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 gathered data of damage caused by drought and high temperatures from 2018 until 2022 in forest ecosystems and combined our data with Europe-wide data sets such as (1) crown defoliation, (2) damaged wood by insects, (3) burnt forest areas, and (4) tree cover loss. We partitioned the data stemming from 16 European countries into four regions: Northern, Central, Alpine, and Southern.

During the 2018-2022 period, forests across all four zones exhibited diminished vitality due to drought and elevated temperatures, albeit with varying severity. We identify several trends affecting more than one climate zone: (1) Conifers have no significantly higher defoliation rates within the Northern zone or individual countries within it, but higher rates are observed in the Central and Southern zones. Broadleaves exhibit significantly higher defoliation rates across the three zones,

(2) There is a significant increase in general tree cover loss in the Northern, Central, and Southern zone. Although in several regions 2021 was an average year high levels of damages were still observed indicating strong legacy effects from the events in 2018- 2020, (3) The Northern and the Alpine zones showed comparatively lesser impacts, and (4) Central Europe and Sweden experienced notable damage to wood from bark beetles. Notable zone-specific trends were: (1) The Central zone experienced notable challenges exacerbated by bark beetle infestations, (2) While wildfires pose a colossal challenge for Southern Europe, their impact during this specific timeframe is not pronounced and (3) ~~while~~ some adaptive responses to heat and drought were discernible in the Southern zone. Overall, given the projected increase in future occurrences of drought and heat, these results emphasise the critical necessity for implementing tailored strategies to alleviate the detrimental impacts of climate change on European forests.

1 Introduction

1.1 General introduction

The global temperature rise, due to the accumulation of anthropogenic greenhouse gases in the atmosphere, causes extreme drought and heat events to become more likely and more extreme (Seneviratne et al., 2021). Even if we manage to stay below the 2°C global warming threshold by the end of the 21st century (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 was one of the warmest across Europe to date (Suarez-Gutierrez et al., 2018). Furthermore, the likelihood of such extremely warm summers co-occurring with extreme drought conditions over Europe is increasing rapidly (Suarez-Gutierrez et al., 2023). When extreme heat occurs jointly with severe drought conditions, it can lead to 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). Extreme drought is often closely linked with extreme heat, which in turn increases heat-related mortality and morbidity (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 the risk of heat-related mortality during the intense 2003 summer heat wave increased in Central Paris by ~70% and by ~20% in London, both attributable to human factors having exacerbated the likelihood for such heat episodes. 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.

The recent hot and dry extremes are part of a long-term trend being observed in Europe over the last 42 years, making it a hot spot for heatwaves in comparison to other regions of the northern hemisphere midlatitudes (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., 2022). This trend includes also consecutive multi-year meteorological summer droughts, such as those of 2018 to 2022 in Central and Western Europe, which are characterised 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; Suarez-Gutierrez et al., 2023).

1.2. Scope, aims and research approach

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 on forest ecosystems because they are not irrigated and thus the effects of climate extremes are clearer, and we avoid a potential bias in the interpretation of results due to variation in irrigation levels. Forests play a fundamental role in our livelihoods and supply wood, a renewable raw-material and other essential ecosystem services. For example, forests contribute significantly to maintaining biodiversity, sequestering carbon, mitigating climate change, preventing land degradation, and offering recreational value (Jenkins and Schaap, 2018).

We partitioned the forest environment of Europe into four main geographical zones with distinct 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 information sources (e.g. government reports) used for this review refer to political boundaries (at country-level), we assigned those sources to whichever geographical zone was the most appropriate. An exception was that four countries were assigned to two zones because they are partly in the Alpine zone.

The evaluation of the extraordinarily intense compound drought and heat event between 2018 and 2022, along with its impacts were derived using an interdisciplinary study integrating different information sources that allow for the assessment of temporal and spatial heterogeneity impacts. We start with the description of the climatic conditions in 2018-2022, with a focus on drought and high temperatures. We describe droughts in the years before 2018 where it is needed to provide a better context for our focal period of 2018-2022. Following this, 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, as the three impacts most well-documented in our sources.

The data source often posed issues and challenges. Concerning fire events, we focus on forest fires, which are defined as uncontrolled fires in at least partly forested areas. However, for some countries only statistics on wildfires (all uncontrolled vegetation fires) were available. Also, the online available data on number and burnt areas from the European Forest Fire Information System (EFFIS) shows number of wildfires and total affected vegetation area. To resolve these issues, we used data about forest fires where available and pointed out when we present information about wildfires. This study examines forest damage spanning 2018-2022, only the exceptional forest fire damage in 2017 in Southern Europe is included, as it provides context for subsequent damage. Post-2017, significant management measures were implemented in Southern Europe to mitigate forest fires, affecting subsequent damage trends. Forest damage of other zones is not discussed for 2017 as it was comparatively minimal.

In order to evaluate and attribute the impacts of heat and drought during the years 2018 to 2022 in Europe, we considered the years 2010-2014 as a reference period. We note that the year 2015 was characterised as an extraordinary drought period in Europe (e.g. Hoy et al., 2017, Laaha et al., 2017) and therefore we did not include 2015 in our reference period. Compared to other periods in the new millennium, the period 2010 to 2014 was characterised by fewer climate extremes, such as intense heat waves, widespread droughts or severe floods, e.g. the water balance levels in Germany show only small deviations from the climatological mean during that ~~p~~period (*cf*. DWD Dokumentation SPEI). The period of 2010-2014 had below-average to average annual mean temperatures (relative to the 1991-2020 average) across Europe, in particular during 2010, 2012, 2013. Moreover, damage data availability was sufficiently available for the period 2010-2014.

In the following sections, we take a closer look at the climatic situation during those five critical years in four European zones (Northern, Central, Alpine, and Southern). 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. Out of the 44 European countries (UN 2024) 28 countries were not included (i.e. Albania, Andorra, Belarus, Bosnia and Herzegovina, Cyprus, Denmark, Estonia, Georgia, Greece, Hungary, Iceland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Moldova, Monaco, Montenegro, North Macedonia, Romania, Russia, San Marino, Serbia, Slovakia, Slovenia, Turkey, Ukraine, and Vatican City). Data collection was conducted as broadly as possible across Europe over months of work by a working-group in the ClimXtreme project (https://www.climxtreme.net/index.php/en/) with additional experts beyond the project contributing their expertise.

Table 1: Four climate zones and the associated 16 countries in total, the countries of the Alpine zone are also assigned to other zones.

Zone	Countries
Northern	Finland (FIN), Sweden (SWE), Norway (NOR), United Kingdom (UK), Ireland (IRL)
Central	Poland (POL), Czech Republic (CZE), Switzerland (CHE), Austria (AUT), Germany (GER), Netherlands (NLD), Belgium (BEL), France (FRA)
Alpine	Switzerland, Austria, Italy (ITA), France
Southern	Italy, Spain (ESP), Portugal (POR)

2. Meteorological conditions

2.1. Occurrence of drought and heat in Europe during 2018-2022

Persistent above average temperatures and extreme deficits in precipitation characterised 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 blocking conditions over Europe, characterised by persistent high-pressure anticyclonic systems, especially in late spring and summer 2018. It was found that a persistent positive North Atlantic Oscillation, a pattern defined by higher-than-average atmospheric pressure over the subtropical North Atlantic and lower-than-average pressure over the North Atlantic (Drouard et al., 2019; Li et al., 2020), combined with a double jet stream configuration, with two instead of one single current of high-speeds winds in the upper atmosphere affecting the intensity and persistence of atmospheric patterns in the inter-jet region, were present before the initiation of the heatwave (Rousi et al., 2023). Furthermore, sea surface temperature anomalies exhibited a tripolar pattern in the North Atlantic which 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), as well as a precursor 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).

