Impacts and damages to European forests from the 2018-2022 heat and drought events

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Abstract

Drought and heat events in Europe are becoming increasingly frequent due to human-induced climate change, impacting both human well-being and ecosystem functioning. The intensity and effects of these events vary across the continent, making it crucial for decision-makers to understand spatial variability in drought impacts. Data on drought-related damage are currently dispersed across scientific publications, government reports, and media outlets. This study consolidates data on drought and heat damages in European forests from 2018 to 2022, using Europe-wide datasets including crown defoliation, insect damage, burnt forest areas, and tree cover loss. The data, covering 16 European countries, were analysed across four regions: Northern, Central, Alpine, and Southern, and compared with a reference period from 2010 to 2014.

Findings reveal that forests in all zones experienced reduced vitality due to drought and elevated temperatures, with varying severity. Central Europe showed the highest vulnerability, impacting both coniferous and deciduous trees. The Southern zone, while affected by tree cover loss, demonstrated greater resilience, likely due to historical drought exposure. The Northern zone is experiencing emerging impacts with less severity, possibly due to site-adapted boreal species, while the Alpine zone showed minimal impact, suggesting a protective effect of altitude.

Key trends include: (1) Significant tree cover loss in the Northern, Central, and Southern zones; (2) High damage levels despite 2021 being an average year, indicating lasting effects from previous years; (3) Notable challenges in the Central zone and Sweden due to bark beetle infestations; and (4) No increase in wildfire severity in Southern Europe despite ongoing challenges.

Based on this assessment, we conclude that: (i) European forests are highly vulnerable to drought and heat, with even resilient ecosystems at risk of severe damage; (ii) tailored strategies are essential to mitigate climate change impacts on European forests, incorporating regional differences in forest damage and resilience; and (iii) effective management requires harmonised data collection and enhanced monitoring to address future challenges comprehensively.

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 (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 human 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 events. 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 study we present the impacts documented in European forests during the years 2018-2022, among the warmest and driest on record over Europe (Figure 1). We focus on forest ecosystems to reduce the risk of bias that could arise from variations in irrigation practices, allowing us to better observe the effects of climate extremes. Furthermore, forests are essential to our livelihoods, they provide wood as a renewable raw material and offer a range of vital ecosystem services. For example, forests contribute significantly to maintaining biodiversity, sequestering carbon, mitigating climate change, preventing land degradation, and offering recreational value (e.g. 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 study refer to political boundaries (at country-level), we assigned those sources to the most appropriate geographical zone. An exception was made for countries that fall within two zones, as they partly overlap with the Alpine zone (see Table 1). The Alpine zone is defined according to the Alpine Space Program 2021-2027 (https://www.alpine-space.eu/).

The evaluation of the extraordinarily intense drought and heat events between 2018 and 2022, along with their impacts, were derived using an interdisciplinary approach 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 prior to 2018 to provide a better context for our focal period 2018-2022. Following this, we focus on the heat and drought impacts on forests and its legacy effects. We collected the damage estimates from research papers, reports, and even media coverage when no other source was available. We focus our assessment on damage caused by drought and heat that induced (i) physiological stress, (ii) insect pests, and (iii) fire events, as these are the three impacts most well-documented in our sources.

The data sources often posed issues and challenges. Concerning fire events, we focus on forest fires, which are defined as uncontrolled fires occurring in areas that are at least partly forested. However, for some countries, only statistics on all-vegetation and uncontrolled wildfires were available. Additionally, the online data from the European Forest Fire Information System (EFFIS) provides information on the number of wildfires and the total affected vegetation area. To resolve these issues, we used data on forest fires (when available) and clearly indicated when the information pertains to wildfires. Although this study examines forest damage spanning 2018-2022, the exceptional forest fire damage of 2017 in Southern Europe was also included to provide context for subsequent damage. Post-2017, significant management measures were implemented in Southern Europe to mitigate forest fires, affecting subsequent damage trends (e.g. REA, 2024). Forest damage in 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, we considered a reference period spanning five years from 2010 to 2014. Year 2015 was regarded as an extraordinary drought year in Europe (e.g. Hoy et al., 2017, Laaha et al., 2017), and thus not included in our reference period. Compared to other periods in the current millennium, years between 2010 and 2014 were characterised by fewer climate extremes, large scale droughts or severe floods. For example, in Germany, the water balance levels show only small deviations from the climatological mean during that period (*cf.* DWD Dokumentation SPEI). The period 2010-2014 experienced below-average to average annual mean temperatures across Europe, relative to the 1991-2020 average, particularly in the years 2010, 2012, and 2013 (IMKTRO 2023a; IMKTRO, 2023b; EC-JRC Drought Reports (2024)). Moreover, damage data availability was sufficiently available for the period 2010-2014.

