 20 folds more than in the average of the previous years (Wulff and Roberge 2020, Öhrn et al., 2021, UNECE, 2022). This increase in mortality and damage was initiated by the heat and drought of 2018, enabling a rapid beetle population growth (Öhrn et al., 2021). In Sweden, the dry and warm period of summer 2018 led to a severe outbreak of forest fires, with estimates reaching roughly 25,000 ha (the total forested area in Sweden is 28 million ha) and 3 million m^3 of wood destroyed (Forestry 2018). Using the estimate of Venäläinen et al. (2016) the costs for the year 2018 are over 166 million € in Sweden. This is a similar estimate as if the 2014 forest fires in Sweden (14,000 ha, costs 1 billion Swedish Krona) would be scaled to 2018: 160-200 million €.

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In **Norway**, the total forested area is over 12 million ha from which 8.6 million ha is suitable for forest production (SSB, 2022). On the national level, drought has not had severe consequences for Norwegian forestry. In 2017, there was a total of 965 million m³ of standing forest, and in 2020 this increased to 987 million m³ (SSB, 2022). Physiological damage expressed as moderate to severe crown defoliation was between 14.9 and 17.2% in conifers in the years 2018-2021 (data for the year 2022 and for broadleaved trees was not applicable; Michel et al. 2022).

Norway's annual roundwood production is about 11 million m³ (ICP 2022). Numbers from NIBIOs forest portal *Kilden* (NIBIO, 2023) show an increase in bark beetles in the region, from 8,540 per trap in 2017, to 20,600 in 2021. This is of some concern, but the number remains below outbreak levels.

The forest area influenced by fires in Norway was over 2,000 ha in 2018 and reduced to less than 1,000 ha in 2019 and 2020 (NIBIO, 2023). During 2018, between January and August there were a record 1906 forest fires. Wells and drinking water resources were almost emptied, low water levels in rivers led to fish dying and electricity production was down 20% compared to normal production levels (-23 TWh) at times, which led to higher electricity costs (MET Norway, 2019). Favorable wind conditions meant that the total affected area was relatively small (2000 ha destroyed by forest fires), so the consequences were more related to cost and social uncertainty. The Norwegian Directorate for Civil Protection - DSB (2019) estimates that about 8.4 billion € (100 million NOK) were spent on fighting the forest fires, while indirect costs are unknown, but expected to be high (loss of infrastructure, houses and cabins). Reports from the county governor of Vestfold and Telemark (Statsforvalteren, 2020; 2021) show some of the consequences for the forests in the region. Vestfold and Telemark county has 6.5 million ha of productive forest, and annual growth of 2.75 million m³ in timber volume. Damage from forest fires led to an increase in tree felling in both 2018, with felling of 1.1 million m^3, 2019, with 1.23 million m³ and 2020, with 1.1 million m³ despite low prices on timber especially in 2020. To mitigate the consequences of the 2018 fires, 296,599 plants were set in the ground in 2019 and a further 250,000 in 2020, compared to an average planting of 200,000 a year between 2006 and 2020.

In the **United Kingdom (UK),** the area of woodland is estimated to be 3.24 million ha, with 1.65 million ha (51%) conifers and 1.59 million ha (49%) broadleaves (Forest Research 2022a). In 2018, early leaf senescence due to drought was observed across much of the southern UK (Michel et al. 2019). In 2019, trees were not strongly affected by drought, since it was both warmer and wetter than average (Michel et al. 2020). Regarding pests and diseases, merely 3% of UK native woodlands are in an unfavorable condition, but problems with oak health have been identified in the South and West of the UK (Quine et al 2019, Michel et al. 2020). In 2020, a year of weather extremes (wet and hot), Ash dieback (*Hymenoscyphus fraxineus*) continues to spread across the UK, accordingly it is expected that the majority of ash trees will subsequently die from or be significantly affected by the disease in the coming years (Michel et al. 2021). The fungus-like pathogen *Phytophthora pluvialis* was discovered in climatically average year 2021, where it was found to be affecting mature western hemlock and Douglas-fir trees (Michel et al. 2022; forest research 2023c). In the very hot and dry year 2022, the trees lost their leaves in august over a large area due to the drought (e.g. Cheshire 2021). A comparison between 2015 and 2020 surveys reveal that 79% of woodland owners in UK observed an increase in pathogen in the last five years (Hemery et al. 2020). To counteract the damages associated with drought about 14,000 ha of new woodland were generated in the UK in 2020-2021, and there was a 4% increase in new planting and a 9% increase in restocking in the UK in 2021-2022 (Forest Research 2022b). In UK, there were harsh forest fires in the years 2018 (17,689 ha burned area), 2019 (28,754 ha), 2020 (13,793 ha) and 2022 (20,362 ha), while over 2021 there were only 6236 ha burnt (EFFIS Annual Statistics for UK, 2023).

The area of woodland in **England** is estimated to be 1,323 million ha, with 343,000 (26%) ha Conifers and 980,000 ha (74%) broadleaves (Forest Research 2022a). In England, just over 79,000 ha land burnt throughout the twelve-year period 2009-10 to 2020-21 (2017-18: 2,352ha, 2018-19: 26,047, and 2019-20: 3,686ha, 2020-21: 6,251, 2022 was not applicable, data from Forestry Commission 2023). In 2018, England witnessed the worst wildfires in recent history (Turner et al. 2021). In the two major fires in the Greater Manchester region, an area of 3,600 ha burned, which could only be extinguished after more than a month: In Saddleworth Moor, seven square miles (i.e. 1,800 ha) of moorland burned (telegraph 2018), in Winter Hill also 1,800 ha (BBC 2018). Surprisingly, the overwhelming majority of wildfires have been in broadleaved woodland (10.4%) and not conifer woodland (1.8%). According to the BBC (2022), fire services in England dealt with almost 25,000 wildfires during the summer 2022, with more than 800 recorded wildfires on one single day (19.7.2022).

The area of woodland in **Wales** is estimated to be 310,000 ha, with 152,000 ha (49%) Conifers and 152,000 ha (51%) broadleaves (Forest Research 2022a). South Wales suffers about 3,000 blazes a year and there is a strong possibility that this will continue to increase (e.g. BBC 2021a, BBC 2021b). Fires in spring 2020 in the sections of the Afan Valley and Seven Sisters forests have caused damage of more than €115,000 (£100,000), destroyed almost 140 ha of Natural Resources Wales (NRW) managed forestry including 80,000 newly planted trees (NRW 2020).

In **Scotland**, Forests and woodlands cover about 1,486 million ha, with 1,092 million ha (74%) Conifers and 395,000 ha (26%) broadleaves (Scottish Government 2019, Forest Research 2022a). Sitka spruce (*Picea sitchensis*) dominated major plantations along the east coast as well as Scottish rainforests along the west coast are particularly at risk, since both are vulnerable to aridity (Kirkpatrick et al. 2021). At a clear-cut area in Harwood Forest, Northumberland, the 2018 drought prevented the development of a Sitka spruce orchard that would have formed from a clear-cut area in the second year after replanting (Xenakis et al. 2020). In Scotland, wildfires are generally more likely to spread through grassland or peatland, however Scotland's forests -which are among the most productive in Europe- provide an abundance of flammable biomass (Forestry and Land Scotland 2023). Several wildfires were reported in April 2018 in the north of Scotland (Copernicus 2023). Wildfire severely affected 11,700 ha by in 2019 (The Herald 2021). Statistics from the Scottish Fire and Rescue Service (SFRS) show that during March and April 2022, 95 incidents of wildfire (involves an area of more than 1,000 m²) were recorded across Scotland (Highland Council 2023). Several Scottish key industries are dependent on water supplies, which can be disrupted by droughts: e.g. whisky production (valued with £5.5 billion) and forestry (valued with £1 billion) GVA per year respectively (Kirkpatrick et al. 2021).

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In **Northern Ireland**, the area of woodland is estimated to be 118,000 ha, with 64,000 ha (54%) Conifers and 54,000 ha (46%) broadleaves (Forest Research 2022a). In spring 2022, wildfires caused damage to an estimated 720ha of land (DAERA, 2022).

Ireland has a forest area of 551,110 (EFFIS 2023) or 770,020 ha (Forest Statistics Ireland 2020) with three quarters conifers (51% Sitka spruce alone) and one quarter broadleaves. Physiological damage expressed as moderate to severe crown defoliation was only applicable for 2020 and 2021, where it was very low for conifers (9.8 and 13.0%), but surprisingly high for broadleves (53.4 and 52.0%; Michel et al. 2022). Furthermore, the national reports about forest conditions states for Ireland that forest health remains good in 2019 and 2020 (Michel et al. 2020, 2021). Regarding tree pests, Ireland is generally known to have a good plant health status due to its island status and high plant protection regulations (O'Hanlon et al. 2021). The eight-toothed spruce bark beetle (*Ips typographus*) for example is absent from Ireland (Forest Health 2021). Around 3,000 ha of forest burned in each of the years 2018-2022 (see Table Fire). Compared to the record years 2011 (16724 ha) or 2017 (7219 ha), this is a moderate level of damage (EFFIS Annual Statistics for Ireland, 2023).