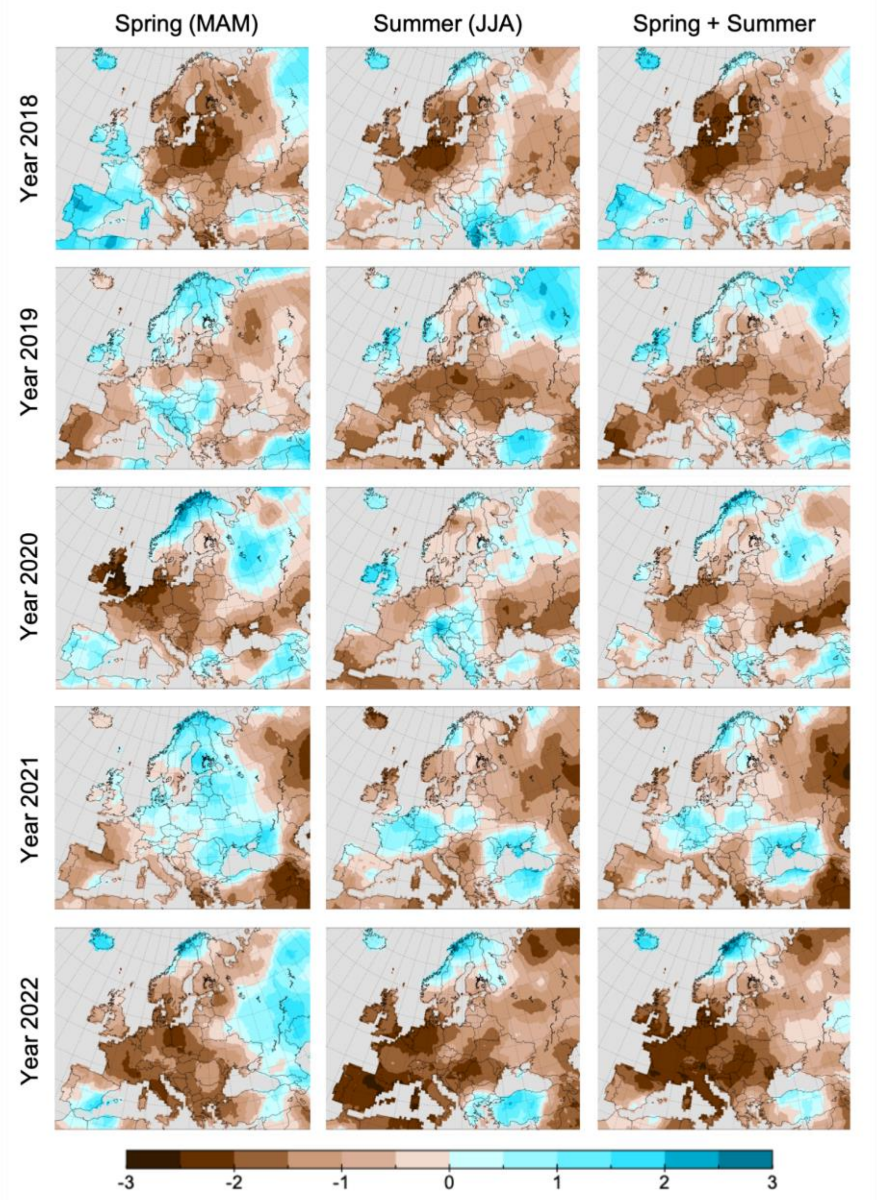


Figure 1. SPEI (Standard Precipitation Evaporation Index) for spring (March to May), summer (June to August) and the entire growing season (March to August) during the 2018 (top row) to 2022 period (bottom row). SPEI results are shown in units of standard deviation from the long-term mean of the standardised distribution. SPEI includes precipitation, effects of temperature and hence evapotranspiration. SPEI uses a climatic water balance D obtained at various time scales (i.e. over three and six months). E.g. for a 6-month SPEI, first a time series is constructed by the sum of D values from five months before ~~to~~ the current month. For a SPEI series comparable in space and time, the D series is transformed using equal probability to a normal

distribution with a mean of zero and standard deviation of one. This way the SPEI values are in standard deviations without seasonal effects (Vicente-Serrano et al., 2012, 2013, Beguería et al., 2013). Data was derived from the Global Drought Monitor, which offers near real-time information about drought conditions at a global scale. (Vicente-Serrano, Sergio M. & National Center for Atmospheric Research Staff (Eds). Last modified 2023-09-04 "The Climate Data Guide: Standardised Precipitation Evapotranspiration Index (SPEI)".

Using pattern climatology data for Europe and linking it with observations over the last 120 years, Hari et al., (2020) claim that alone the consecutive 2018-2019 drought was unprecedented during the last 250 years. Including also 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 +2.8°C 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 critical drought conditions (Fig 1). Throughout the summer of 2022, heat waves and exceptionally low rainfall led to very dry conditions in Central Europe. Observed runoff anomalies highlighted the 2022 European drought as potentially 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).

2.2. Drought and heat in the Northern zone 2018-2022

Finland had a warm and dry year in 2018. The summer was long with many days over 30°C temperatures and rainfall levels were at a record low in some areas. In Central Finland, the all-time lowest groundwater table levels were measured in small and shallow aquifers (Veijalainen et al., 2019). Furthermore, the summer of 2018 saw uncommonly large algal blooms and the death of fish and mussels and a 20% reduction in crop yields (Winland-project Policy Brief VII 2019). Summer 2019 was not as severe as 2018, but with significant impacts, for example, on the ground water levels, which were very low already from the previous year. Summertime temperatures were about 1°C higher than normal in Southern and Western Finland, but slightly lower in eastern and northern parts. Summer 2019 was drier than normally, especially in Central and Eastern Finland, where such dryness was last experienced in 1955 (Ilmastokatsaus, 2019). The year 2020 was a record breaking warm-year in Southern and Central Finland. Summer and autumn were exceptionally warm, but also many rainfall records were broken (Ilmastokatsaus, 2020). Year 2021 was not overall exceptional, but June and July were warmer than normally. June temperatures were in many parts of the country higher than ever recorded before. Summer was also unusually dry, although only in June and July (Ilmastokatsaus, 2021). The year 2022 was warmer than normal and summertime temperatures were almost 2°C higher than normal. Southern and Western Finland experienced less rainfall than normally, whereas Central and Northern Finland experienced more rain (Ilmastokatsaus, 2022).

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 in Sweden (Teutschbein et al., 2022). 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 eased in the following years, with the return of slightly drier conditions in 2022.

Norway also experienced periods of drought in the years 2018-2022. In the spring and summer of 2018 temperatures were up to 4.7 °C above normal levels. Precipitation between May and September 2018 was only between 18-46% of the average precipitation level for the years 1991-2020 (Norwegian Center for Climate Services, 2023). The summer of 2018 had 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 being August 2021 (Norwegian Center for climate services, 2023). This led to a reduction in groundwater levels down to 75% of the average levels in most of South-eastern Norway below the treeline in August 2018 and August 2022, causing problems for agricultural production in the region (NVE, 2023). As predicted by climate models (projection for 2031-2060, RPC 4.5. Reference period 1971-2000), precipitation is becoming more concentrated, leading to periods of floods (during early spring and on 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 a 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 harmful flood events (Sefton et al., 2021). The year 2020 was 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 (Met Office 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 (Met Office 2022, Royal Meteorological Society 2023). At Coningsby, Lincolnshire, a temperature above 40°C was recorded for the first time in the weather record history of the UK (Met Office 2022).

2.3 Drought and heat in the Central zone 2018-2022

Due to its geographical location and unfavourable hydrological conditions, **Poland** has few water resources relative to Europe (Ministry of Climate and Environment, 2023, SUSZA 2023). The relative scarcity of water resources is illustrated by the fact that almost 40% of arable and forested land in Poland is permanently threatened by drought (Polish Supreme Chamber of Control, 2021). Drought in Polish agriculture typically occurs every five years, and recently 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 (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 (as 2015 was the worst drought until 2018). 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 extent of drought affected areas in Germany reached almost 40% of the country in 2022, followed by 2019 (30%), 2018 (19%) and 2020 (16%).

2.4 Drought and heat in the Alpine zone 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 instrumental measurements in 1864 (Bader et al., 2019). While summer 2018 received only 70% of the long-term mean precipitation (1981–2010), winter rainfall (including snowfall) was above normal, which helped alleviate the worst impacts of the summer. Between 2019 and 2021, frequent heat episodes occurred during the summer seasons, but mean precipitation during winter was about normal. This changed in winter 2021/2022, when 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 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 the warmest summer on record with 2003 (since at least 250 years). Summer 2022 was the 4th warmest in recorded history, taking place right after a rather dry and mild winter, and while several heavy rainfall events occurred, they barely alleviated the drought conditions due to the high runoff.

2.5 Drought and heat in the Southern zone 2018-2022

Italy was affected by the 2018 drought to a lesser extent compared to Central and Northern European countries. For instance, there were no significant soil moisture anomalies and forest disturbance during 2018 in Italy (see Fig. 1 in Senf and Seidl, 2021a). 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 of 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 was 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 the extremely persistent hydrological and meteorological drought conditions in 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 for 1971-2000. Compared to previous years of drought, 2021/2022 it is the 3rd driest hydrological year after 2004/05 and 1944/1945, presenting a sharp deficit in relation to the average value throughout the year (APA, 2023).

For the period 2018 to 2020, Portugal was affected by drought to a lesser extent, and mostly in the southern part of the country (Figure 1). The drought conditions impacted water storage, with monthly storage deviations from the average in the last hydrological years, showing that in 2019/2020 the hydrological drought was more severe with five of the eleven hydrographic basins in Portugal maintaining negative deviations throughout the year. The 2020/21 hydrological year ended with only four watersheds with below-average storage levels (APA, 2023).

2.6 Drought attribution

As discussed earlier in the general introduction, a long-term drying trend has been observed in Central and Southern Europe in recent years and climate--simulations project these trends to continue (Stagge et al., 2017, Ukkola et al., 2020, Bakke et al., 2023). There is high confidence that both temperature increase, and precipitation decrease has already led to increased aridity in the Mediterranean region (IPCC, 2021a). According to the last IPCC report (IPCC, 2021b), the combined warming and drying trend is already attributable to human causes. This trend is less clear 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) in a warmer climate (IPCC, 2021a). 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 in CMIP6 model simulations. South-eastern Europe is also affected based on rainfall and precipitation minus evaporation reanalysis data (1950-2018; Christidis and Stott, 2021). A similar result is found when analysing longer-term SPEI trends (1902-2020), where hotspots in terms of drying were found in Spain, Portugal, Southern France, Italy, Eastern Germany, the Czech Republic, Poland, Hungary, Slovenia, and Croatia, with the opposite trend in Norway (Ionita et al., 2021a). The same authors hypothesise that those observations might be linked 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 based on proxy data (climate indicators like pollen, tree rings, etc) and (2) longer-term climate model projections.

(1) Looking at climate reconstructions based on proxy data 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 from paleoclimatic records that reach 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. We can thus only conclude that neither the location (central part of Europe in case of Ionita et al., (2021b)), the method (the latter based on the Old World Drought Atlas; Cook et al., 2015), nor the spatial extent considered may be different. What the results do highlight though is that it remains difficult to draw definite conclusions as far as current drought intensity in a historic or paleo-climatic context is concerned.