Countries were selected based on exposure to heat and drought during 2018-2022, as well as on data availability and language barriers (Table 1). Therefore, out of the 44 European countries (UN 2024), 28 countries could not be included in this study (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 extensively across Europe over several months 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: The four climate zones and associated 16 countries in this study. The countries of the Alpine zone were 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)

Physiological stress indicators, specifically crown defoliation data segregated into conifers and broadleaves, were sourced from ICP Technical reports (http://icp-forests.net/page/icp-forests-technical-report). Insect pest data was gathered by analysing wood damage from reliable sources, including statistics, government reports, and scientific publications. Forest fire data were derived from the EC-JRC Technical reports (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). To broaden our understanding, we incorporated tree cover loss (TCL) 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 (Supplement Table 1). In the following sections, we take a closer look at the climatic situation during the five critical years 2018-2022 in four European zones (Northern, Central, Alpine, and Southern).

2. Meteorological conditions

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

Persistent drought conditions characterised the spring and summer seasons during 2018-2022 across Europe as shown by the Standardised Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2012, 2013, Beguería et al., 2013) (Figure 1). These prolonged droughts co-occurred in cases with hot conditions across large parts of Europe (Xoplaki et al., 2023), and were linked to strong atmospheric blocking conditions over Europe, characterised by persistent high-pressure anticyclonic systems. A persistent positive North Atlantic Oscillation (NAO) was found before the heatwave (Drouard et al., 2019; Li et al., 2020). This pattern was further associated with a double jet stream configuration and two high-speed wind currents in the upper atmosphere that influenced the intensity and persistence of atmospheric conditions in the inter-jet region (Rousi et al., 2023).

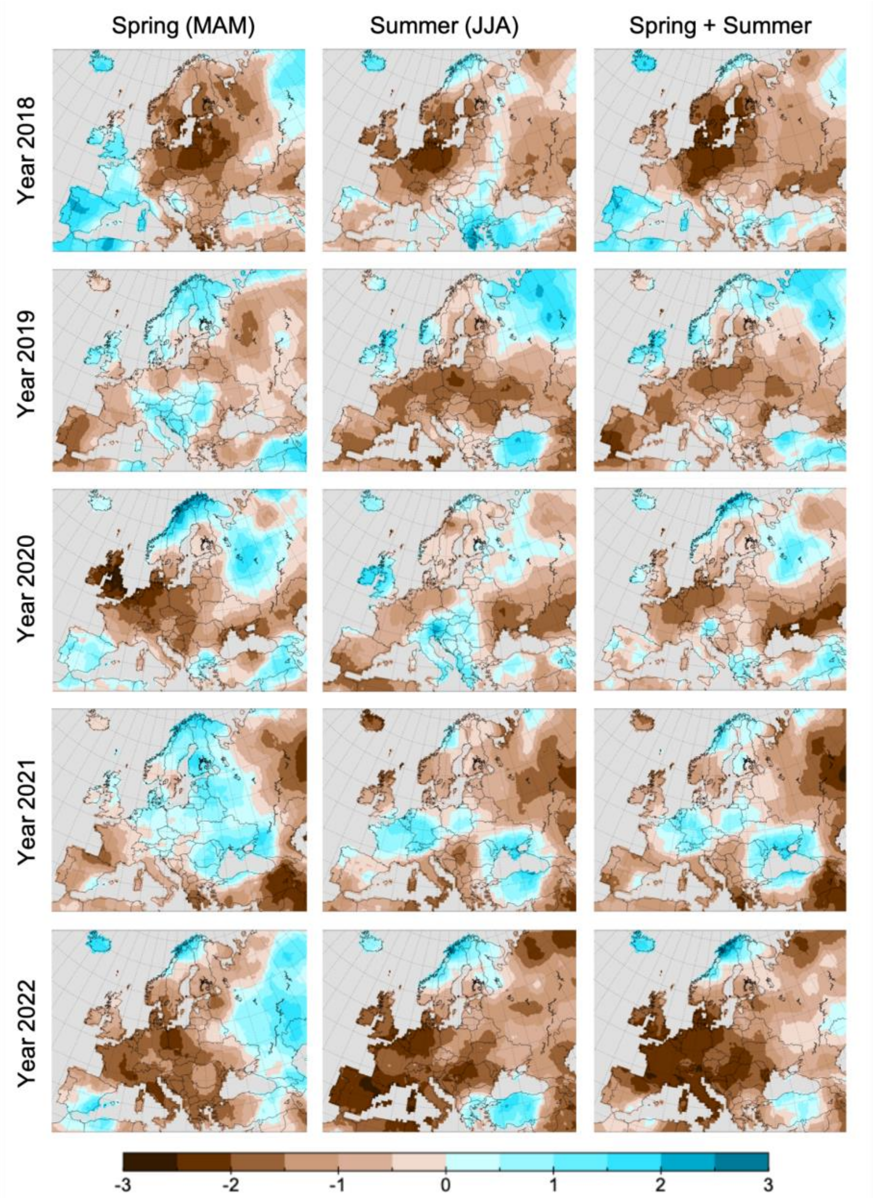


Figure 1. SPEI (Standardized Precipitation Evaporation Index) for spring (MAM - March to May), summer (JJA - June to August) and the entire growing season (March to August) during the 2018 (top row) to 2022 period (bottom row). SPEI results are shown in units of standard deviation from the long-term mean of the standardised distribution. Window length for MAM and JJA is 3 months and 6 months for Spring + Summer.

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).