2.3 Damages to forests in Central Europe

Poland has a forest area of 9,242,000 ha (Central Statistical Office, 2017). In 2018, the drought has significantly weakened the condition of the forests in an area of 43.500 ha. The same year forest damage was observed in 29,400 ha (Jabłoński et al., 2019a; Jabłoński et al., 2019b). In 2019, the order of species from healthiest to most damaged was determined based on an analysis of three parameters: average defoliation, the proportion of healthy trees (up to 10% defoliation), and the proportion of damaged trees (above 25% defoliation), is as follows: *Fagus sylvatica*, *Alnus* spec. < *Abies* < other deciduous, other coniferous < *Pinus sylvestris* < *Betula spec.* < *Picea abies* < *Quercus spec.* (Wawrzoniak, 2019). In 2020, symptoms of weakened or damaged forest stands caused by disruption of water relations, mainly by drought, were reported in 253 of 430 (i.e. 59%) of all forest districts (Lech, 2021).

Pests, which until a few years ago were considered of little concern in Polish forests, today cause the death of entire hectares (Perlińska, 2019). As a result of the drought in the years 2015-2019, secondary factors leading to the death of pine stands (which represent 58,2 % of the Polish forests), have become active (Perlińska, 2019). The key role played the following pests: The bark beetle (*Ips acuminatus*), mistletoe (*Viscum spec.*), Sphaeropsis blight (*Sphaeropsis sapinea*), *Phaenops cyanea*, Heterobasidion root disease, and *Armillaria spec.* (Sierota & Grodzki, 2020). Observations in Poland indicate a significant correlation between drought and engraver beetle (*Ips acumintus*) outbreaks (Jabłoński et al., 2019a; Jabłoński et al., 2019b; Plewa & Mokrzycki, 2022), a species that until not long ago was not considered a significant forest pest (Głowacka, 2013). Underestimated was also the occurrence of mistletoe (*Viscum spec.*). After prolonged drought periods, the area of the coniferous (mostly pine) forests heavily infested by mistletoe has drastically increased from 1,400 ha in 2017 to almost 23,000 ha in 2018 (Jabłoński et al., 2019a). The mistletoe was found on 14 species of forest trees: most severely infested by mistletoe were fir and pine trees and to a lesser extent birch, and a mixture of deciduous species and spruce (Lech et al., 2019). Also,

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well-known forest pests such as European spruce bark beetle (*Ips typographus*) continue to pose a huge threat to the Polish Forests. The dieback of Norway spruce stands increased already through the 1970s and 1980s in Central and Eastern Europe (Sierota et al., 2019). After the drought of 2015 the Norway spruce decline continues with new bark beetle outbreaks, affecting stands in the western Carpathian and Sudetes mountains. The ongoing climatic conditions, combined with high bark beetle populations, make the risk of a further outbreak extremely high (Grodzki, 2010). Surface losses occurred in recent years on State Forest land in Poland (source: DGLP, Dyrekcja Generalna Lasów Państwowych) in terms of drought (2018: 40,852 ha, 2019: 60,356 ha, 2020: 58,056ha, 2021: 34,673 ha, and 2022: 20,258 ha) and in terms of high temperatures (burns, wilt and dieback) it was (2018: 80ha, 2019: 340 ha, 2020: 2574 ha, 2021: 197 ha, and 2022: 244 ha). Long-lasting drought in Poland has also led to a lowering of the surface and groundwater table, a decrease in the growth of trees, the vitality of stands, and their resistance to pathogens and pests (Kwiatkowski et al., 2020). Affected by this process are, among others, oak trees, where the impact of declining groundwater has been observed since the late 1980s (Przybył, 1989). Current groundwater fluctuations are further weakening the oak trees and accelerating their decline (Jakoniuk, 2022), e.g. on the Krotoszyn Plateau.

Furthermore, the prolonged drought increases dramatically the risk of forest fires. The number of fires is increasing, but contrary to other countries in this geographical zone, the situation in Poland is relatively good. According to official statistics, almost 25,000 fires with a total area of 6,049 hectares occurred in areas managed by the State Forests between 2011 and 2020, causing a loss of approximately PLN 39 million. Since, the average forest fire in the state forests has an area of 0.25 hectares, it indicates that a high effectivity of the fire protection system. However, the year 2020 was marked by an extreme large fire (6,000 hectares) of Biebrza National Park in northeastern Poland. (see Figure 3).

In **Czech Republic** spruce accounted for 50.5% of stands, and pine for 16.4% respectively at the beginning of the massive bark beetle attacks (Zahradník & Zahradníková 2019). This abundance of trees sensitive for the bark beetle lead to the suggestion that the Czechia may have been the epicenter of bark beetle outbreaks in Europe (Hlásny et al. 2021), since more than 50% of Czech forests were seriously threatened by this pest, leading to high ecological and economic losses (Fernandez-Carrillo et al. 2020). Common harvested volume per year is about 15 million m³ and around 1 million m³ of wood infected by insects (WII). In 2018, 25.6 million m³ were harvested, 13 million m³ were infected by insects (WII); in 2019—32.5 million m³ were harvested with 22.8 million m³ of WII, and 2020, the estimate is ranking between 40 and 60 million m³ of WII (Fernandez-Carrillo et al. 2020). Damaged wood is practically exclusively infested with European spruce bark beetle (*Ips typographus* L.). The largest fire in Czech history broke out in the Bohemian Switzerland in northern Czech Republic and spilled over into Germany, it burned for 20 days, and affected an area of about 1,060 ha (al-Arabiya 2022). On the German side of the border, an area of about 150 ha in the Saxon Switzerland National Park was affected (DAV 2022). During the decade 2010 - 2020, in Czech Republic almost 100 mio. m³ of solid timber has been harvested linked to bark beetle attacks, which leads to financial losses in the Czech forestry sector of ca. 1.12 billion Euro (Toth et al. 2020). More than half of this volume has been mined since 2017. In the Czech Republic this amount of unplanned salvage logging represent an increase of about 3-folds from 2017 to 2018 (Moravec et al., 2021).

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In the **German** forest sector, the years 2018-2020 are considered dry years (e.g. DFWR, 2021). In 2021 there was more precipitation and largely did not set new heat records, while 2022 was a dry year (Toreti et al. 2022). Monthly data from the Earth observation satellites Sentinel-2 and Landsat-8 shows dramatic canopy losses in Germany, in which coniferous forests in the middle of the country were particularly affected: from Saxon-Switzerland in the east, through Thuringia to the Harz Mountains, to the Sauerland region and finally to the Eifel in the west (Thonfeld et al. 2022). From January 2018 up to and including April 2021, tree losses were recorded on around 501,000 ha in Germany, which corresponds to 5% of its total forest area. The results of the German Forest Condition Survey show that in 2018 29% of the investigated trees showed moderate to severe crown defoliation(≥25%), which is the highest value since records began in 1984, when it was 23% (BMEL 2023). In the years that followed, this value increased to about 26-37% during the years 2019-2022. Also on a regional scale, results show the same, e.g. the forest condition survey in the German federal state Lower Saxony shows that the defoliation values are at the highest level in the time series since 1984 (NWFVA 2022). High water availability enabled trees to maintain growth in a floodplain forest in Germany during summer 2018, but the consecutive drought in 2019 caused strong reductions to tree growth, even in a forest ecosystem with comparably high levels of water supply demonstrating the accumulating effect of consecutive drought years (Schnabel et al., 2021). Even if deciduous forests in Germany are not dying off to the same extent as coniferous stands, they are also strongly affected by climate change. In the forest condition survey (BMEL 2020), more dead trees were recorded than ever before, across all tree species examined. Only about 20% of the trees do not show any crown thinning, for European beech it is only 11%, older beeches (>60 years) and trees at drier sites show especially a reduced growth and increased mortality (BMEL 2020, Leuschner 2020). Even tree species that are considered to be relatively drought-resistant, such as Scots pine (*Pinus sylvestris*) experienced massive mortality since 2018 in Germany (e.g. Kunert 2019). In this case in addition to the hot and dry summers, the fungus *Spaeropsis sapinea* (or *Diplodia pinea*) causes pine dieback (Mette and Kölling 2020).

In Germany, the European spruce bark beetle (*Ips typographus*) caused in the periods of heat and drought large-scale forest damage. In many cases, harvest was lost and there was a need for emergency fellings and even deforestation to prevent the pest from spreading (e.g. HessenForst 2022; Thonfeld et al. 2022). In the German federal state Thuringia almost 21 million m³ in the period 2018 until 30.9.2022 deciduous (mainly beech) and coniferous (mainly spruce) dead wood incurred, of which around 65% due to insect infestation fall and 35% due to drought and storms (TMIL 2022). In 2022 around 344,000 m³ of damaged wood (202,000 m³ of hardwood and 142,000 m³ of coniferous) registered by drought alone, without that primary pests were involved. In the period 2018-2022 4.9 million m³ of damaged wood resulted from heat and drought (TMIL 2022). The estimates are that about 500,000 ha (4.4% of the German forest area) forest damaged by drought and bark beetles and need to be afforested in order to offset the damages from the drought years 2018-2022 (BMEL 2023c). For the approx. 13.3 million m³ of damaged wood by bark beetles, 95.6% goes back to activities of the European spruce bark beetle and 2.76% to the Spruce wood engraver (*Pityogenes chalcographus*). Although the latter still plays a subordinate role, this could gain increasing importance since the engraver specialized on weaker dimensions, which is a large-scale threat in the future regarding

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reforestation means or rejuvenation with conifers (TMIL 2022). 2018, 2019, and 2022 were extreme years for forest fires in Germany.