(2) Climate model projections based on the latest CMIP6 assessment broadly confirm the historical trends deduced from observations. As shown in ICCP (2021b), the rainfall deficit is projected to be most pronounced during the summer season (end 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 negative trend is only going to intensify in summer for the time being. In this context, it is important to note that annual mean rainfall changes are not informative when it comes to drought attribution. In fact, drought and heavy precipitation is often occurring in the same season, leading to adverse conditions for the agricultural and forest sector despite a climatologically balanced mean rainfall amount. In tandem with the rainfall deficit, it is very likely that meteorological drought conditions will occur much more often than under recent climate conditions (e.g. Mömken et al., 2022 for the Iberian Peninsula). It is highly unlikely that the current string of extreme drought years is an exception, rather it is a harbinger of what will soon be the new normal in large parts of Europe. That said, these projections are valid only for transient warming conditions. If we stop emitting carbon to the atmosphere, the planet will slowly

transition from its current transient warming state and enter the equilibrium warming phase following an e-folding trajectory. Thermodynamically, the transient warming state is characterised by a maximised 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 if the climate system is allowed to return to a new equilibrium state, which has recently been highlighted by Dittus et al., (2024) as well.

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, 2021a), the fact that the signal-to-noise ratio for drought events is still low despite attributable global warming of 1.2-1.3°C, which leaves the attribution community in a limbo as far as robust results are concerned. For example, Van der Wiel et al., (2022) concludes that drought events like 2018-2020 are part of the realm of possibilities in the present-day climate, that is, a comparable event was expected to occur based on the average frequency or return period as eventually the signal will emerge from natural variability with the detrimental effects for biodiversity and human health in general.

As it is difficult to reconcile the existing lines of evidence, only a few drought attribution studies have tried to quantify the role of humans thus far. 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). The authors concluded that while the magnitude of historical trends vary between different observation-based soil moisture products, they 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) analysed 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 trend in potential evapotranspiration. Given that these trends match results from climate model simulations, the authors conclude that the observed trend in agricultural drought can at least in part be attributed to human-induced climate change.

3. Damages to forests

Drought and heat are environmental factors that can have harmful impacts on forest ecosystems. Drought events compounded by heat waves can fundamentally transform the composition, structure, and biogeography of forested ecosystems (Allen et al., 2010, 2015). Overall, the consequences on forests can be summarised in three major impact categories: (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 have 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 (Patacca et al., 2023).

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 can be highly sensitive to drought 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 may experience carbon starvation and face greater risks of embolism, which can cause a failure in water transport (Allen et al., 2015, Schuldt et al., 2016). Such physiological stress can lead to mortality but also to milder consequences such as crown defoliation, early leaf shedding or death of branches that reduces the vitality and growth of the trees (Schuldt et al., 2016). Soil drying may lead to water repellency (soil hydrophobicity), which slows down the infiltration of rainwater following the end of the drought and produces a heterogeneous soil wetting front (Grünzweig et al., 2022). Soil hydrophobicity has been observed in various temperate forests and diverse soil types in Europe, which may increase drought stress and tree die-off (Gazol et al., 2018, Gimbel et al., 2016, Hewelke et al., 2018, Seaton et al., 2019). 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 mammals, birds, reptiles, amphibians or invertebrates such as insects and microorganisms (Liebhold et al., 2017).

At the same time, other processes like outbreaks of forest pests can co-occur and follow 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 in available resources 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 also increase 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 heat waves can also negatively affect some insect pest species or pathogens because of their response to the heat stress (Sire et al., 2022).

Heat and dry conditions can create favourable conditions for wildfires to start and spread (Kirchmeier-Young et al., 2019), 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 over the last decade 2010-2020, there have been years with the highest level of fire damage ever recorded in Europe in the past decade (Grünig et al., 2023; Patacca et al., 2023). Several regions (inter alia Central Europe) are likely to face larger and more frequent wildfires in the future (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 (Senf and Seidl, 2021a), there is strong evidence that wildfires 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). Wildfires commonly lead to hydrophobic soils (Davies et al., 2013, Mao et al., 2019), thus reducing water infiltration and causing further damages to trees (Grünzweig et al., 2022).

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, employing 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 probably 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 when compared with the average levels over the past three decades, and disturbances remained above average also in 2019 and 2020 (Senf et al., 2021). However, there are opportunities to better understand the damage, offering opportunities to mitigate future harm.

3.1. Europe-wide damages to forests 2018-2022

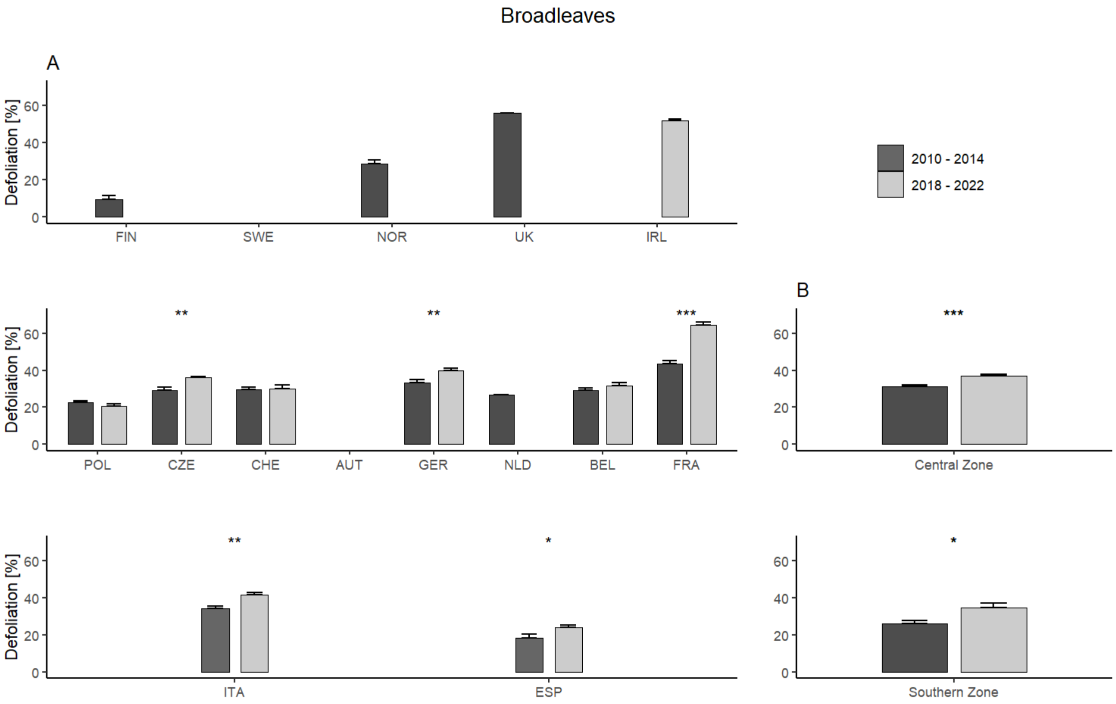
To comprehensively assess the diverse effects of drought and higher temperatures on forests, we gathered Europe-wide data where applicable (Table 2). This multifaceted approach allowed for a comprehensive view of the multifarious impacts of drought and temperature elevation on forest ecosystems. Our objective was to elucidate the impacts by comparing the consequences of the drought period spanning 2018-2022 with a reference period from 2010-2014. Physiological stress indicators, specifically crown defoliation data segregated into conifers and broadleaves, were sourced from ICPTechnical reports (http://icp-forests.net/page/icp-forests-technical-report). Information regarding insect pests was obtained by analysing the extent of wood damage caused by insects, drawing from various reliable sources. Forest fire data were derived from the JRC Technical reports (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). To broaden our understanding, we incorporated tree cover loss data from Global Forest Watch (https://www.globalforestwatch.org/).

Significant differences between the study period (2018-2022) and the reference period (2010-2014) were discerned utilising a t-test conducted with RStudio 2022.12.0.

Table 2: Differences between the study period 2018-2022 (18-22) to reference period 2010-2014 (10-14), where available. Denoted next to the higher average value (x̄) in each cell are the results of the statistical tests: n.a. (not applicable), n.s. (not significant), * significant (p<0.05), ** highly significant (p<0.01), *** very highly significant (p<0.001).