Hari et al. (2020) use pattern climatology data for Europe and long-term observations to claim that the consecutive droughts of 2018 and 2019 were unprecedented in the last 250 years. Adding 2020 in the 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. The authors identified the 2018–2020 drought event having an unprecedented intensity that persisted for more than 2 years, exhibiting a mean aerial coverage of 35.6% of Europe.

Following the 2018-2020 extreme drought years, 2021 marked a rather normal to wet year. However, persistent hot and dry conditions prevailed during spring and summer 2022, which led to depleted soil water levels (similar to 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 experienced 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

From 2018 to 2022, **Finland** experienced a series of unusually warm and dry years. In 2018, prolonged heat and record-low rainfall caused significant groundwater depletion, algal blooms, fish and mussel deaths, and a 20% crop yield reduction (Veijalainen et al., 2019; Winland-project Policy Brief VII, 2019). Groundwater levels remained low in 2019, with Central and Eastern Finland experiencing the worst dryness since 1955 (Ilmastokatsaus, 2019). The year 2020 saw record-breaking warmth and rainfall, particularly in Southern and Central Finland (Ilmastokatsaus, 2020). June and July of 2021 were exceptionally hot and dry (Ilmastokatsaus, 2021). In 2022, summer temperatures were nearly 2°C above normal, with varying rainfall patterns across the country (Ilmastokatsaus, 2022).

Sweden experienced dry years in 2016 and 2017, particularly in Southern Sweden where streamflow was 28% below normal, prompting local water use restrictions (Geological Survey of Sweden, 2017). This drought persisted and peaked in 2018, leading to the most severe wildfires in modern Swedish history (Swedish Board of Agriculture, 2019; Teutschbein et al., 2022 a, b). Current climate conditions made such fires approximately 10% more likely compared to pre-industrial times (Krikken et al., 2021). Drought conditions eased in subsequent years, with slightly drier conditions returning in 2022 (SMHI, 2023).

Norway experienced significant droughts from 2018 to 2022. In spring and summer 2018, temperatures were up to 4.7°C above normal, and precipitation from May to September was only 18-46% of the 1991-2020 average (Norwegian Center for Climate Services, 2023). This year marked the longest drought period in five years of study. The years 2021 and 2022 were also dry, with 83% and 84% of average annual precipitation, respectively, and August 2021 being the driest month (Norwegian

Center for Climate Services, 2023). Ground-water (GW) levels below the tree line dropped to 75% of average in southeastern Norway in August 2018 and August 2022, impacting agricultural production (NVE, 2023). Climate models predict more concentrated precipitation, leading to floods in early spring and some summer days, followed by droughts in late spring to summer (Hanssen-Bauer et al., 2017).

In 2018, the **United Kingdom (UK)** experienced combined heatwaves and droughts (Holman et al., 2021). This extended into late 2018 and 2019 in some areas (Turner et al., 2021). From June 2019 to February 2020, humid conditions caused harmful floods (Sefton et al., 2021). The year 2020 saw a hot, dry spring followed by a wet summer (Kendon et al., 2021). In 2021, temperatures and rainfall were slightly below the long-term average (Met Office, 2021). In 2022, the UK recorded its first annual average temperature exceeding 10°C, while total rainfall remained below average (Met Office, 2022; Royal Meteorological Society, 2023). The areas of Coningsby and Lincolnshire recorded temperatures over 40°C for the first time in UK history (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 relatively few natural water resources compared to the rest of central/eastern? Europe (Ministry of Climate and Environment, 2023; SUSZA, 2023). Almost 40% of Poland's arable and forested land is permanently threatened by drought (Polish Supreme Chamber of Control, 2021). Drought impacts Polish agriculture approximately every five years, but recently it has affected large areas nearly annually, including 2015, 2016, 2018, 2019, and 2020. In 2018, severe soil drought resulted in over 50 days of no plant-available water in regions like Wielkopolska and Kujawy (Wawrzoniak et al., 2019). Soil droughts have also been observed in extensive forested areas in recent years (Lech et al., 2021).

The 2018 severe drought centred over southwest **Germany**, the **Benelux countries**, and northeastern **France**. The 2019 drought shifted east, impacting Eastern Germany and neighbouring countries. Although the 2019 drought was not exceptionally severe, consecutive drought years exacerbated the water deficits in Germany (soil moisture impacts, Xoplaki et al., 2023) and France. GRACE data indicated severe drought conditions in western Germany in autumn 2018, shifting to Eastern Germany and Poland in summer 2019 (Boergens et al., 2020). Germany and France, excluding Southern Germany, experienced continued drought until late summer 2020. Summer 2021 saw heavy precipitation and a severe flooding event in Central Europe (Mohr et al., 2023). In 2022, extreme drought conditions affected Germany and France due to low precipitation amounts, and occurrence of early heatwaves in May and June. Drought-affected areas in Germany reached 40% of the country in 2022, followed by 30% in 2019, 19% in 2018, and 16% in 2020.