The burnt area of 2022 is more than five times the annual average (since 1991) of almost 776 ha, the pure wood damage and was estimated at 30 to 40 million € (Feuerwehrverband 2022). In Germany, during 2018 – 2019 damages due to natural disturbances were estimated at 2.5 billion EUR (DW 2020). How to disentangle the exact costs of a big disturbance in a field like the German forestry sector, which generates about €170 billion annually and employees directly and indirectly more than 1.1 million people (Popkin 2021). Möhring et al. (2021) estimated the economic damage caused by the extreme weather events of 2018 to 2020 in forestry with an amount of more than 12.7 billion Euro – this corresponds to ten times the annual net profit of the entire forest economy in Germany.

Please note: **Austria** and **Switzerland** are assigned to the Alpine zone.

In the **Netherlands**, there are clear signs trees suffered from the drought and heat in 2018, where especially deciduous tree species had stunted or no growth (measurements by dendrometers, see Lerink et al. 2019). On a national level, the average volume of living and dead wood continued to increase for the period 2017-2021 although at a slower rate due to the dry summers in 2018-2020 (the seventh systematic national forest inventory; NBI-7, 2022). There are several indications for tree mortality: the volume of standing dead wood compared to the NBI-6 (2012-2013) shows an increase from 6.1 to 10.0 m^3 ha^{-1} from 2012-2013 (NBI-6) to 2017-2021 (NBI-7), respectively, and lying dead wood increased from 6.6 to 9.2 m^3 ha^{-1} for the same periods. However, there is no information for the crown defoliation. The next systematic monitoring of forests in the Netherlands started in 2022, but the publication of those results is expected within the next few years.

In the northern part of **Belgium**, in Flanders, new forest plantations have suffered from the droughts, especially on sandy soils, of which several have died in 2018, without further quantification available (CIW, 2019). In 2019, besides young trees, widespread dying of mature deciduous trees was also observed, including Norway spruce and larch trees. Also, oak and beech trees exhibited dead tops or crowns, and dying juvenile trees of chestnut, sycamore, and silver birch were observed (CIW, 2020). Also, in 2020 it is reported that several trees exhibited needle and leaf loss, and especially Norway spruce trees had died (CIW, 2021). The annual forest vitality inventory for Flanders (Sioen et al., 2022) provides information on the state of the forests for each year by monitoring trees in about 70 locations with a radius of about 18 metres. The loss of leaves and needles, and other indicators define vitality. The annual inventories (Sioen et al., 2019; 2020; 2021; 2022) provide an indication of trends in vitality, but do not provide an overall estimate of the total damage to the complete stock of forests and wood in Flanders. Despite the effects of drought in the years 2019-2020, the year 2021 demonstrated some recovery, with a significant reduction in the loss of leaves and needles. Information for 2022 is not yet published. The inventories also show that the number of damaged trees in the samples increased since 2008 (Figure 16 in Sioen et al., 2022), with a recent peak in 2020 (30% damaged broad-leaved trees; 20% damage deciduous trees), and a decline in 2021.

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In Wallonia, the southern part of Belgium, nearly one third of the 550,000 ha forest is covered with spruce. Accordingly, mortality has been high throughout Wallonia since the beginning of the drought years in 2018. In 2018, 500,000 m³ of spruce were infested by bark beetles, compared to 5-10,000 m³ in normal years. This number increased to approximately 1 million m³ in the years 2019 and 2020 (OEWB 2019, Saintonge et al. 2021). In the course of the colder and wetter year 2021, the newly infested timber volume has dropped again to about 500,000 m³ (Saintonge et al. 2021). Wildfires occur in Belgium, but not excessively and were highest in 2021 with 659 ha (EFFIS 2023).

In **France**, from 2018 to 2020 300,000 ha were affected by forest dieback in public forests alone (ONF 2020). The northeast is particularly affected by bark beetles. In the two most affected regions, Grand Est and Bourgogne-Franche-Comté, 170 000 ha of forest, equivalent to 58 million m³ of wood, are covered with spruce at altitudes below 800 m before the 2018-2022 drought event (Saintonge et al. 2021). The 2018-2019 drought and associated bark beetle damage was the main reason for the dieback (ONF 2020). Salvage logging of the damaged public forests led to the harvest of 6.5 million m³ of low value wood in the period 2019-2020 compared to less than 1 million on average in a normal year, which represents 26% of the total harvest in public forest (ONF 2021). If the share of affected spruce stands is extrapolated to private forests, 19 million m³ of spruce can be considered as killed by bark beetles in the two most affected regions in the period 2018-2021 (Saintonge et al. 2021). Interestingly, the damage increases from year to year, reaching a temporary peak of 9 million m³ in 2021 (Saintonge et al. 2021), although this year was the only one in the period 2018-2022 that was not particularly hot and dry. The French government has allocated 150 million for the period 2021-2022 to regenerate and adapt the impacted surfaces (Gouvernement Français 2020).

Another indicator to measure the impact of drought is the share of wood declared as accidental or sanitary products. This indicator only refers to commercially used timber, which could explain the lower numbers compared to the numbers on killed forest areas, which are often based on remote sensing data. The accidental products are often related to storm damage, while the sanitary products, which are responsible for the bulk of the total damage, relate to drought damage or to pest infestation and thus indirectly mostly to drought as well (MAA 2021a). The share of harvested wood of all tree species declared as accidental and sanitary products in metropolitan France evolved from 0.8% in 2017 to 1,5% in 2018 (MAA 2019a) to 5.5% in 2019 (Beaufils 2022, MAA 2021a), to 10.6% or 3.8 million m³ in 2020 (MAA 2022a) and 4.1 million in 2021 (MAA 2023). Spruce is particularly impacted with more than 2 million m³ in 2020 (MAA 2022a).

In addition, an increased defoliation has been observed since 2015, which is probably largely due to the droughts and heat waves and a resulting increase of pests. While in 1997 only 2.2% of the deciduous trees and 1.8% of the conifers were affected, in 2019 it is already 9.6% and 4.3%. In addition to Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*) is particularly affected (Piton et al. 2020).

In terms of forest fires, the situation in France in the period 2018-2022 is also exceptional. With the years 2019, 2021 and 2022, the 3 years with the largest cumulative forest fire area since the beginning of the systematic Copernicus observations in

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2006 fall in the period 2018-2022. In 2022, the largest cumulative burnt forest area so far was measured, with 66,393 ha, it was more than 13 times higher than the 2006-2017 average (EFFIS 2023).

2.4 Damages to forests in the Alpine zone

In **Austria**, the centres of drought and heat are in the lowlands, especially in the east (Vienna, Lower Austria, Burgenland), but also in the southeast (Styria) and in the northern foothills of the Alps (Upper Austria, Flachgau, Salzburg). Austria was hit hard by bark beetle attacks between 2018 and 2022. In particular, in 2018 (5,210,000m³), 2019 (4,690,000m³), and 2022 (3,750,000m³, see Table pest) the wood losses were large. Overall, the forest damage balance in Austria 2022 - primarily caused by climate change - is around 28 million euros (Bundesforste 2023). Around 940,000 m³ wood were damaged wood in 2022, which corresponds to around 50% of the total amount of wood harvested (2021: 59%). The main reason for this is an increase in bark beetle wood. Due to climate change, Austria's largest forest pest has already spread to the tree line at around 2,000 meters above sea level (Bundesforste 2023). In October 2021, a huge forest fire raged in Reichenau an der Rax in Lower Austria, with an area of 115 ha it was one of the largest forest fires that have ever occurred in Austria (Standard 2021).
In the Alps, due to rainfall in the summer months, it is usually less hot and dry than in lower areas (climate monitoring of GeoSphere Austria). A study based on NDVI data confirms that drought impacts decrease with elevation: especially at above 1,500m (Rita et al. 2019). Damage caused by forest insects could only be detected sporadically, as 2022 in East Tyrol (cipra 2022). In Tyrol, there was a major fire in the Alps in March 2022, directly across the border to Germany around 35 ha of mountain forest burned down in Pinswang in Tyrol (SZ 2022, Merkur 2022). In Austria, the total direct costs for firefighting and for necessary measures on burned areas (without preventive measures) in connection with forest fires are currently estimated at around 75 million € per year in the Alpine region. (BFW 2021).