Zone	Crown defoliation [%]		Damaged wood by insects [1000m³]	Burnt forest area [ha]	Tree cover loss [%]
	Broadleaves	Conifers			
Northern	x̄ (10-14) = 23.3 n = 7 x̄ (18-22) = 51.9** n = 3	x̄ (10-14) = 16.9 (n.s.) n = 16 x̄ (18-22) = 15.9 n = 10	n.a.	x̄ (10-14) = 884.12 n = 20 x̄ (18-22) = 1750.8 (n.s.) n = 25	x̄ (10-14) = 0.70 n = 25 x̄ (18-22) = 1.05*** n = 25
Central	x̄ (10-14) = 31.29 n = 30 x̄ (18-22) = 37.11*** n = 30	x̄ (10-14) = 27.9 n = 23 x̄ (18-22) = 35.29** n = 24	x̄ (10-14) = 739.22 n = 20 x̄ (18-22) = 11507.67*** n = 31	x̄ (10-14) = 1655.1 n = 27 x̄ (18-22) = 1991.1 (n.s.) n = 38	x̄ (10-14) = 0.39 n = 40 x̄ (18-22) = 0.76** n = 40
Alpine	n.a.	n.a.	n.a.	x̄ (10-14) = 62.3 n= 10 x̄ (18-22) = 110.6 (n.s.) n= 10	n.a.
Southern	x̄ (10-14) = 26.25 n = 10 x̄ (18-22) = 34.83* n = 9	x̄ (10-14) = 20.02 n = 8 x̄ (18-22) = 26.99** n = 8	n.a.	x̄ (10-14) = 41510 n = 15 x̄ (18-22) = 50630 (n.s.) n = 15	x̄ (10-14) = 0.57 n = 15 x̄ (18-22) = 0.87* n = 15

A pairwise t-test comparing the averages presented in Table 2 examined whether the observed changes (difference in means) between the two periods (2010-2014 and 2018-2022) are statistically significant. The test results indicate that the difference between the two periods was not statistically significant (p= 0.06) for defoliation of both conifers and broadleaves, with a mean difference of 9.4%. The t-test results for forest fire occurrence clearly showed no significant difference (p=0.34, mean difference: 3400.9 ha). However, for tree cover loss, the mean difference of 0.34% was highly significant (p=0.004). A similar statistical test for damaged wood by insects was not feasible due to insufficient data availability.


Broadleaves
A
Defoliation [%]
0
20
40
60
FIN
SWE
NOR
UK
IRL
2010 - 2014
2018 - 2022
B
**
**
***
***
POL
CZE
CHE
AUT
GER
NLD
BEL
FRA
Central Zone
**
*
*
ITA
ESP
Southern Zone

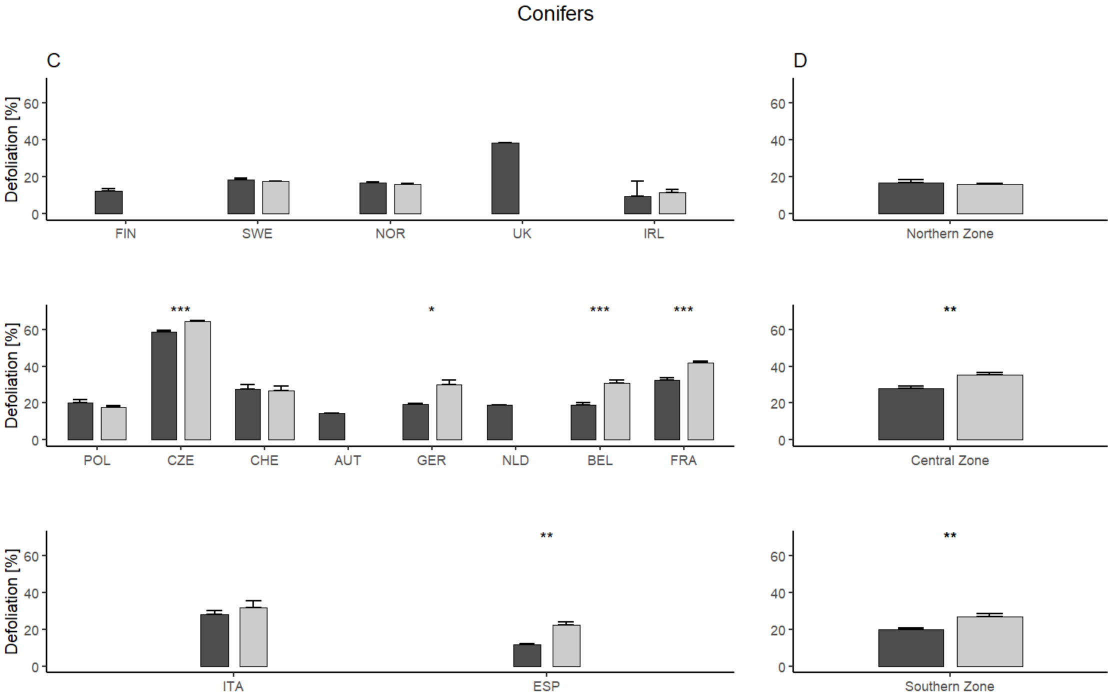

Conifers
C
D
Defoliation [%]
0
20
40
60
FIN
SWE
NOR
UK
IRL
Northern Zone
***
*
***
***
**
POL
CZE
CHE
AUT
GER
NLD
BEL
FRA
Central Zone
**
**
ITA
ESP
Southern Zone

Figure 2. Relative crown defoliation of broadleaves (A, B) and conifers (C, D) during the dry period 2018-2022 and the reference period 2010-2014 (> 25% needle/leaf loss, i.e. moderate to severe defoliation); data from ICP-forests (2022). For Broadleaves in the Northern zone data was not sufficiently available.

In the examination of conifer defoliation patterns across European regions, no significant differences in defoliation were discernible in the Northern zone or within individual countries situated in it (Figure 2). However, within the Central zone, a substantial and statistically significant discrepancy in defoliation levels was evident between the periods of 2018-2022 and 2010-2014, with the former exhibiting markedly higher rates. This disparity was particularly pronounced in the Czech Republic, Belgium, and France, where the differences were highly significant. Additionally, significant differences in defoliation were noted in Germany. The Southern zone displayed notable deviations during the dry period 2018-2022 compared to the reference period, with Spain also registering significant differences.

Notably, data for the Northern zone were not applicable for broadleaves. In the Central zone, a significantly higher defoliation level was evident in the dry period (2018-2022) than in the reference period (2010-2014). This discrepancy was particularly pronounced in France. Similar significant differences in defoliation were observed also in the Czech Republic and Germany. In the Southern zone, similar significant differences were detected between the two investigated periods in Italy and Spain.

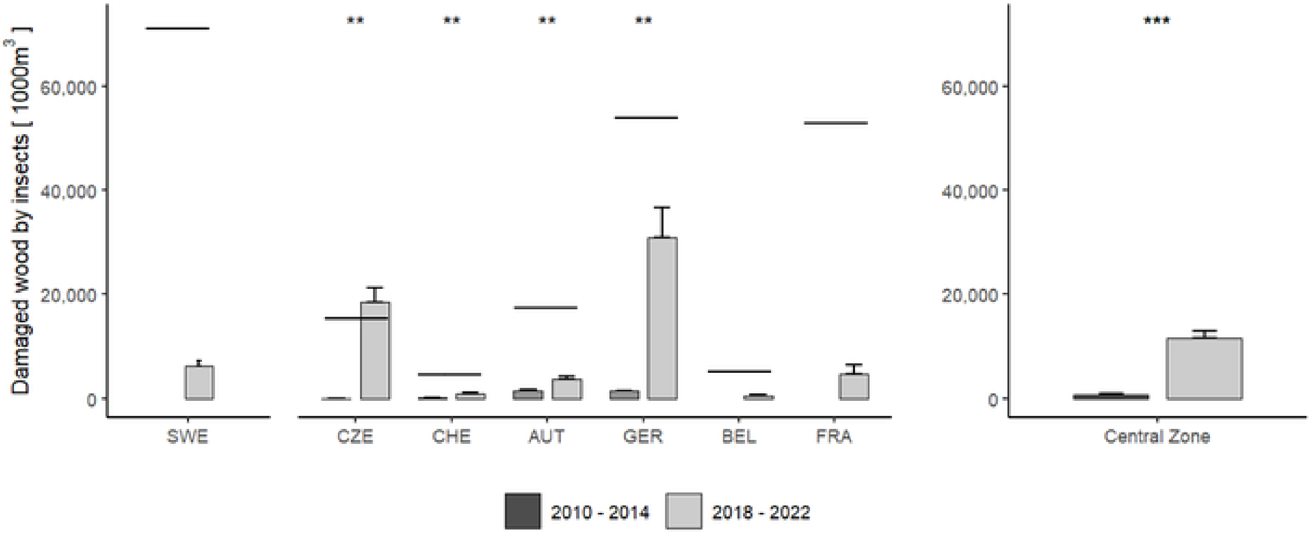


Figure 3. Damaged roundwood (1000 m³) by insect pests in Europe in the period 2018-2022, partly in comparison with the reference period 2010-2014. The black lines show the Total roundwood production average per year 2010-2014. Wood data derived from different sources (EUROSTAT 2016, Wulff and Roberge 2020, Öhrn et al., 2021, EUWID 2022, ICP 2022,

DESTATIS 2020, DESTATIS 2023, Waldschutz 2023, WSL 2023, BFW 2020, 2023, Czech Statistical Office). For the other countries data was not available.

Damaged wood caused by insect infestation was significantly higher across Central Europe in the study period of 2018-2022 than the reference period (2010-2014), being particularly evident in countries such as the Czech Republic, Switzerland, Austria, and Germany (Figure 3). Notable is the situation in the Czech Republic, where instances of insect-induced wood damage even surpassed the mean annual roundwood production (2010-2014). Sweden also experienced a degree of roundwood damage attributable to insects during the assessed drought period. While data on damaged roundwood by insects was accessible for select countries, it was not uniformly available across all regions. Notably, acquiring such data was comparatively easier during the more recent period, indicative of heightened pressures exerted by insect pests within forest ecosystems and a greater interest in monitoring forest damage.