2.4 Drought and heat in the Alpine zone 2018-2022

In 2018, **Switzerland** experienced the fourth warmest spring and third warmest summer since instrumental measurements began in 1864 (Bader et al., 2019). Summer 2018 received only 70% of the long-term mean precipitation (1981–2010), though above-normal winter rainfall helped mitigate the summer's worst impacts. From 2019 to 2021, frequent summer heat episodes occurred, with normal winter precipitation. However, winter 2021/2022 saw anomalously warm and dry conditions, especially in Southern Switzerland and Northern Italy. Summer 2022 had record-breaking temperatures, with July being one of the hottest months since 1864, and low rainfall led to record-low levels in many lakes in Eastern and Central Switzerland.

Austria, despite its generally water-rich Alpine areas, faced exceptional heat and drought in 2018 and 2022, raising concerns about water availability (Stelzl et al., 2021). A significant decline in snow depth in the Alpine region, that could balance the increased summer evaporative demand, exacerbated these impacts (Matiu et al., 2021). The summer of 2019 was less dry but record-breakingly hot (Olefs et al., 2021). Summer 2022, the fourth warmest on record, followed a dry and mild winter, and while rainfall events occurred, they were too heavy to alleviate drought conditions due to the high runoff (GeoSphere Austria, 2024).

2.5 Drought and heat in the Southern zone 2018-2022

Italy experienced less impact from the 2018 drought compared to Central and Northern Europe, with no significant soil moisture anomalies or forest disturbances reported (Senf & Seidl, 2021a).

However, drought conditions persisted into the summers of 2021 and 2022 (Toreti et al., 2022a), exacerbated by a winter rainfall deficit (Toreti et al., 2022b; Bonaldo et al., 2023). The year 2022 was particularly extreme, characterised by nine consecutive months almost without precipitation, leading to the desiccation of the Po River (Montanari et al., 2023). The winter of 2022/2023 remained relatively dry (Toreti et al., 2023).

In **Spain**, precipitation in the 2020/2021 water year was 5% below normal. From October 2021 to early March 2022, accumulated rainfall was 38.2% below average (BOE, 2022). As of early March 2022, the peninsular water reserve was 40.5%, markedly below the 5-year average of 52.5% and the 10-year average of 60.8%. The water reservoir system, designed to manage demand during dry periods using reserves from wetter years, has been strained by consecutive years of below-average precipitation since 2012/2013, except for 2017/2018. The 2021/2022 hydrological year was among the three driest on record, with precipitation 25% below average and reservoir levels at 35%, the lowest in 27 years (Greenpeace, 2022).

Over the past 20 years, mainland **Portugal** has experienced significant drought, with 6 of the 10 driest years occurring post-2000, including 2017-2018, 2019, and 2021/2022. The 2021/2022 hydrological year recorded 488.3 mm of precipitation; a deficit of 393.8 mm compared to the 1971-2000 average. It ranks as the 3rd driest year since 1944/1945, following 2004/2005 (APA, 2023). From 2018 to 2020, drought in Portugal was less severe, predominantly affecting the southern regions (Figure 1). During 2019/2020, drought conditions were more pronounced, with five of eleven hydrographic basins showing negative monthly storage deviations throughout the year. The 2020/2021 year saw four basins with below-average storage levels (APA, 2023).

2.6 European droughts from past to future: an attribution challenge

A long-term drying trend has been observed in Central and Southern Europe in recent years, with climate simulations projecting these trends to continue (Stagge et al., 2017; Ukkola et al., 2020; Bakke et al., 2023). There is high confidence that temperature increases, and precipitation decreases have already led to increased aridity in the Mediterranean region (IPCC, 2021a). According to the latest IPCC report (IPCC, 2021b), this combined warming and drying trend is attributable to human causes. This trend is less clear in Western and Central Europe, but there is high confidence in decreased aridity in response to increased precipitation in Northern Europe (IPCC, 2021a). However, Christidis and Stott (2021) found increased drought risk in France and Germany based on summer SPEI trends between 1950-2018. South-eastern Europe is also affected, following an analysis based on rainfall and precipitation-minus-potential evapotranspiration (P-PET) reanalysis data (Christidis and Stott, 2021). Longer-term SPEI trends (1902-2020) indicate drying hotspots in Spain, Portugal, Southern France, Italy, Eastern Germany, the Czech Republic, Poland, Hungary, Slovenia, and Croatia (Ionita et al., 2021a). Changes in large-scale atmospheric circulation in the North Atlantic region may be linked to these drying conditions (Ionita et al., 2022) and possibly to the slowdown of the Atlantic Meridional Overturning Circulation (AMOC; Caesar et al., 2018). The extent to which these trends are attributable to anthropogenic impact remains a question.

Two approaches have been widely used to address this question: i) the paleo-climatic perspective based on proxy data and ii) longer-term climate model projections. Büntgen et al. (2021) found that recent drought extremes (2015-2018) are unprecedented over the past 2,000 years in the Czech Republic and neighbouring regions, while Ionita et al. (2021b) suggest that mega-droughts during the 15th and late 18th/early 19th centuries were longer and more severe in Europe. Despite differences in methods and regions studied, these findings highlight the challenge of drawing definitive conclusions about current drought intensity in a historical context.