In **Switzerland,** 2018 and 2022, the canopies of many beech trees had already changed colour by the end of July, and in the Mendrisiotto large areas of the forest were brown in August (WSL 2022a). The volume of spruce wood damaged by bark beetle calamities amounts to approximately 800,000 m³ in 2018, twice as high as in 2017. In 2019 the volume increases further to 1.5 million m³ before decreasing in 2020 (Dubach et al. 2021) and 2021 to 1.2 million and 600,000 m³ respectively because of colder and wetter spring and summer (Saintonge et al 2021). A Study based on Swiss NFI data (5092 NFI plots) until 2017 showed, that only 14% were classified as 'naturally disturbed', most of them (59%) by wind, but only 16% by insects (predominantly bark beetle), 1,2% by fire and 1.6% by drought (Scherrer et al. 2022). The interim results of the fifth state forest inventory (NFI5) over the survey years 2018 to 2022 clearly show that there are more dead and damaged trees (WSL 2023b): Spruce has declined in the Jura, the Mittelland and the foothills of the Alps, and the sweet chestnut on the southern side of the Alps. The ash is declining everywhere due to a fungal disease. The annually growing amount of wood is lower than five years ago. In addition, fewer young trees are growing in a quarter of all forests throughout Switzerland. The Alps and especially the southern side of the Alps are particularly affected. Besides the interim results of NFI5, only a few reports could

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be found at high altitudes in Switzerland, for example about a regional increase in bark beetles in the Alps in 2020 (e.g. Schreiner Zeitung, 2020).

In **Italy**, after the Vaia windstorm in 2018, the number of pests was rather moderate, but at the beginning of June 2021, there was a pronounced heat wave, which triggered a massive swarming of the spruce bark beetle (Agrar-&Forstbericht Südtirol, 2021). In 2022, around 5,000 ha of the 350,000 ha of forest in South Tyrol were infested with the bark beetle (Tagessschau 2022). From mid-May 2022, the bark beetle then spread rapidly in Tyrol (cipra 2022). In 2021 around 105,000 m³ of wood were affected, 2022 it is around one million m³. The amount of damaged wood in the years 2018-2022 corresponds to around 15 times the amount of normal use in a year (Dolomitenstadt 2023). In 2017, a long-term drought during growing season led to the largest fire outbreak regarding simultaneous fires of the last 30 years in the Alpine region: in autumn 2017, there were 11 simultaneous large fires in the Piemonte Region, Italy, burned almost 10,000 ha in a week of mainly broadleaved forests (BMRLT 2020). In October 2018, one of the largest forest fires ever with 632 ha occurred in Monte San Lucano, in the Veneto region in Italy (BMRLT 2020).

Table 3: Fire situation in the Alpine countries (without Slovenia). All data in bold derives from BMLRT (2020). Data of forest fires in Austria (2003-2022) derives from Waldbrand-Datenbank Österreich Institut für Waldbau, BOKU Wien. Data from France derives from the Prométhée database (http://www.promethee.com) of the Departments Hautes-Alpes, Alpes-de-Haute-Provence, Alpes-Maritimes, and Drôme; the departments of Haute-Savoie, Savoie and Isère, which also belong to the Alps were not available. Data from Germany derives from the Bayerische Landesanstalt für Wald und Forstwirtschaft (LWF), collected by the AELFS (Ämter für Ernährung, Landwirtschaft und Forsten); Bavarian Alps including the foothills of the Alps; fires at military training facilities (Bundesforste) are excluded, since they can't be assigned to climatic conditions. Italian data is extracted from EFFIS annual fire reports for the Italian Alpine regions (Valle d'Aosta, Piemonte, Lombardia, Trentino Alto Adige, Veneto, Friuli Venezia Giulia and Liguria). Data for the Swiss Alps (without the Swiss Mittelland and Jura). Data input for 2022 is not completed.

Country	Alpine	Mean annual		2018		2019		2020		2021		2022	
	Forest area (ha)	Area (ha)	Nr.	Area (ha)	Nr.	Area (ha)	Nr.	Area (ha)	Nr.	Area (ha)	Nr.	Area (ha)	Nr.
AU	**2,892,100**	**64** 2003-2017: 55.3	**122** 2003-2017: 188.1	15	174	19	244	51	234	116	164	551	217
GER	**403,600**	n.a.	n.a.	3,007	3	1,405	3	0,08	2	0	0	0,05	2
ITA	**2,262,300**	**9,984**	**1043**	1,209.5	323	2,894.7	629	1,802.4	549	1,712.9	593	n.a.	n.a.
CH	**992,900**	**515** 2000-2017: 118.82	**105** 2000-2017:8 0,83	44.59	93	13.87	63	9.15	49	24.21	46	262.17	98
FRA	**1,409,900**	**818**	**213**	95		973		653		141		2,078	

2.5 Forest damages in Southern Europe 2018 – 2022

Italy was not under extreme drought conditions in spring and summer 2018 (Senf and Seidl, 2021; Rousi et al., 2023), but it suffered from extended forest damages caused by the extra-tropical windstorm Vaia over northeastern Italy in autumn 2018 (Motta et al., 2018). Vaia damages accounted for more than 70% of the total roundwood removed in Italy in the year 2018 (Pilli et al., 2021). Although there was no extreme drought in northern Italy in 2018, the precipitation was below normal for the months April, June, and September (Desiato et al., 2018), which might have contributed to the forests being drier than normal and thus more vulnerable to the strong winds of Vaia in October 2018. Italy did suffer from an extreme heatwave and drought in 2017, which contributed to significant wildfire activity and subsequent burned forest of a total of 161,987 ha, the highest annual total since 2007 (European Commission, 2018; RAF Italia 2017-2018, 2019).
More generally, for the period 1998-2021 there was an increase in defoliation in Italian forests and especially in montane conifer forests, with the maximum level in 2021 (Bussotti et al. 2022). Moreover, also increasing and peaking in 2021, were forest mortality and the number of trees suffering from leaf discoloration, the latter mainly in deciduous and evergreen oak forests. These high damage levels in 2021 are a result of a combination of increased summer drought and the lagged effect of the storm Vaia of 2018 that compromised the stability of the trees and increased the probability of insect attacks due to the large accumulation of dead wood in the forests (Bussotti et al., 2022).
The summer of 2022 Italy was affected by severe-to-extreme meteorological drought (Toreti et al. 2022a). Northern Italy has been heavily affected, facing the warmest and driest winter in record of the last 30 years (Toreti et al. 2022b), resulting in strong hydrological drought and unusually low streamflow in the Po river, which is also related to the snow drought in the Italian Alps that winter (Koehler et al., 2022). A study looking at the impacts of the 2017-2022 drought and heatwaves in forest areas of Tuscany found that the most severe impacts were observed on the evergreen Mediterranean tall woodlands and the aged coppices (on holm oak trees), including defoliation and mortality (Bussotti et al., 2023). The study suggests that the impact of the 2022 prolonged drought on forests could have been larger, but it seems that the trees might be responding to current climate change via rapid acclimation based on epigenetic modifications (Rico et al. 2014).
Please also see **Italy** in the Alpine zone.

In **Spain**, in the period 2018-2019, there was some recovery or stabilisation in terms of forest defoliation and discoloration with respect to the 2017 due to an increase in precipitation (AIEF 2019). However, more recent reports over parcels in Northern East Spain reveal a deterioration in defoliation in the period of 2019-2021 due to more severe heat and drought conditions and, in particular, due to extreme events occurring during critical vegetation growth periods (GAN-NIK 2019). In the period of 2018-2020, physical damages such as drought and wind are the main drivers of forest defoliation, followed by insects. Both drivers exhibit forest damages 3 to 5 times larger than every other driver (e.g., fungi, fires, etc.), and their impacts have increased drastically since 2014 (AIEF 2020). In this period, physical damages and insects together with forest fires are the three main drivers of tree mortality in Spain (AIEF 2020). In 2022, Spain has experienced almost 300.000 ha of burned area, a drastic increase from previous years amounting up to 3 to 6 times larger surface compared to 2018-2021. In the 2018-2021 period, around 300 fires per year were recorded versus 400 fires in 2022, indicating not only more fires and larger burned area, but also larger burned area per fire on average (see Figure 3).

Although **Portugal** (Western Iberia) has recently shown increasing frequency of drought conditions coupled with heatwave events (Bezak and Mikoš, 2020; Vogel et al., 2021; Ribeiro et al., 2020), leading to exacerbated limiting climatic conditions for plant growth, the situation of Maritime pine (*Pinus pinaster*, one of the most frequent species) is according to Kurz-Besson et al. (2016), not completely discouraging. Detailed information regarding defoliation in Portugal is unavailable since 2006 (ICP Forests 2007). Also data of damaged wood by insects was not available.

Since 1980, the mean annual burnt area has been around 115.000 ha with a large interannual variability, and including particularly severe years, such as 2003 (~425 000 ha), 2005 (~350 000 ha), or the all-time record value of 2017 (~540 000 ha, EFFIS 2023). The inter-annual variability of burned areas in Portugal is attributable to high temperatures and drought as a result from the amount of precipitation during and prior the fire season (from May to September). In addition, the occurrence of atmospheric circulation patterns in the summer induces extremely hot and dry spells over western Iberia (Pereira et al., 2005; Russo et al., 2017). Dry conditions contributed extensively to the massive wildfires that took place in Portugal during 2017 (Turco et al., 2019; San-Miguel-Ayanz et al., 2020). The total burned area in Portugal in 2017, corresponds to nearly 60% of the total burned area in Europe in 2017. The economic losses due to the 2017 wildfires in Portugal totaled almost 1.2 billion USD, and the local insurance sector declared it as the costliest natural disaster in the country's history with payouts exceeding USD 295 million (AON, 2018).