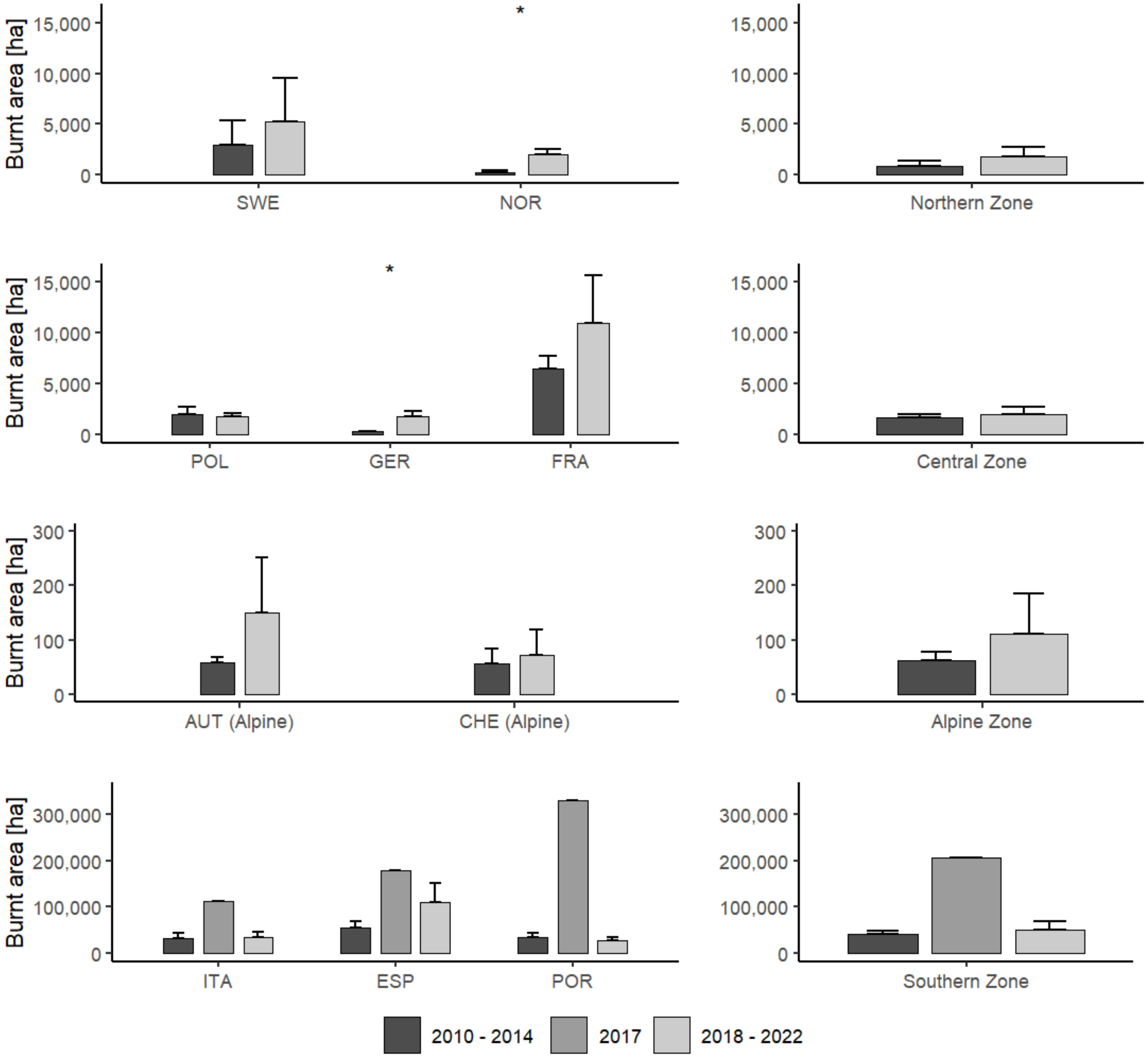


Figure 4. Burnt forested area (mean for the two periods under consideration) in selected European countries. Italy and Portugal had large fires in 2017 (accordingly, value for 2017 is given for the Southern zone). All data from JRC Technical Reports of the years Forest Fires in Europe, Middle East and North Africa of the years 2010 to 2022 (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). The data utilised here stems from the JRC national reports of the years 2010 until 2022, where areas are designated as forested regions. Absolute values were employed instead of relative values due to inconsistent forest area data across all countries within the dataset. Please note the different scales.

In our analysis of forest fire occurrences, we did not find significant differences between the dry period of 2018-2022 and the reference period of 2010-2014, except for Norway and Germany (Figure 4). This lack of significance was consistent across the Northern, Central, Alpine, and Southern zones. Generally, countries in the Southern zone experienced severe impacts from forest fires. For example, the damage in Sweden and France, who had the highest values of burned area in their climatic zone (5,000 and 10,000 hectares, respectively), during the period of 2018-2022 was only a fraction of that observed in Portugal during 2017.

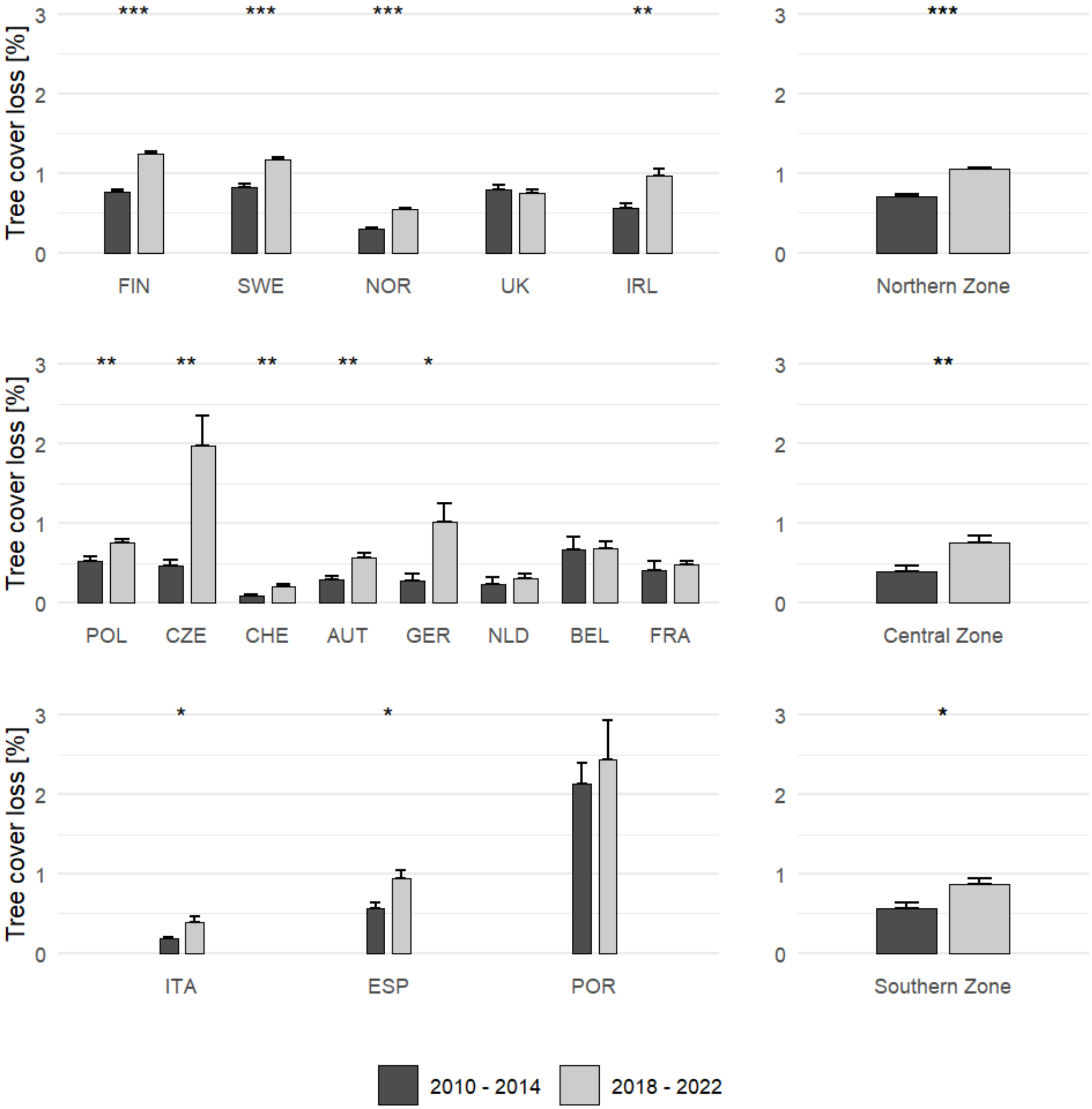


Figure 5. Relative tree cover loss (mean for the two periods under consideration); data from GlobalForestWatch.

The loss of tree cover can stem from various human and natural factors, such as forestry activities (e.g., logging or deforestation), natural occurrences (e.g., diseases or storms), and fire incidents (Figure 5). Notably, very highly significant disparities between the dry period (2018-2022) and the reference period (2010-2014) were observed in the Northern zone. Specifically, Finland, Sweden, and Norway exhibited very highly significant differences, while Ireland showed highly significant variations. Within the Central Zone, significant differences were detected between the two study periods, with Poland, the Czech Republic, Switzerland, and Austria all displaying such disparities. Additionally, significant differences were noted for Germany. Turning to the Southern zone, significant differences were evident, with Italy and Spain also showing significant differences.

3.2 Damages to forests in the Northern zone 2018-2022

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, followed by an increase in 2022 (damage levels over 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). These numbers are high for Finland, because the accumulated forest drought damage previously for years 2009-2015 were 8,700 ha (Nevalainen and Pouttu, 2017).