Climate model projections based on the latest CMIP6 assessment confirm historical trends observed in drought conditions. According to the IPCC (2021b), rainfall deficits are expected to be most pronounced during the summer by the end of the 21st century in Central and Southern Europe. While increased winter and spring precipitation may offset some summer water deficits (i.e. a negative hydrological balance), this is unlikely for France, Germany, and the Mediterranean region. Trends in evapotranspiration, already negative annually, are projected to worsen in summer. Annual mean rainfall changes are not informative for drought attribution, as drought and heavy precipitation events can occur in the same season, creating adverse conditions for agriculture and forestry despite balanced mean rainfall.

Meteorological drought conditions are likely to become more frequent under current climate projections (Mömken et al., 2022). The current series of extreme drought years is likely a precursor to a new normal in Europe. These projections apply to transient warming conditions; if carbon emissions cease, the climate will transition to an equilibrium warming phase, reducing the land-ocean temperature contrast and potentially altering the drying trend (Byrne and O'Gorman, 2013; Dittus et al., 2024).

Attribution studies of individual extreme drought events are complex due to the low signal-to-noise ratio. While heat waves are easily attributed to anthropogenic climate change (Vogel et al., 2019; IPCC, 2021a), drought events remain challenging to attribute robustly. Van der Wiel et al. (2022) found that droughts like those from 2018-2020 are within the realm of current climate possibilities, with the signal emerging from natural variability over time, impacting biodiversity and human health.

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). Human influence on the increased likelihood of Central European droughts could only be detected when using the largest possible forcing difference in CMIP5 models. 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 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, Salomón 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 together with 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). As a consequence, reduced forest cover can exert a negative (buffering) feedback on climate change impacts by decreasing the aerodynamic resistance of heat transfer from trees to the surrounding air. The reduced resistance increases sensible heat flux, decreases forest temperature, and enhances water savings because of a reduced need for cooling by transpiration (Rotenberg and Yakir, 2010, Banerjee et al., 2017). For example, during the 2003 extreme heatwave in Central and Western Europe, surface temperatures rose less in forests than in non-forested areas, allowing forests to conserve water (Teuling et al., 2010). This “canopy convector effect” is an adaptation mechanism, which can prevent long-term amplification of the consequences of extreme heat and drought (Grünzweig et al., 2022). 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, making their quantification challenging.

At the same time, other processes like outbreaks of forest pests can co-occur and follow droughts. Resin release plays a pivotal role in the resistance of conifers to bark beetles (Morcillo et al., 2019). However, resin production is very costly in terms of available resources and strongly linked to tree vigour and water availability (Zas et al., 2020). But 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 given their response to the heat stress (Sire et al., 2022).

Heat and drought 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., 2013), and the cultural and recreational qualities of forests can suffer (Winkel et al., 2022).

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 (Liebhold et al., 2017), and drought can disrupt these complex ecosystems (Krumm et al., 2020, Vicente-Serrano et al., 2020). 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. Many recent publications discuss the impact of drought and heat on forest carbon balances, a critical aspect that could not be specifically addressed within this study; relevant information can be found e.g. at Peters 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 increased significantly across much of Europe in 2018, particularly in Central and Eastern regions, and remained above average in both 2019 and 2020 (Senf & Seidl., 2021a). However, there are opportunities to better understand the damage and to mitigate future harm.

3.1. Europe-wide damages to forests 2018-2022

The Central zone exhibited the most significant impacts and damage between 2018 and 2022, showing high or very high significance in crown thinning, pest outbreaks, and TCL compared to the reference period (Figure 2). In the Southern zone, while still affected, the extent of damage was less pronounced, though significant differences in crown thinning and TCL were observed. The Northern zone experienced highly significant TCL. In the Alpine zone, no statistically significant differences were detected. Additionally, across all zones, there were no significant differences in damage caused by wildfires.

A pairwise t-test comparing the averages 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 TCL, 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.