Following the information from the Global Forest Watch (GFW, 2023, Figure 4), from 2000 to 2020, Portugal experienced a reduction of 104,000 ha (-3.4%) in tree cover. From 2001 to 2021, Portugal lost 1.13Mha of tree cover, equivalent to a 49% decrease in tree cover since 2000, with 10% of the loss occurring between 2018 and 2021. For the same period, 0.57% of tree cover loss occurred in areas where the dominant drivers of loss resulted in deforestation, which in case of permanent deforestation was dominated by urbanization and shifting agriculture.

4. Drought legacy effects

4.1 Introduction

Beyond the immediate damage caused by drought and heat to vegetation, there can be long-term effects that can persist for many years. Therefore, the short-term assessment of damage can strongly underrepresent the overall damage caused by an event in forest ecosystems. The duration of a legacy damage can vary between different aspects of the observed ecosystem. For example, the carbon cycle recovery and compositional change can take several years (Mueller & Bahn 2022). More specifically, long recovery periods were found in a temperate forest, in which severe droughts caused growth reduction lasting

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up to 6 years, depending on tree species (Orwig & Abrams 1997). Further complicating the damage assessment is that over long periods the target vegetation adapts to the persistent conditions. For example, structural changes related to hydraulic traits in trees before an extreme climate event can mitigate or enhance the damage caused during an extreme event, depending on the direction of the shift in plasticity (López et al. 2016), and an interspecies comparison showed that trees growing in drier sites were more drought resistant (Orwig & Abrams 1997).

Since the period in which damage after an extreme event can occur is long, it is not a trivial matter to disentangle the damage caused by a specific event and the conditions that followed which can enhance or maintain the hazard level present. Here, we face the non-trivial task of separating the effects of the different years in a consecutive drought. We first address the long-term changes in water availability due to extreme droughts, to better understand the long-term conditions that the vegetation will experience. Next, we describe the expected or observed legacy damage from the 2018-2022 drought events to forest ecosystems. While the focus of this section is on damage, it is worth noting that also long term positive effect can occur after a climate extreme event (Mueller & Bahn 2022)

4.2 The connection of vegetation drought legacy with groundwater drought legacy

Groundwater is a key component of the terrestrial water cycle and contributes dynamics and feedbacks with vegetation process at time scales far beyond the weather and seasonal time scale (Aesbach-Hertig and Gleeson, 2012), which are especially important for the evolution and persistence of droughts. The vegetation water supply under meteorological and hydrologic drought is determined by the redistribution of moisture in the shallow subsurface (soil) and its hydraulic connection with groundwater (GW) (Yu et al., 2007). Thus, the impact and legacy of drought strongly depends on the local and regional distribution of soil moisture, infiltration and groundwater recharge, capillary rise, and baseflow along river corridors. These fluxes and their spatiotemporal dynamics are a function of the heterogeneity of the subsurface, land surface processes, and climatology. The feedback of groundwater with vegetation is strongly non-linear, and occurs capillary rise of water from the free water table or direct extraction of water from GW due to root water uptake. Both processes can be especially pronounced under drought conditions and depend on the vegetation type and associated root depth distribution (Fan et al., 2017). In turn, if the free GW table is at the critical depth along e.g. a hillslope, even small changes on the order of 10^{-1}m may result in significant feedback with root water uptake and changes of evapotranspiration (Kollet et al., 2008). Thus, GW drought legacy that is manifested in increased GW table depths will impact drought legacy effects in forests, and, as a matter of fact, in all types of vegetation and land surface process. Because water use by vegetation is consumptive, vegetation constitutes a sink for GW under these conditions. Thus, a positive feedback loop may arise in which GW drought legacy influences vegetation drought and, in turn, vegetation influences GW drought legacy. Since the timescale of GW drought legacy acts far beyond the weather and seasonal time scale (Aesbach-Hertig and Gleeson, 2012; Loon, 2015), one can expect a strong connection to shallow moisture redistribution and drought legacy over very large time scales in regions of critical groundwater depths. While there is a dependence on climate, and local and regional terrestrial conditions, the basic physical principles of the processes described above are universal.

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In order to assess the connection of drought legacy with groundwater drought legacy from observations, the state of GW (including soil water) must be known in space and time . Commonly the state of GW is observed in boreholes via in-situ GW table or piezometric head measurements. These measurements provide information at the point scale in space and commonly at low frequency in time, because they are usually performed manually and, thus, not logged continuously. This leads to discontinuous images of the GW state in space-time, which commonly is interpolated with the help of models, inversion, and data assimilation. Note, however, no collated GW observational data base exists over Europe or for specific countries. Thus, the data remains fragmented and dispersed across a large number of political and private institutions and is not generally not publically available. This renders a formal analysis of the connection infeasible within the scope of this study; only the general principles can be discussed here.

In Mid Europe, dispersed bore hole observations of groundwater levels reveal that the 2018 drought was indeed one of the most severe in decades and comparable with the drought of 1976 (Schuldt et al., 2018). In 2018, in many observation wells, groundwater levels were at or close to the lowest levels ever observed by in-situ measurements (Bakke et al., 2020) resulting in the cessation of capillary rise, reduction of root water uptake and server drought stress also beyond the year 2018 (Schuldt et al., 2020). The long-term effect may be especially pronounced, because groundwater recovery after drought is a slow process leading to strong memory effects and an increased probability of drought at the interannual time scale which was indeed observed in the ensuing years 2019 and 2020 in addition to precipitation deficits (Hartick et al., 2021). It is important to note that vegetation stress under the 2018 to 2022 drought conditions also showed distinct spatial patterns from observations, with limited stress along river corridors and extreme stress in the upper parts of hillslopes along ridges (Cartwright et al., 2020). These patterns are directly related to groundwater processes that are the groundwater discharge and recharge, respectively. Under drought conditions, along rivers corridors, groundwater discharges as baseflow toward the stream constituting essentially an outcrop of the groundwater table, thus, leading to shallow groundwater tables connected to the land surface via capillary rise and root water uptake. In contrast, along hillslopes and ridges, capillary rise for root water uptake is mainly sustained by shallow soil water without connection to the groundwater compartment leading to tight coupling of root water uptake and plant stress with quite limited soil moisture storage. In case of GW, these patterns are well-known and reflected in in-situ groundwater measurements. However, the lack of remote sensing information for the subsurface, data scarcity and fragmentation lead to a much more incomplete spatial coverage of information.

4.3 Drought legacy effects in forests – the accumulation of long terms damages

Legacy of a drought event in forests can take many forms (Müller & Bahn 2022, Rukh et al. 2023), depending on the tree demography most influenced. The mortality of adult trees can create opening in a forest, influencing the long-term profitability of an economic forest but also the carbon and water cycle and species composition. Similarly, the mortality or reduction in vitality of saplings can prolong affect these processes by slowing the recovery of the forest. Additionally, damage that do not cause mortality may weaken the trees and make them more susceptible for future droughts or to a different type of extreme events, e.g. storms (Gliksman et al., 2023) or fires and pests as described in detail in previous sections. We present several examples for the long lasting damage of drought during the 2018-2022 period on forests in Europe. However, we expect that future literature will examine this topic more in depth in the years to follow 2022, as either examination of recovery rates if the drought will come to an end, or, if the drought will continue for several years longer, than it would be possible to study the ongoing adaptation to drought. Below, we offer examples mostly relating to saplings and young trees as the more reliant aspects of legacy that can be observed during this drought period.

When assessing the long-term damage to seedling establishment there is variation depending on location and the target tree species studied (Salomon et al., 2022). In a large field study in Central Eastern Germany, the drought of 2018 caused defoliation on average 65% of the saplings across multiple tree species, and for several species, the rate of affected saplings reached 85% and more (Beloiu et al., 2020). Although the sapling showed a rapid recovery in the following year, in 2019 and 2020 still 25-32% of the saplings showed damage (Beloiu et al., 2022). More localized reports are also present such as the loss of 50,000 seedlings at a single large Sitka spruce orchard in Galloway, Scotland because of the 2018 and 2020 droughts (Locatelli et al. 2021). Similarly, in Poland at the Brodnica Forest District (RDSF Torun) in 2018, around 20% of the trees planted did not survive the drought season. This means that nearly 30 ha of young forest have to be replanted, with losses in excess of around 33,000€ (150,000 PLN; LASY, 2023). Similar damages were observed in many other locations in Germany including damage and mortality of young spruce and beech trees (BMEL 2019). In Scotland, Locatelli et al. (2021) report significant mortality of younger forest stands rates by private sector forest managers for both restored sites and newly planted forests.

Growth reductions were also observed in North Germany following 2018 due to insufficient water recharge during the winter of 2018/2019 (Scharnweber et al. 2020), and similarly in Germany in 2019 and 2020 (Beloiu et al 2022). Additionally, relating to growth reduction due to 2018, the GPP of the forests in Switzerland recovered during 2019 (due to normal amount of precipitation but with heat waves) in about 50% of the forested area but 49% remained damaged at the levels of 2018, showing a strong legacy effect (Sturm 2022).