The areas influenced by drought and bark beetles were localised and, on an annual scale, quite small when compared to, for example, snow and moose-based damage (Nuorteva, 2019; Nuorteva et al., 2022a, 2022b; Melin et al., 2022, Terhohen et al., 2023). In Finland, the bark beetle population slightly grew between 2018-2020 and the damages increased from 12,600 ha to 21,400 ha, but slightly declined in 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 2022: from 249,000 ha to 276,300 ha (being highest in 2021: 307,100 ha) and forest damage could be influenced by the overall well-being of the trees. Additionally, the efficiency of collecting the fallen trees influences the bark beetle spread and outbreaks since they 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 damaged 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 financial losses of forest fires in Northern Karelia and the Republic of Karelia for the years 2009 to 2012. They considered 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 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 damaged (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 upscaled to 2018: 160-200 million €.

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 did not yield severe consequences for Norwegian forestry. In 2017, there was a total of 965 million m^3 of standing forest, and in 2020 this increased to 987 million m^3 (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 m^3 (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, and while concerning, these levels remain 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 occurred 1906 forest fires, a new record. 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). Favourable wind conditions meant that the total affected area was relatively small (2000 ha affected by forest fires), so the consequences were more related to costs 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 m^3 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 m^3 and 2020, ~~with~~ 1.1 million m^3 despite low prices on timber especially in 2020. In comparison, the average felling in the 2010-2014 reference period was 896.000m3/annum. To mitigate the consequences of the 2018 fires, 296,599 saplings were planted in 2019 and a further 250,000 in 2020, compared to an average planting of 131.000 in the reference period. While there were some short-term consequences, there have not been lasting negative effects of the drought in Norway so far.

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). Merely 3% of UK native woodlands are in unfavourable condition due to pests and diseases, 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 large wildfires 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 6,236 ha burned (EFFIS Annual Statistics for UK, 2023). The mean burnt area from 2011 to 2022 was 10,000 ha.

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%). The rest of the wildfires took place across all other land covers including built-up areas, gardens, and grassland. 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 from 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 in 2019 (The Herald 2021). Statistics from the Scottish Fire and Rescue Service (SFRS) show that during March and April 2022, 95 wildfire incidents (involving 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).

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 720 ha 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 broadleaves (53.4 and 52.0%; Michel et al., 2022). Furthermore, national reports about forest conditions state 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), which provides protection from pest such as the eight-toothed spruce bark beetle (*Ips typographus*), which 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).

3.3 Damages to forests in the Central zone 2018-2022

Poland has a forest area of 9,242,000 ha (Central Statistical Office, 2017). In 2018, the drought 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 many 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 more 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, 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: 58,056 ha, 2021: 34,673 ha, and 2022: 20,258 ha). Surface losses in terms of high temperatures were relatively small (burns, wilt and dieback) were (2018: 80 ha, 2019: 340 ha, 2020: 2574 ha, 2021: 197 ha, and 2022: 244 ha). Recent years have seen significant surface losses on Poland's State Forest land due to drought and high temperatures (Source: DGLP, Dyrekcja Generalna Lasów Państwowych): Drought-related losses were specified with 40,852 ha (2018), 60,356 ha (2019), 58,056 ha (2020), 34,673 ha (2021), and 20,258 ha (2022). High temperature losses (burns, wilt, dieback) ~~were~~ reported with 80 ha (2018), 340 ha (2019), 2,574 ha (2020), 197 ha (2021), and 244 ha (2022). Long-lasting drought in Poland has also led to a lowering of the surface and groundwater table, and a decrease in the growth of trees, the vitality of stands, and their resistance to pathogens and pests (Kwiatkowski et al., 2020). Among the species affected by this process are 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 (Danielewicz, 2016).

Furthermore, the prolonged drought increases the fire hazard in forests. Although the number of fires is high, the situation in Poland is relatively good. As the average forest fire in the state forests is only 0.25 ha, indicating a high efficiency of fire protection systems. 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. However, the year 2020 was marked by an extremely large fire (6,000 hectares) in the Biebrza National Park in Northeastern Poland (see Figure 3).

In the **Czech Republic**, forest disturbances, mainly by pests, were triggered by drought and higher temperatures: Near Kostelec nad Černými Lesy, studies found that bark beetle outbreaks were related to the duration of April's solar radiation in the previous year and the current year's average annual air temperature (Pirtskhalava-Karpova et al., 2024). In the Bohemian forest, it was observed that the surface temperature in stands subsequently attacked was higher in the year preceding pest colonisation when compared to intact stands (Kozhoridze et al., 2023). At the beginning of the massive bark beetle attacks, spruce accounted for 50.5% of stands, and pine for 16.4% respectively (Zahradník & Zahradníková 2019). This abundance of trees sensitive for the bark beetle led to the suggestion that the Czech Republic may have been the epicentre 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 WII; in 2019—32.5 million m³ were harvested with 22.8 million m³ of WII, and for the year 2020, the estimate is ranking between 40 and 60 million m³ of WII (Fernandez-Carrillo et al., 2020). The timber damage was almost exclusively caused by infestations with European spruce bark beetle (*Ips typographus* L.). The largest forest fire in Czech history broke out in Bohemian Switzerland in the Northern Czech Republic and spilled over into Germany. The fire affected an area of about 1,060 ha, over 1,000 firefighters, 5 helicopters and two firefighting aircraft were needed to get the fire under control (Worlds Aid 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 the 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 represents an increase of about 3-folds from 2017 to 2018 (Moravec et al., 2021). There are also clear signs of loss of vitality during the dry period in the Czech Republic (in this study 2015-2019), where growth reductions in five major species due to drought conditions were observed when compared to the reference period of 2005–2009 (Jiang et al., 2024).

In the **German** forest sector, the years 2018 until 2020 and 2022 are considered dry years (e.g. DFWR, 2021, 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 2023a). 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 did 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, outbreaks of European spruce bark beetle (*Ips typographus*) have inflicted widespread damage on forests, particularly during episodes of heat and drought. In many cases, the harvest was lost and there was a need for emergency felling 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 the primary pests being 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 specialised on weaker dimensions, which is a large-scale threat in the future regarding reforestation means or rejuvenation with conifers (TMIL 2022). 2018, 2019, and 2022 were above average 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). It is difficult to disentangle the exact costs of a big disturbance in a field like the German forestry sector, which generates about €170 billion annually and employs 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.

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 of 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 about crown defoliation. The next systematic monitoring of forests in the Netherlands has started in 2022 and will be completed in 2026.

In the northern part of **Belgium** (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, and also Norway spruce and larch trees. 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 annual inventories (Sioen et al., 2019; 2020; 2021; 2022) provide an indication of trends in vitality (e.g. loss of leaves and needles), 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.

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 m^3 of spruce were infested by bark beetles, compared to 5-10,000 m^3 in normal years. This number increased to approximately 1 million m^3 in the years 2019 and 2020 (Saintonge et al., 2021). During 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 burned (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 elevations 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 increased 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, higher defoliation rates have 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 wildfires, the situation in France in the period 2018-2022 is also exceptional. During this period, the 3 years (namely 2019, 2021 and 2022) with the largest cumulative wildfire burnt area since the start of systematic Copernicus observations in 2006 have been observed. In 2022, the largest cumulative burnt wildfire area so far was measured, with 66,393 ha, it was more than 13 times higher than the 2006-2017 average (EFFIS 2023).

3.4 Damages to forests in the Alpine zone 2018-2022

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, Northern 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 Figure 3) the wood losses were large. Overall, forest damage in Austria 2022, which is primarily caused by climate change, is estimated at around 28 million euros (Bundesforste 2023). Around 940,000 m³ wood was damaged in 2022, which corresponds to around 59% of the total amount of wood harvested in 2021. The main reason for this is an increase in bark beetle damage. 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 March 2022, a huge wildfire raged in Allentsteig in Lower Austria. With a burnt area of about 800 ha, of which 400 hectares were forested, it was one of the largest forest fires that have ever occurred in Austria (Müller 2022).

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 during 2022 in East Tyrol (cipra 2022). In Tyrol, there was a bigger 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). An EUSALP study, initiated by the Austrian ministry, highlighted that the total direct costs for firefighting and for necessary measures on burnt areas (without preventive measures) in connection with forest fires are currently estimated at around 75 million € per year in the Alpine region. (Müller et al., 2020).

In **Switzerland**, during both 2018 and 2022, the canopies of numerous beech trees had already changed colour by the end of July, with extensive areas of the forest in the Mendrisiotto region appearing brown by 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 down 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 is an increase in 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 decline of ash trees, attributed to ash dieback caused by the fungus *Hymenoscyphus fraxineus*, spread rapidly and reached the inner Alpine valleys within a few years, with East Tyrol being affected in 2010 at the latest (Heinze 2017). 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 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, while in 2022 around one million m³ were affected. 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, that burned almost 10,000 ha in a week, consuming mainly broadleaved forests (Müller et al., 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 (Müller et al., 2020).

3.5 Forest damages in the Southern zone 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 damage caused by the extra-tropical windstorm Vaia over North-eastern 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 storm 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, forest mortality and leaf discoloration in Italian forests, especially in montane conifer forests, with the peaks reached in 2021 (Bussotti et al., 2022), and leaf discoloration mainly occurring 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 was strongly 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).

In **Spain**, in the period 2018-2019, there was some recovery or stabilisation in terms of forest defoliation and discoloration following the drought of 2017 due to an increase in precipitation (AIEF 2019). However, more recent reports over parcels in North-eastern 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 dramatically 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 270,000 ha of burned area, a drastic increase from previous years amounting up to 3 to 6 times larger surface area 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 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 totalled almost 1.2 billion USD, and the local insurance sector declared it as the costliest natural disaster in the country's history with pay-outs exceeding 295 million USD (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 1.13 million ha 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 urbanisation and shifting agriculture.