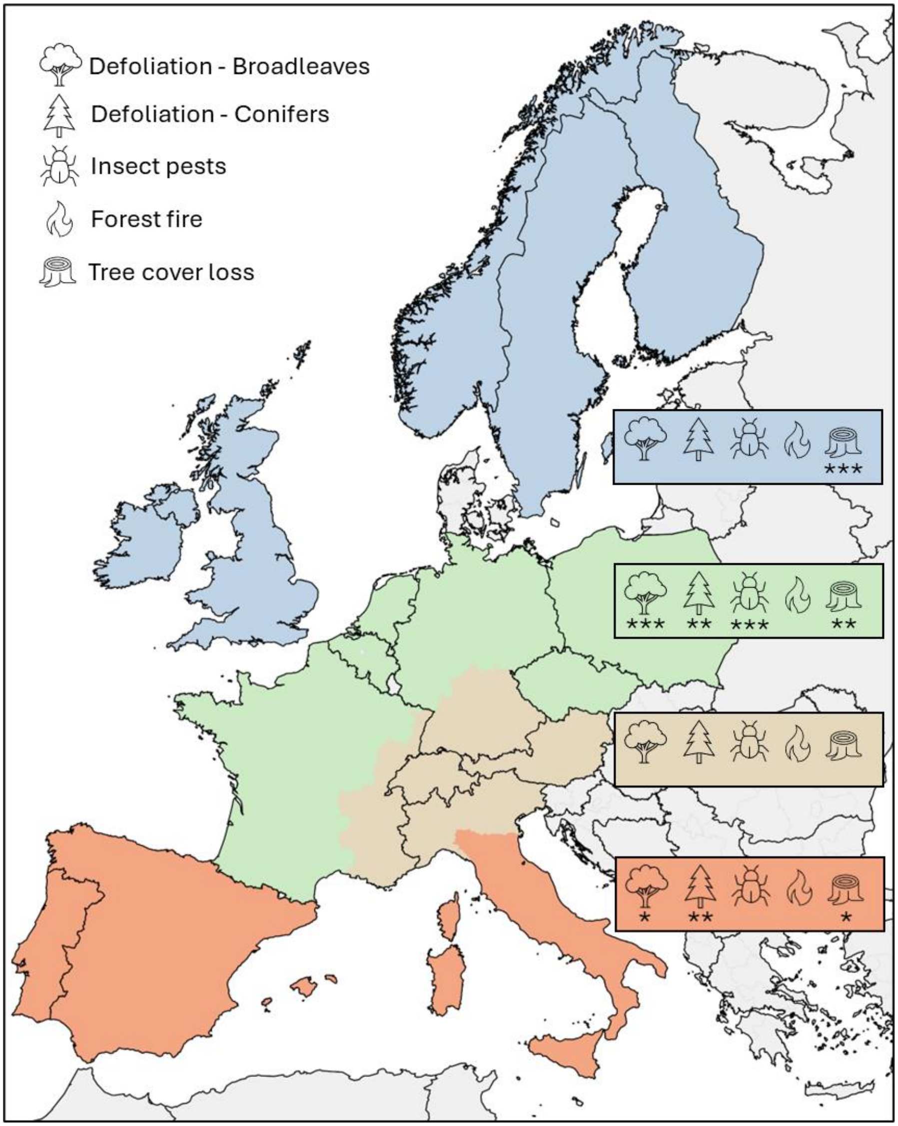


Figure 2: Differences in impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period (2018-2022) and the reference period (2010-2014). * significant ($p<0.05$), ** highly significant ($p<0.01$), *** very highly significant ($p<0.001$). Map created with mapchart.net.

Significant differences were observed across the 16 countries (Figure 3). In the Central zone, coniferous trees showed highly significant crown thinning in the Czech Republic, Belgium, and France, while significant effects were observed in Germany (see Figure 4 for more detailed results). For deciduous trees, France exhibited highly significant crown thinning, while Germany and the Czech Republic showed significant effects. In the Southern zone, deciduous trees in Italy were highly significantly affected, and in Spain conifers were highly significantly and broadleaves were significantly affected. In the Northern zone, no increased crown thinning was observed during the drought period in individual countries. However, a particularly high incidence of wood damage due to pest infestation was found in the Central zone, which was highly significant in the Czech Republic, Switzerland, Austria, and Germany (see Figure 5 for detailed results). An increase in wildfires during the drought period was only observed in Norway and Germany, where the affected area was significantly higher during 2018-2022 (see Figure 6 for detailed results). TCL was most significant in Finland, Sweden, and Norway, with Ireland also showing highly significant impacts (see Figure 7 for detailed results). In the central zone, Poland, the Czech Republic, Switzerland, and Austria were highly significantly affected, with Germany showing significant effects. In the Southern zone, Italy and Spain were significantly affected by TCL. No significant differences in impacts were found for the United Kingdom, the Netherlands, and Portugal.