5. Discussion / Outlook

5.1 General discussion

Defoliation rates between 2018-2021 show that in most countries the defoliation rates for broadleaves were significantly higher than for conifers (Figure 2). The development of conifer defoliation over the period 2018 to 2022 shows that the rates were rather stable except for Italy with a strong increase in 2021. The development of defoliation in broadleaves over this period remains constant, with the exception of Italy with a strong decline and France with a strong steady increase. For Northern Europe only data of two years for Ireland was available with surprisingly high values.

Insects pests could be detected for large parts of Central Europe and Sweden (Table 2). In Europe, climate change is expected to increase the level of bark beetle disturbance sevenfold up to 2030 compared to the period 1971–1980 (Seidl et al., 2014). Other studies have suggested an increase in bark beetle disturbance during the 21st century by 60–220%, depending on the

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level of climate forcing and forest conditions (e.g. Dobor et al., 2019, Dobor et al., 2020b). The cumulative growing stock affected by bark beetles was 59.0% higher under moderate climate change scenario, and 204.8% and 221.1% higher in the hot and wet climate change scenarios, respectively, compared to baseline climate (Sommerfeld et al. 2020).

A concrete increase in the occurrence of **forest fires** in the period 2018-2022 could not be detected based on the available data (Figure 3). Isolated years of greater magnitude have been identified during 2018 until 2022, however this is also true for other periods. In addition, it must also be noted that the forest fires recorded by EFFIS only start at an area of 30 ha. Accordingly, not all fires can be depicted. On request at individual offices (e.g. in Austria), it was found that there were many more fires and affected area during 2018 - 2022. An additional factor why it is difficult to assign fires directly to climate change is the way people in different regions deal with the forest in times of risk (e.g. access restrictions) and forestry measures (firebreaks, back roads, extinguishing management).

The highest rates of **tree cover loss** (Figure 4) were detected in CZ and Germany, followed by Italy and Portugal (in 2017) In terms of legacy in 2020 the average was 7.8% slightly reduced to 7.6 in 2021 and further declining to 6.0% in 2022, thus showing literally no reduction in damage level during 2021 indicating a strong legacy effect in year 2021
With similar values just for central Europe (9.5% - 2020 and 9.2% - 2021).

Northern Europe

Overall, in Fennoscandia, the forest management during the last decades has favoured conifer monocultures, leading Norway spruce and Scots pine to be the dominant species (Huuskonen et al., 2021). This means that the large forest ecosystems are more vulnerable to climate extremes.

The example of Norway may make it clear that Scandinavie is probably the area where climate change has the least consequences for forest ecosystems. In Norway, larger seasonal differences in precipitation/drought and temperature are expected. Periods of drought are replaced by periods of heavy rains and flooding. The consequences are moderate for forestry – but can be severe for agriculture in particularly dry seasons – and also for hydroelectric dams. So far, the effects seem to cancel each other out. For example, winter, spring and summer 2021 were dry, but then Norway had an autumn and winter with more rain than usual, groundwater levels went above normal and our hydroelectric dams were filled. Insect attacks after the 2018 drought could have become severe, but cold and wet preceding years probably mitigated this. Overall, the major concern in Norway is periods of drought followed by periods of heavy rains leading to passing floods. Damaged wood by insect pests was in the Northern zone only available for Sweden, with very high values in the years 2018, but especially for 2019, 2020, and 2021.

Differences in, for example, early detection, forest road network density, and the number of local voluntary fire brigades are the main reasons why there was such a variation in forest fires and damages in the Nordic Countries (Lehtonen and Venäläinen, 2020).

Also at the British Isles, not an exceptional amount of damage could be ascertained during the investigation period according to the data. Only some indirect signs were detectable. A survey published by Forest Research (2021) shows that the effects of the previous years of drought damage were also clearly noticeable for forest visitors: 83% in the UK (82% in England) agreed that 'A lot more trees should be planted' in response to the threat of climate change. 77% in the UK (76% in England) agreed that 'action should be taken by authorities and woodland managers to protect trees from damaging pests and diseases'. Regarding insects, no damage data was found. However, the great spruce bark beetle (*Dendroctonus micans*) is today an established pest in southern Scotland (Scottish Forestry 2023a). Sitka spruce is Scotland's most important commercial tree species and the primary host of this pest. The '*D.micans* distribution map in Scotland' clearly shows its expansion northwards in the period 2018 until 2022 (Scottish forestry 2023b). A synopsis of spatial modelling research (Forest Research 2008) even expects due to a warmer climate an improvement of tree growth in Scotland in the future: particularly in southern and eastern Scotland for high-quality broadleaved trees on suitable deep, fertile soils and for conifers on sites where water and nutrients are not limiting. It should also be noted that when it comes to drought damages recorded in England and Scotland in 2018, wildfires only came in third place, while impacts on freshwater ecosystems and water quality ranked ahead (Turner et al. 2021).

Central Europe

The less drought-adapted ecosystems of central and northern Europe experienced a record hot drought (Buras et al. 2020) that caused early-wilting during summer 2018 in about 11% of Central European forested area. Most affected forests were located in Central and East Germany, and in the Czech Republic (Brun et al., 2020).For the forest damage caused during 2019-2020 in Central Europe, the 2018 drought and heat were the preconditions, while the main driver was a water vapor pressure deficit above average (Senf and Seidl, 2021a). The low soil moisture content in 2018 and the higher than normal water vapor pressure deficit of the following two years were viewed as the main drivers for the forest disturbances of about 4.74 million ha during 2018-2020, mainly in Germany, Czech Republic and Austria (Senf et al., 2021). The main cause for tree mortality in 2018 is likely due to physiological damage (Schuldt et al., 2020). Greenness was strongly reduced in Austria, Germany and Switzerland during 2018 (Schuldt et al., 2020). Reduced greenness was also observed in the spring of 2019 when compared to the greenness before the drought in spring 2018 (Brun et al., 2020). During the hottest summer on record in Europe in 2022, large parts of temperate forest regions were negatively affected, and forest greenness decreased stronger than any other summer since 2002 by breaking the former record drought in 2018 (Hermann et al. 2023, Buras et al. 2023; the five aforementioned studies are based on satellite-derived Normalized Difference Vegetation Index (NDVI).

Over the last decades, an increased occurrence of spruce bark beetles (*Ips typographus* L.) in Central Europe emerged (Fernandez-Carrillo et al. 2020). Between 2018 and 2022, drought and heat facilitated the outbreak of an unprecedented size on standing timber in Central Europe – especially in the Czech Republic, Germany, and Austria (e.g. Hlásny et al. 2019, 2021, Nardi et al.2023, Kautz et al. 2023). For example, in Austria and Germany >50 % and in the Czech Republic > 90% of all harvests in 2019 were related to salvage logging (Senf and Seidl, 2021a). However, not only the climatic conditions are decisive, but also the species composition of the stocks. Especially Norvegian spruce monocultures are particularly vulnerable.

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Economic losses in the forestry sector of Central Europe were also considerable during the period 2018 until 2022. The exact costs are difficult to determine, because our understanding of the economic impacts of disturbances remains incomplete (Knoke et al. 2021). Consequential damage along the value chain or losses due to immaturity of harvested trees can still be calculated, but the destabilization of the remaining and neighboring stocks, the fall in market prices or the heat effect on forest workers and machines can hardly be quantified.

In addition to the drought, storm lows must still be taken into account. As of today, one cannot necessarily say that the storms in Germany are increasing massively, but the damage caused by windthrow does. In addition to various silvicultural reasons, there is a development in Germany towards less severe winters or an increase in precipitation outside the growing season (UBA 2015). In other cases, the soil is so wet that the roots just don't have enough to counter strong winds. Of course, weakened stands by drought are also much more susceptible to strong winds.

Alpine Zone

Mountain forests are specifically under pressure of climate change impacts due to their temperature limitation and high exposure to warming (Albrich et al. 2020). However, those impacts can vary greatly with elevation and topography (e.g. Lindner et al. 2010, Thrippleton et al. 2020). Main tree species in Central European mountain forests are Norway spruce, European beech and silver fir. All of them are late-successional and shade-tolerant (Dyderski et al. 2023), while the first two are sensitive to drought stress. Drought can also destabilise mountain forests and result in soil erosion, landslides and rockfalls. Warmer temperatures and a shortening of cold periods can lead to reduced snow cover and trigger the distribution of harmful organisms or alien and invasive species and therefore can have a disastrous impact on biodiversity (Eriksen & Hauri 2021). Since the length of growing season decreases with altitude, a warmer climate could also lead to more growth as long as there is enough access to water. This was confirmed by a study that measured tree aboveground biomass increment in temperate mountain forest (e.g. Thom and Seidl 2022, Dyderski et al. 2023). Tree line will shift upwards over a longer period and tree species from the lowlands will establish at higher altitudes. A simulation on forest dynamics in the Northern Alps predicts for the first half of the current century a probability for increasing gains in stem density, structural complexity, and tree species diversity i.e. less conifers (Thom et al. 2022). An inventory of Alpine drought impact reports by Stephan et al. (2021) shows that the pre- Alpine areas are more affected than those at higher elevations. Additionally, most reported impacts were categorized to agriculture and public water supply, while impacts on forestry and terrestrial ecosystems were less mentioned. According to this study, drought impacts occur mostly in summer and early autumn, likely due to snowmelt in spring, which mitigates water shortages. At the same time, this study also observed a spatial heterogeneity across the Alps surprisingly with more impacts in the northern Alpine regions. Eriksen and Hauri (2021) mention that forest fires have traditionally been more common on the southern side of the Alps, which may have improved handling of forest fires.