4. Drought legacy

4.1. Drought legacy effects

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 up to 6 years, depending on tree species (Orwig and 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., 2017). 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 via 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). For example, Rabbel et al., (2018) showed sap flow density data for a Norway Spruce stand in the Eifel mountains, Germany, from observations in a riparian zone and nearby hillslope exhibiting shallow and deeper water table depth. In the riparian zone, the shallow routing spruce exhibited generally large evapotranspiration compared to the hillslope Thus, GW drought legacy that is manifested in increased GW table depths will impact drought legacy effects in forests 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.~~

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 publicly 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). For example, Süßel and Brüggemann (2020) studied tree water relations in 20~~2~~8 in mature oak stands in southwest Germany. They found that sites with continuous capillary rise toward the root zone maintained a canopy conductance at 50% of the maximum, while sites with hydraulic disconnection from the water table showed a collapse of conductance and significant leaf shedding. In these settings, the long-term effect of droughts 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 river 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 the 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. Preliminary inspection of LAI products from remote sensing do not show a systematic pattern at the large scale depending on topography or potential groundwater convergence zone. In future, a merger of in-situ, remotely sensed and model data with ensuing in-depth analyses ~~are~~ required in order to identify potential tree legacy effects induced by groundwater drought legacy. In this context, data from hyperspectral remote sensing on photosynthetic activity may be useful.

4.3 Drought legacy effects in forests – the accumulation of long-term damages due to soil moisture deficit

Legacy of a drought event in forests can take many forms (Müller & Bahn 2022, Rukh et al., 2023), depending on the tree demographic processes that are most affected (See Section 1.4 for more on soil moisture deficit and Rousi et al., 2023). The mortality of adult trees can create gaps in a forest, influencing the long-term profitability of an economic forest but also the carbon and water cycle and species composition. Forest gaps also increase solar radiation, temperature and dryness in the understory and the soil, which may lead to further damage caused by soil hydrophobicity aggravating soil dryness, horizontal translocation of water, nutrients and soil, and additional dryland mechanisms of ecosystem functioning (Grünzweig et al., 2022). Similarly, the mortality or diminished vitality of saplings can impede these processes, slowing down the overall recovery of the forest. Additionally, damage that does 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 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, then 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 localised 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 had 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) observe notable mortality rates among younger forest stands managed by the private sector, encompassing 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

For **conifers**, no significant differences in **defoliation** were observed in the Northern zone or within the individual countries situated in it (Figure 2). This suggests a relative stability in conifer health in this region, despite variations in environmental conditions. Conversely, the Central zone exhibited a substantial and statistically significant increase in defoliation levels during the period of 2018-2022 compared to the reference period. This discrepancy was particularly evident in the Czech Republic, Belgium, and France, where the differences were highly significant. Additionally, significant differences in defoliation were noted in Germany, indicating a widespread trend of deteriorating conifer health in this region. In the Southern zone, notable deviations during the dry period of 2018-2022 compared to the reference period were observed, with Spain also registering significant differences. Overall, our findings suggest that conifers in the Northern zone exhibit a greater resilience to drought and heat stress compared to those in other regions.

Regarding **broadleaves defoliation**, we observed a highly significant disparity in defoliation levels between the dry period of 2018-2022 and the reference period in the Central zone. This discrepancy was particularly pronounced in France, where the differences were highly significant. Additionally, significant differences in defoliation were noted in the Czech Republic and Germany, suggesting a region-wide trend of increased defoliation among broadleaved trees in response to environmental stressors such as drought and heat. These findings suggest that broadleaved trees, naturally distributed across large parts of Central Europe, are facing significant challenges due to the escalating frequency and duration of drought and heat events associated with climate change. Also in the Southern zone, similarly significant differences in defoliation were detected between the two investigated periods, with Italy showing highly significant differences and Spain registering significant differences. This indicates that broadleaved trees in the Southern zone, which are adapted to Mediterranean climates, are also susceptible to the impacts of drought and heat stress. Data for broadleaved trees in the Northern zone were not ~~applicable~~, suggesting potential limitations in data availability or species distribution in this region.

The observed severity of damaged wood caused by **insect infestation** across Central Europe during the study period of 2018-2022 compared to the reference period is of particular concern, especially in Central Europe, but also in Sweden (Figure 3). These findings align with projections indicating a significant increase in bark beetle disturbance in Europe due to climate change. Studies suggest that the level of bark beetle disturbance could increase up to sevenfold by 2030 compared to the period from 1971 to 1980 (Seidl et al., 2014). Additionally, projections for the 21st century indicate a potential twofold increase in bark beetle disturbance, contingent upon the 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 is projected to increase substantially under moderate climate change scenarios, with even greater impacts anticipated under hot and wet climate change scenarios compared to baseline conditions (Sommerfeld et al., 2020).

Contrary to expectations, we did not find significant differences in **forest fire** outbreaks between the dry period of 2018-2022 and the reference period of 2010-2014 (Figure 4). This trend is observed consistently across the Northern, Central, Alpine, and Southern zones. Also, on request to individual offices (e.g. in Austria), it was found that there were neither more fires nor larger burnt areas in the years 2018 - 2022 compared to the reference period. These findings indicate a complex interplay of factors influencing fire activity, including climatic conditions, prevention measures, forest management, awareness raising, and firefighting effectiveness, which may vary across regions. However, countries in the Southern zone experienced severe impacts from forest fires not only during the period of 2018-2022. Our decision to include data from 2017, despite not being originally part of the study design, provided insights into the significant impact of fires during that year, particularly evident in Portugal, where a vast area of forest land was affected. This emphasises the importance of considering extreme events and their implications for forest management and conservation efforts. Further research is needed to explore the underlying drivers of fire activity and develop effective strategies to mitigate the impacts of forest fires in vulnerable regions and highlights the need for effective fire management strategies. However, research in the USA has unequivocally attributed forest fires to climate change: In Northern and Central California a fivefold increase in the summer burned forest area between 1996 and 2021 compared to 1971 - 1995 was reported (Turco et al., 2023). Across the western United States, climate change and other drivers have led to a doubling of the cumulative forest fire area since 1984 (Abatzoglou and Williams, 2016). Global projections for the twenty-first century indicate that climate change heightens fire weather conditions, impacting a substantial portion of burnable land surfaces worldwide (Abatzoglou et al., 2019).

The significant disparities in **tree cover loss** observed across European regions between the dry period of 2018-2022 and the reference period of 2010-2014 highlight the complex interactions between human activities, natural phenomena, and climate change, emphasising the importance of comprehensive forest management strategies to mitigate the impacts of environmental changes on forest ecosystems (Figure 5). The escalating frequency and intensity of extreme weather events, such as storms, droughts, and wildfires, pose significant threats to forest health and resilience. However, forests are under increasing pressure, not only from climate extremes, but also from human activities such as logging, deforestation, and urbanisation. Notably, the three zones Northern, Central, and Southern experienced losses of 0.34% of forest land during the analysed period, with varying degrees of significance, underscoring the urgent need for proactive measures to address these challenges. Further research is needed to better understand the specific drivers behind these disparities and to develop targeted interventions for sustainable forest conservation and management.

In the **Northern zone**, it appears that we may be witnessing the initial stages of the impact from drought and heat. However, the severity of the situation in the Northern zone does not appear to be pronounced at present. Nonetheless, these findings emphasise the vulnerability of the Northern zone to the adverse effects of drought, underscoring the imperative for ongoing monitoring and conservation initiatives to mitigate potential future impacts. In analysing Europe-wide data, we discovered indications that the Northern zone experienced adverse effects during the drought years of 2018-2022. There was a notable increase in the proportion of moderately to severely defoliated trees by approximately 30% compared to the reference period, alongside evidence of damaged coniferous wood in Sweden. Damaged wood by insect pests in the Northern zone was only available for Sweden, with very high values in the years 2018, but especially high for 2019, 2020, and 2021. Additionally, tree cover loss increased significantly from 0.7% to more than 1%. Intriguingly, conifers did not exhibit a corresponding increase in crown defoliation. Although the burned forest area showed a slight increase during the drought period, it was not significantly different from the reference period.

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 likely to be more vulnerable to climate extremes. However, the example of Norway may make it clear that Scandinavia is probably the area where climate change has had 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 during 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 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.

Differences in 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 in the British Isles, the amount of damage was not exceptional during the investigation period. 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 clearly noticeable for forest visitors: 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 an improvement of tree growth due to a warmer climate 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. However, a breeding population of European spruce bark beetle (*Ips typographus*) has now become established in South-east England probably arriving by flight across the English Channel following a large-scale dispersal from continental Europe due to extreme weather in 2021-2022 (Inward et al., 2024). This poses a future threat to the spruce in the UK, which is the dominant timber species. 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 higher (Turner et al., 2021).