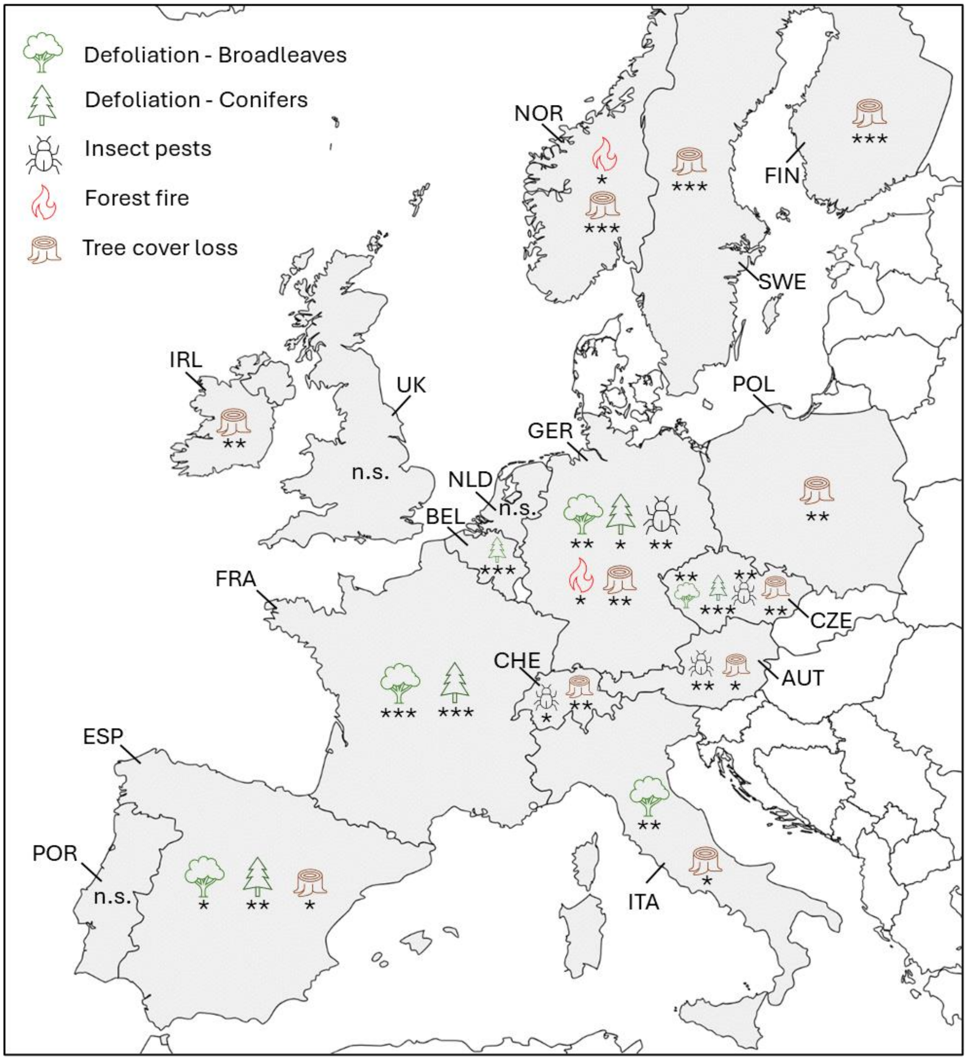
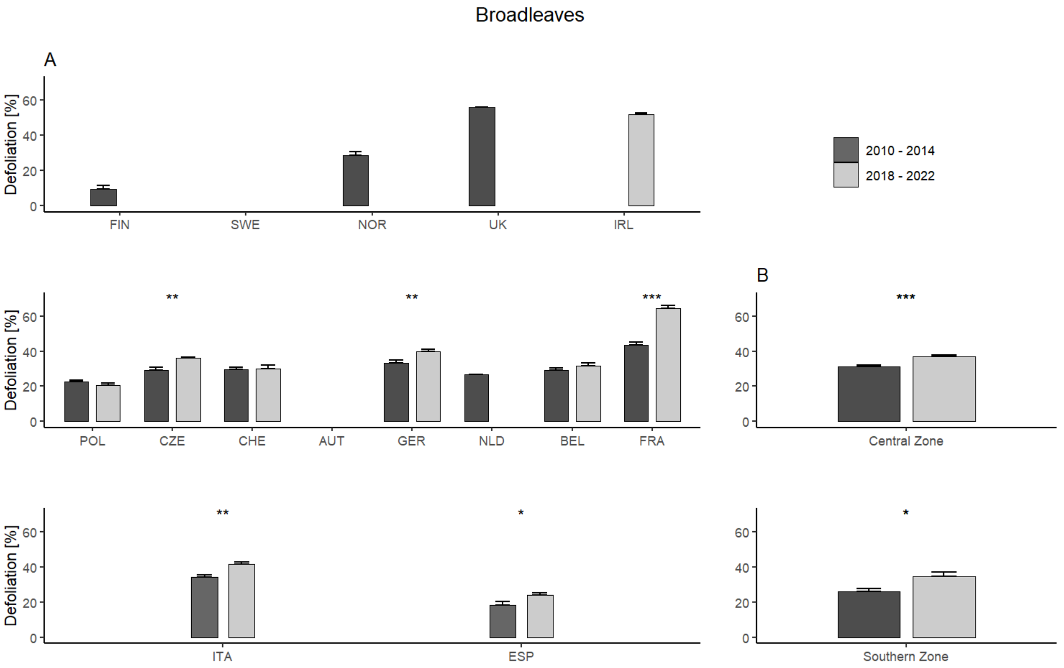


Figure 3: Significant differences in the 16 countries regarding impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period 2018-2022 and a reference period (2010-2014); n.s. (not significant), * significant ($p<0.05$), ** highly significant ($p<0.01$), *** very highly significant ($p<0.001$). Map created with mapchart.net.