Fire is one of the major natural disturbance factors in the European alpine forests and shows heterogeneity in frequency, spatial extent and seasonality, driven by climatic, environmental and anthropogenic factors (Morresi et al 2020). However, if there is an increased risk of forest fires in alpine regions is not so easy to disentangle, because each Alpine country has its own forest

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fire documentation system with different attributes, criteria and accuracies (BMRLT 2020). The proportions of Alpine forests are significant for many countries. According to the values compiled for this review for the period 2018 to 2022, it does not appear that the forest fires in the Alps are far from the long-term average (Table 3).

A supra-regional body would really have to be created by politicians to harmonize and bring this data together. Because under the given circumstances it is not easy to see what is currently happening in the Alps. In order to understand the impact of climate change on the Alps, a larger context needs to be considered across national borders, since many systems do not stop at national borders (e.g. river basins such as the Danube or the Rhône). Cooperation across national borders and disciplines (climate research, ecology) is necessary.

Southern Europe

In the southern zone one can repeatedly see individual strong effects of heat and drought. In Portugal, for example, there were exceptionally strong wildfires in 2017, and in 2022 as well. However, wildfires are also generally part of the southwestern European ecosystems. Italy was also strongly affected by the windstorm Vaia in 2018. Based on our research, we could not find an increase in impacts on forest ecosystems with regard to insect infestation or physiological damage such as defoliation between the period 2018 and 2022 examined here and the years before. Up to 2018, 3 million hectares of forests have been reported to be converted into shrublands or grasslands in the Mediterranean countries of the European Union. Fire and drought are the main drivers underlying this deforestation (Karavani et al., 2018).

In Spain, in the period 2018-2019, there was even some recovery in forest health in Spain which is in contrast to the larger damages recorded over entire Europe, in particular over Central Europe, which experienced both drier conditions and larger vegetation damages (AIEF 2019, ESOTC 2019).

The situatione of Maritime pine (*Pinus pinaster*, one of the most frequent species) in Iberia is according to Kurz-Besson et al. (2016), not completely discouraging. According to Kurz-Besson et al. (2016), wood radial growth and density highly benefit from the strong decay of cold days and the increase of minimum temperature. Yet, the benefits are hindered by long-term water deficit, which results in different levels of impact on wood radial growth and density. Despite of the intensification of long-term water deficit, tree-ring width appears to benefit from the minimum temperature increase, whereas the effects of long-term droughts significantly prevail on tree-ring density. This is in accordance with the results from Gazol & Camarero (2022) which show that mortality and defoliation in NW Iberia was not as bad as in other regions in Europe. Wood radial growth and density highly benefit from the strong decay of cold days and the increase of minimum temperature. Yet, the benefits are hindered by long-term water deficit, which results in different levels of impact on wood radial growth and density. Despite of the intensification of long-term water deficit, tree-ring width appears to benefit from the minimum temperature increase, whereas the effects of long-term droughts significantly prevail on tree-ring density. This is in accordance with the results from Gazol & Camarero (2022) which show that mortality and defoliation in NW Iberia was not as bad as in other regions in Europe.

Since the particular extreme year of 2017, severe measures have been applied and comparing the periods 2007-2017 and 2018-2022, the total number of fires decreased in half, particularly on days of greater fire risk. Larger fires have slowed since 2017, with larger fires with more than 1000 ha reducing from an average of 19 events to 8 in more recent years. Although forest losses are decreasing in the last period, Portugal is still among the countries with a mean annual area of forest loss due to fire ≥10 km^2/yr, seeing an increasing trend in forest loss due to fire between 2001 and 2019 (Tyukavina et al., 2022). In this sense, the decrease in fire events may not have been so predominant without the unique events of 2017, indicating that the difficulties of interpretation long term trends of damage.

5.2 Future trends and biophysical feedbacks of forest cover changes

Future global warming is expected to lead to more frequent and intense periods with heat and dry conditions in European regions (e.g. Seneviratne et al. 2021), which will further enhance climate related risks on European forests.. For example, Hari et al. (2020) found a sevenfold increase in the occurrence of consecutive droughts as of 2018-2019 in Europe under the highest Representative Concentration Pathway RCP 8.5. Gazol & Camarero (2022) expect an increase in forest drought mortality over the next decades due to more frequent compound events of extreme drought and heatwaves. Martinez del Castillo et al. (2022) project severe future growth declines of European beech forests ranging from −20% to more than −50% by 2090, depending on the region and climate change scenario (i.e. CMIP6 SSP1-2.6 and SSP5-8.5).

This is in line with CMIP6 (SSP2-4.5) multi-model mean simulations, which support the notion that mean annual precipitation decreases most the closer one gets to the Mediterranean, linked to roughly similar spatial changes in surface runoff (see *IPCC AR6*). At the same time, evapotranspiration increases the further east in Europe one gets (see *IPCC AR6*). Combined, those two meteorological aspects lead to a pronounced surface soil moisture deficit, which increases the (hydrological) drought risk substantially (see *IPCC AR6*). Accordingly, forest disturbance regimes are expected to intensify with continuing climate change, leading to increasing forest biomass losses due to windthrows, fires and insect outbreaks (Forzieri et al. 2021, Patacca et al. 2022).

At the same time, the increase in European forest coverage and green spaces are foreseen as essential measures to combat climate change and its impacts (e.g. European Commission 2021). Forests play a key role in the European Green Deal climate change mitigation strategy (Fetting 2020). However, more frequent and severe droughts and heatwaves would further increase the vulnerability of European forests to disturbances and lead to increasing tree mortality and reduced forest growth. This would decrease carbon sequestration in forests (e.g. Albrich et al. 2022) and could counterbalance efforts of reforestation and climate smart forest management. Forest damage and reduced forest cover can even locally increase the intensity of hot days in northern mid-latitudes (e.g. Lejeune et al. 2018), and thus could even further enhance forest damage.

Increase in forest cover are foreseen as important measures to mitigate climate extremes. Changes in forest cover due to land use & climate change modulate local and regional climate conditions through changes of land surface properties, such as land surface reflectance, water holding capacity and aerodynamic roughness. This affects biophysical land surface processes such

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as the exchange of energy, momentum and water, or the partitioning of turbulent fluxes into sensible and latent heat flux. A quantitative understanding of regional and local biophysical effects of such land use changes is required to enable effective land-based mitigation and adaptation measures (e.g. Perugini et al., 2017). However, these effects are complex and strongly depend on local conditions, their quantification is still largely unclear.

Biophysical feedbacks of land use changes on near surface temperature can be locally or regionally of the same order of magnitude as those associated with the effect from global greenhouse gas forcing (e.g. de Noblet-Ducoudré et al., 2012). First regional climate model (RCM) ensemble experiments in the frame of the CORDEX Flagship Pilot Study LUCAS investigate the effects of extreme forest cover changes on local and regional climate in Europe (Rechid et al., 2017). The LUCAS RCM inter-comparison study by Davin et al. (2020) reveal significant biophysical effects of re-/afforestation on the regional and local climate at seasonal scale. It shows an overall agreement of RCMs in winter warming with consistently simulated albedo change, but no agreement on the sign of temperature response in summer, with disagreement in evaporative fraction. The study concludes that summer temperature response is dominantly driven by land processes, whereas atmospheric processes are important for winter response. Breil et al. (2020) found opposing effects of re-/afforestation on the diurnal temperature cycle at the surface and in the overlying atmospheric layer: Most RCMs simulate colder summer surface temperatures during day and warmer summer surface temperatures during night, which is in line with observation-based studies. In contrast, the diurnal temperature cycle in the overlying atmospheric surface layer is increased, due to higher surface roughness, which increases turbulent heat fluxes. Sofiadis et al. (2022) investigate the impact of re-/afforestation on the seasonal cycle of soil temperature over the European continent with the LUCAS RCM ensemble. The multi-model mean shows a reduction of the annual amplitude of soil temperature over all European regions, although this is not a robust feature among the models. In addition, pair FLUXNET sites are investigated in order to compare the simulated results with observations. In line with models, observations indicate a summer ground cooling in forested areas compared to open lands. The vast majority of models agree with the sign of the observed reduction in the annual amplitude of soil temperature, although with a large variation in the magnitude of changes. Daloz et al. (2022) evaluate the snow-albedo effect of FPS LUCAS RCMs in sub-polar and alpine climates, and Mooney et al. (2022) investigate the FPS LUCAS simulations under extreme forest cover changes: Results show that re-/afforestation reduces the snow-albedo sensitivity index and enhances snowmelt. While the direction of change is robustly modelled, there is still uncertainty in the magnitude of change. The results of the FPS LUCAS Phase 1 simulations show the importance of biophysical effects and feedbacks of forest cover changes in Europe. Climate change-driven changes in forest cover in Europe will intensify under further climate change and may become regionally and locally self-reinforcing through biophysical processes and feedbacks.