The observation of harm that are clearly due to rising temperatures and drought in the **Central zone**, make it evident that these forests are facing significant impacts and challenges. The severity of the situation in the Central zone is underscored by pronounced increases in crown defoliation observed in both coniferous and broadleaved trees, alongside an extraordinary rise in bark beetle-infested wood and an overall increase in tree cover loss. These findings paint a concerning picture for the Central zone's forest resilience, highlighting the vulnerability of its forests to climatic stressors. The cumulative effects of rising temperatures and prolonged drought periods have evidently taken a toll on the forest ecosystems in 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 the Central European forested area. The most affected forests were in Central and East Germany, and in the Czech Republic (Brun et al., 2020). The drought and heat of 2018 were the prerequisites for the forest damage caused in Central Europe in the period 2019-2020, while the main driver was an above-average water vapour pressure deficit (Senf and Seidl, 2021a). The low soil moisture content in 2018 and the higher-than-normal water vapour 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, the Czech Republic and Austria (Senf et al., 2021). The main cause for tree mortality in 2018 is likely due to physiological damage as 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 the temperate forest regions were negatively affected, and forest greenness decreased more strongly than any other summer since 2002 by breaking the former record drought in 2018 (Hermann et al., 2023, Buras et al., 2023). These observations of changes in forest greenness are based on satellite-derived Normalised 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 were important, but also the species composition of the affected stands, with Norwegian spruce monocultures being particularly vulnerable.

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 destabilisation of the remaining and neighbouring stands, the fall in market prices, or the heat effect on forest workers and machines is extremely difficult to quantify.

In addition to the drought, storms need still be considered. Currently, one cannot necessarily determine that the storms in Germany are increasing substantially, but, for example, the damage caused by windthrow increased remarkably in 2018-2022 (BMEL 2023a). In addition to various silvicultural reasons, there is a development in Germany towards less severe winters and an increase in precipitation outside the growing season (UBA 2015). Heavy or prolonged rainfall can result in roots not being able to hold onto the soil sufficiently to withstand strong winds. At the same time, stands weakened by drought are also significantly more vulnerable to strong winds.

Regarding the **Alpine zone**, it must be noted that accessing data was particularly challenging. We were unable to precisely identify which datasets specifically pertained to Alpine areas. Concerning fires in Alpine forests, we could only obtain data from Austria and Switzerland for both periods, where we did not observe any significant differences. Based on this research, we did not observe a significant increase in the impacts of drought and heat in the Alps during the period of 2018-2022. But it should be noted that mountain forests are particularly under pressure from climate change impacts due to their temperature limitation and high exposure to warming (Albrich et al., 2020). Such impacts can vary greatly with elevation and topography (e.g. Lindner et al., 2010, Thrippleton et al., 2020) and require a careful study addressing the target species and the abiotic conditions. The 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) and sensitive to drought stress. Additionally, drought can also destabilise mountain forests and result in soil erosion, landslides, and rock-falls. 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 strong impact on biodiversity (Eriksen & Hauri 2021). Since the length of the growing season decreases with altitude, a warmer climate could also lead to more growth so 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 lines will shift upwards over a longer period and tree species from the lowlands will establish at higher altitudes. A simulation of 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 (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 categorised as agriculture and public water supply, while impacts on forestry and terrestrial ecosystems were less mentioned. According to that study, drought impacts occur mostly in summer and early autumn, likely due to snowmelt in spring, which mitigates water shortages. At the same time, that study also observed a spatial heterogeneity across the Alps with, surprisingly, 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 and that those countries have an improved handling of forest fires.

Fire is one of the major natural disturbances 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 danger of forest fires in Alpine regions, it is not so easy to identify such a pattern, because each Alpine country has its own forest fire documentation system with different attributes, criteria, and accuracies (Müller et al., 2020). According to the values compiled for this review for the period 2018 to 2022, it does not appear that the occurrence of forest fires in the Alps are very different from the long-term average (Table 3).

A supra-regional body would be required to unify the different data sources for 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.

Observing the obvious damage attributed to increasing temperatures and drought conditions in the **Southern zone**, it becomes apparent that forests are encountering significant repercussions. The gravity of the situation in the Southern zone is accentuated by marked increases in crown defoliation, particularly noticeable in broadleaved trees. While data on damage caused by wood-boring insects are unavailable, it suggests that insect pests might not pose a major threat during the investigated drought years from 2018 to 2022. Nevertheless, there is a significant increase in tree cover loss compared to the reference period. Assessing the incidence of wildfires, it's not possible to assert that the situation worsened significantly during the period of 2018-2022. However, the exceptionally severe year of 2017, particularly in Portugal, with staggering losses, necessitates its inclusion in this study. The devastation caused by wildfires presents a challenge for Southern Europe. However, wildfires are also generally part of the South-western 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, over the period 2018-2019, there was even some recovery in forest health in Spain which contrasts with the larger levels of damage recorded across Europe, in particular in Central Europe, which experienced both drier conditions and larger levels of vegetation damage (AIEF 2019, ESOTC 2019).

The situation for Maritime pine (*Pinus pinaster*, one of the most common species) in Iberia is according to Kurz-Besson et al., (2016) ~~is~~ not completely discouraging. According to Kurz-Besson et al., (2016), wood radial growth and density highly benefit from the strong decrease 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 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. Since the particularly 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 high fire danger. Larger fires have slowed since 2017. Fires with a burnt area of more than 1,000 ha reduced from an average of 19 events to 8 in more recent years. Although forest losses are decreasing in the last period, Portugal has seen an increasing trend in forest loss due to fires between 2001 and 2019 (Tyukavina et al., 2022). Fires occurring from recent forest loss due to other drivers were excluded, e.g. burning of felled logs following mechanical canopy removal, which is common in slash-and-burn agriculture and large-scale deforestation. In this sense, the decrease in fire events may not have been so obvious without the unique events of 2017, indicating the difficulties of interpreting long term trends of damage.

6. Outlook

6.1 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. Furthermore, extreme levels of compound heat and drought stress are projected to occur successively year after year with much higher likelihoods in the next few decades compared to recent years (Suarez-Gutierrez et al., 2023). 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 heat waves. 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 increasingly strongly 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 windthrow, fires and insect outbreaks (Forzieri et al., 2021, Patacca et al., 2023).

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 disturbance 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 seen as important measures to mitigate climate extremes. Changes in forest cover due to land use and 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 as the exchange of energy, momentum and water, and 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, and therefore 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). The first regional climate model (RCM) ensemble experiments in the frame of the CORDEX Flagship Pilot Study (LUCAS) investigated 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 the day and warmer summer surface temperatures during the 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) investigated 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 not all the models show this trend. In addition, paired FLUXNET sites were investigated to compare the simulated results with observations. In line with models, observations indicate a summer ground cooling in forested areas when compared to open areas.

While most models align with the observed reduction in the annual amplitude of soil temperature, there is notable variability in the magnitude of these changes. Addressing the broader climatic implications, Daloz et al., (2022) specifically examined the snow-albedo effect of FPS LUCAS RCMs in sub-polar and alpine climates. Additionally, Mooney et al., (2022) explored FPS LUCAS simulations in the context of extreme forest cover changes. The findings from these studies collectively indicate that re-/afforestation plays a role in diminishing the snow-albedo sensitivity index, thereby contributing to enhanced 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 from 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.

Trees and forests may adapt to a hotter and drier climate, inter alia, by mechanisms currently predominant in drylands (Grünzweig et al., 2022). By 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). Non-rainfall water, such as dew and fog are also a source of moisture, whereby trees absorb water through leaves and bark, thus alleviating drought-stress and enabling humidity-enhanced biotic activity (Earles et al., 2016, Wang et al., 2017). In addition, heat stress in forests can be mitigated by lowering the aerodynamic resistance of heat transfer from trees to the surrounding air, a mechanism termed the canopy convector effect (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 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). These pathways of adaptation may diminish or even prevent damage caused by water scarcity and high temperatures.

6.2 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 complex 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. More dramatic consequences are likely given that multiple risk factors for political instability will increase as a consequence, e.g. wildfires, plant and human mortality, crop failure, or famine. The recent extreme events like the drought and heat wave in Central Europe in 2018 (e.g. Rousi et al., 2023) 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 society to face such extraordinary events is insufficient. This is the case for the forecasting capacities, including impact modelling chains, in which several agencies are typically involved and currently often lead to inefficient and late warning for civil protection and for the population at large. Moreover, it has become clear from 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 information accessibility for the public, e.g., on how to 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 extreme heat and drought are expected ~~to~~ not only to be more extreme but also to affect our region for a longer period of the year (e.g. Hundhausen et al., 2023) and to occur more frequently over successive years (Suarez-Gutierrez et al., 2023). In fact, some parts of Europe like the Iberian Peninsula may be by 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 tailored forecasts products for the civil protection, public agencies, and the 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 the adequate communication of information and political measures, as this was often an issue in the past. Existing language barriers and accessibility of information must be overcome, leading to a raised awareness in the population of the severe impacts of drought and heat on our livelihoods under current and future climate conditions.

6.3 Issues due to 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 were available at the time only until 2020 (AIEF, 2020). Initially, a description of the damage due to heat and drought to grassland was also planned. However, the data availability regarding grassland is very limited, although this is the second large-scale non-irrigated ecosystem providing many ecosystem services that are important for our well-being.

A uniform data collection that is accessible across languages would be valuable considering 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.

6.4 Conclusions

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 mitigate this damage. The extent to which we comprehend the damage already incurred can guide us in making informed decisions for the future, whether in selecting appropriate tree species or implementing effective management techniques. But mitigating this damage caused by heat and drought in forests requires a multi-faceted approach that includes forest management and monitoring 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 vigour, 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 damage. Finally, global efforts to mitigate climate change by reducing greenhouse gas emissions are essential because this is the root cause of heat and drought impacts on forests.

Competing interests: At least one of the co-authors is a member of the editorial board of Natural Hazards and Earth System Sciences.

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