5.3 Dryland mechanisms exacerbating damage or enable adaptations to mitigate drought stress in Europe

The heat and soil and atmospheric dryness, symptomatic of the recent climate extremes across Europe, led to the deterioration of forest tree canopies, stem dehydration, leaf shedding and plant die-back (Peters et al., 2020, Rohner et al., 2021, Schuldt et al., 2020, Sturm et al., 2022). Indirect implications of heat and dryness include increased vulnerability to damages by fire and by pests and diseases, while legacy effects reduced tree growth even after the end of climate extremes (Schnabel et al., 2022, Schuldt et al., 2020, Sutanto et al., 2020). Beyond these direct and indirect impacts, heat and dryness can trigger the emergence of ‘dryland mechanisms of ecosystem functioning’, which are processes at the organism and ecosystem level, so far mainly, though not exclusively observed in dry regions (Grünzweig et al., 2022). Dryland mechanisms are driven by heat, solar radiation and soil dryness, and are enhanced by reduced vegetation cover and canopy gaps, caused, e.g., by plant dieback, pest-induced mortality and fire. These mechanisms can be of high importance for the functioning of ecosystems, are likely to emerge in a drier and warmer climate, and some of them will cause damage by amplifying other deteriorating impacts of climate change.

Soil hydrophobicity (soil water repellency) is such an amplifying mechanism characterised by slowed and spatially heterogeneous infiltration of water into the soil, which has been observed in various temperate forests and diverse soil types in Europe and other continents (Gimbel *et al.*, 2016, Hewelke *et al.*, 2018, Seaton *et al.*, 2019). In drylands, soil hydrophobicity might be an adaptive mechanism contributing to conservation of water and ecosystem resilience under dry conditions (Ruthrof *et al.*, 2019, Seaton *et al.*, 2019). However, in ecosystems not adapted to dryness, soil hydrophobicity can exacerbate drought-induced damages to forests by further reducing plant production, increasing vulnerability to pests and diseases, rising mortality rates, and exacerbating soil erosion. For instance, a prolonged drought in a Scots pine forest in Spain induced soil hydrophobicity, which may increase drought stress and tree die-off (Gazol *et al.*, 2018). An additional amplifying feedback of soil hydrophobicity involves fire. In an afforested peatland in Scotland, a long-lasting smoldering wildfire during hot and dry weather left behind hydrophobic, charred peat, potentially reducing water infiltration and causing further damages to surviving trees (Davies *et al.*, 2013).

Increased heat and drought often reduce vegetation cover and increase areas of bare patches, thus promoting spatial connectivity and transfer of materials across the landscape. These conditions enable horizontal redistribution of resources, which lead to loss of water and nutrients by runoff and soil erosion (Okin *et al.*, 2018). Further degradation of vegetation and reduced plant productivity are likely consequences of such a loss of resources (Schlesinger *et al.*, 1990).

Functioning as adaptations to dry climate, dryland mechanisms may diminish or even prevent damages caused by water scarcity and high temperatures. By the ability for hydraulic redistribution, plants transport water from moist to dry soil layers through their root system along a water potential gradient, thus improving plant nutrition, extending root lifespan and preserving hydraulic conductance in the xylem during dry periods (Prieto et al., 2012). In a temperate pine forest, hydraulic redistribution mitigated the impact of soil dryness on plant activity (transpiration, photosynthesis) during a drought (Domec et al., 2010). Non-rainfall water (dew, fog) is an additional source of moisture, whereby trees, such as coastal redwood, absorb water through leaves and bark, thus alleviating drought-stress and enabling humidity-enhanced biotic activity (Burgess & Dawson, 2004, Earles et al., 2016). In addition, the canopy convector effect can mitigate heat stress in forests by lowering the aerodynamic resistance of heat transfer from trees to the surrounding air (Banerjee et al., 2017; Rotenberg and Yakir, 2010). For instance, surface temperatures in forests rose less than those in non-forested ecosystems during the 2003 extreme heatwave

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in central and western Europe, thus enabling forests to save water and prevent long-term amplification of the consequences of extreme heat (Teuling et al., 2010). The canopy convector effect operates during hot droughts even under current forest structure and will be enhanced in forests with a more open canopy as a consequence of tree dieback or mortality (Grünzweig et al., 2022).

Our understanding of the involvement of dryland mechanisms in causing additional damages or providing pathways of adaptation to hot and dry conditions in Europe is very limited (Grünzweig *et al.*, 2022). Beyond increasing research efforts, these mechanisms should also be routinely monitored to record their operation prior, during and after climate extremes (Halbritter *et al.*, 2020).

5.4 Policies related to drought and heat waves

Based on the above assessment, it is very clear that recurrent heat wave and drought events lead to very sticking and multi-faceted impacts to our society. The impacts of enduring heat wave and drought include not only reduced water resources, crop failure, limited renewable energy, and pressure on human health, but also others like land use planning and human activities. The recent extreme events like the drought / heat wave in Central Europe in 2018 (e.g. Rousi et al., 2013) or the severe floods in the border region between Germany, Belgium, Netherlands and Luxembourg in July 2021 (e.g. Mohr et al., 2023) has clearly demonstrated that the preparedness our our society to face such extraordinary events is not sufficient. This is both for the case of the forecast – impact modelling chains, in which several agencies are typically involved, often leading to inefficient and late warning for the civil protection and population. Moreover, it has become clear from the recent events that the population also does not know how to act properly under extreme weather conditions. In fact, much more efforts need to be put into place regarding the information of the general public, e.g., on how for example save water under long-term drought, or to protect "endangered groups" like old or sick citizens when affected by an enduring heat wave. This is particularly important, as heat waves are expected to not only to be more extreme but also to affect our region for a longer segment of the year (e.g. Hundhausen et al., 2023). Some parts of Europe like the Iberian Peninsula may be in the late 21st century under the influence of constant drought (e.g. Moemken et al, 2022).

In the face of these events, the need to act has been recognized by agencies and stakeholders at least in Germany. Joint task forces have been put into place to develop to provide tailored forecasts products for the civil protection, public agencies and population, which will serve as a basis both to act under adverse conditions and to develop new policies and streamline procedures between public agencies. A key factor will be indeed the adequate communication of the information and political measures, as this was often a point that failed in the past. Here, the existing language barriers and accessibility of information must be taken in serious consideration. This will hopefully raise the awareness in the general population for the severe impacts of drought and heat on our livelihoods under current and future climate conditions. In fact, the German government has started (June 2023) a new national protection "heat plan" to be in place in the summer of 2023 (focus, 2023).

5.5 Data availability and reporting

Different impact reporting strategies and timelines across sectors and across countries hinder the rapid assessments of multi-country drought impacts. In particular, we found a systematic lack of consistent reporting for specific regions and ecosystems, e.g., grasslands over the Iberian Peninsula. Furthermore, we also find substantial delays or discontinuities in official impact reporting efforts, which we found were often no longer available for recent years, e.g. Spain's National Forest Damage Inventories available only until 2020 (AIEF, 2020). Initially, a description of the damage due to heat and drought to grassland was also planned. However, the data situation regarding grassland is very modest, although this is the second large-scale non-irrigated ecosystem that has many ecosystem services that are important for our well-being.
The lack of a uniformed data collection that is accessible across languages will be valuable with the existing lack of coverage. Our intent is to support or initiate a platform where all relevant data for drought damage is collected. This daunting task requires the collaboration of many researchers across different subjects.

5.6 Conclusions

Mitigating the damages caused by heat and drought in forests requires a multi-faceted approach that includes forest management strategies, climate change adaptation measures, and global efforts to reduce greenhouse gas emissions. Forest management practices, such as thinning, prescribed burning, and reforestation, can help increase forest resilience to heat and drought by reducing competition for water, improving tree vigor, and promoting more diverse species composition. Climate change adaptation measures, such as increasing water availability through irrigation, improving forest monitoring and early warning systems, and implementing strategies to reduce wildfire risk, can also help mitigate damages. **I**mpacts of heatwaves and droughts on carbon sequestration and thus on climate change mitigation potential of forests is a complex topic. Finally, global efforts to mitigate climate change by reducing greenhouse gas emissions are essential to address the root causes of heat and drought impacts on forests.

In conclusion, heat and drought are significant drivers of forest damages, including increased tree mortality, shifts in species composition, changes in productivity and carbon sequestration, and increased wildfire risk. Mitigating these damages requires a holistic approach that includes forest management, climate change adaptation measures, and global efforts to reduce greenhouse gas emissions. Understanding the impacts of heat and drought on forests and implementing appropriate strategies to mitigate these impacts is crucial for the conservation and sustainability of forest ecosystems in the face of climate change.
However, there are opportunities to limit this damage, which are depended on how well we understand the damage that already occurred might help us in the future regarding which tree species to use or which management techniques to apply.

Finally, we are aware that the discussion of different types of damage (e.g. fire, bark beetle and storm) is too isolated from a mechanistic point of view. For instance, the damage caused by wind is easily recognized in the aftermath of a storm, but scale can be very much dependent on other events such as drought (Gliksman et al., 2023). However, to tease apart the contribution of each driver is beyond the scope of this review. This review can provide valuable information to policy and decision makers concerning the preparation for the expected future droughts.

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