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

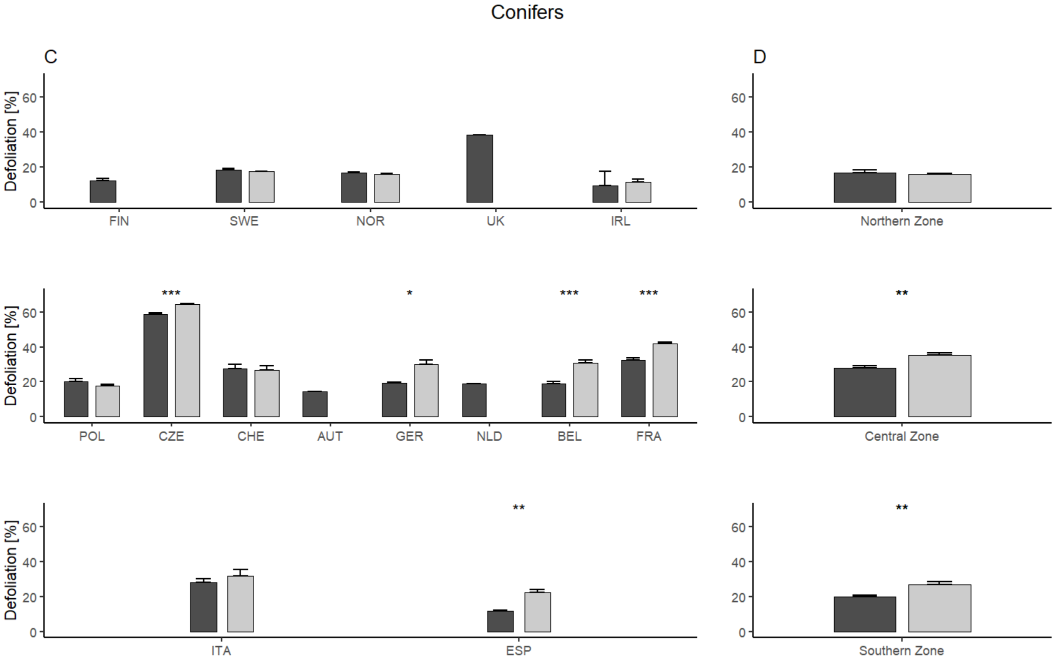
Conifers
C
D
Defoliation [%]
0
20
40
60
FIN
SWE
NOR
UK
IRL
Northern Zone
***
*
***
***
POL
CZE
CHE
AUT
GER
NLD
BEL
FRA
**
Central Zone
**
ITA
ESP
**
Southern Zone

Figure 4. 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.

Damaged wood caused by insect infestation was significantly higher across Central Europe in the study period of 2018-2022 than the reference period (Figure 5). 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.

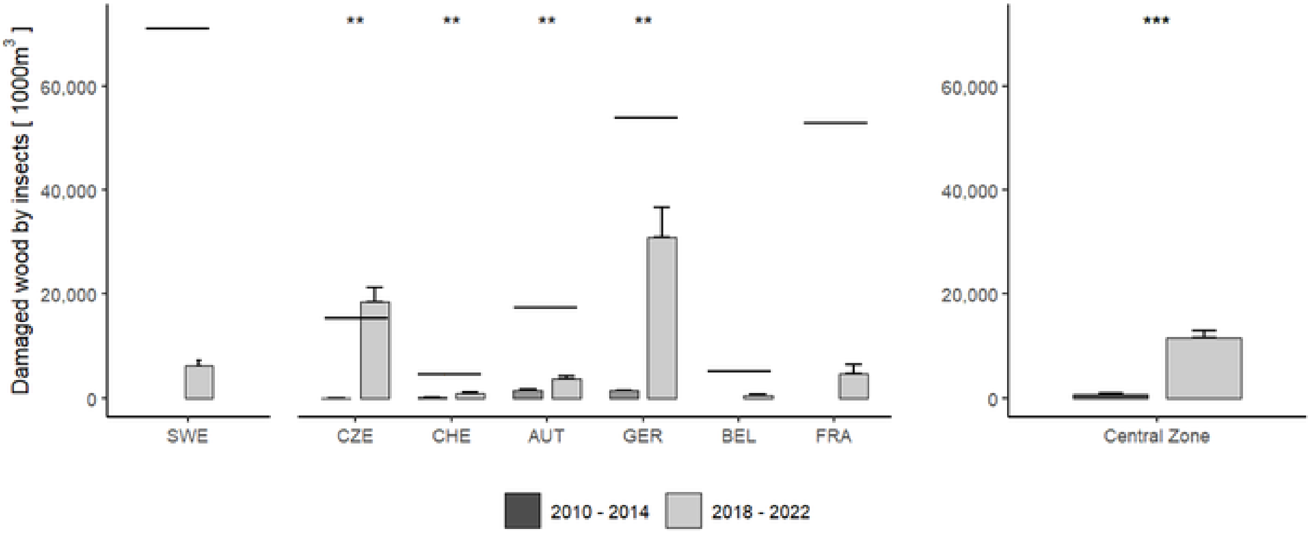

Figure 5. Damaged roundwood (1000 m³) by insect pests in Europe in the period 2018-2022, partly in comparison with the reference period 2010-2014. The black lines show the total roundwood production average per year 2010-2014. Wood data derived from different sources (EUROSTAT 2016, Wulff and Roberge 2020, Öhrn et al., 2021, EUWID 2022, ICP 2022, DESTATIS 2020, DESTATIS 2023, Waldschutz 2023, WSL 2023b, BFW 2020, 2023, Czech Statistical Office upon request). For the other countries no data was available.

In our analysis of forest fire occurrences, we did not find significant differences between the dry period 2018-2022 and the reference period 2010-2014, except for Norway and Germany (Figure 6). This lack of significant differences 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 2018-2022 was only a fraction of the one observed in Portugal during 2017.

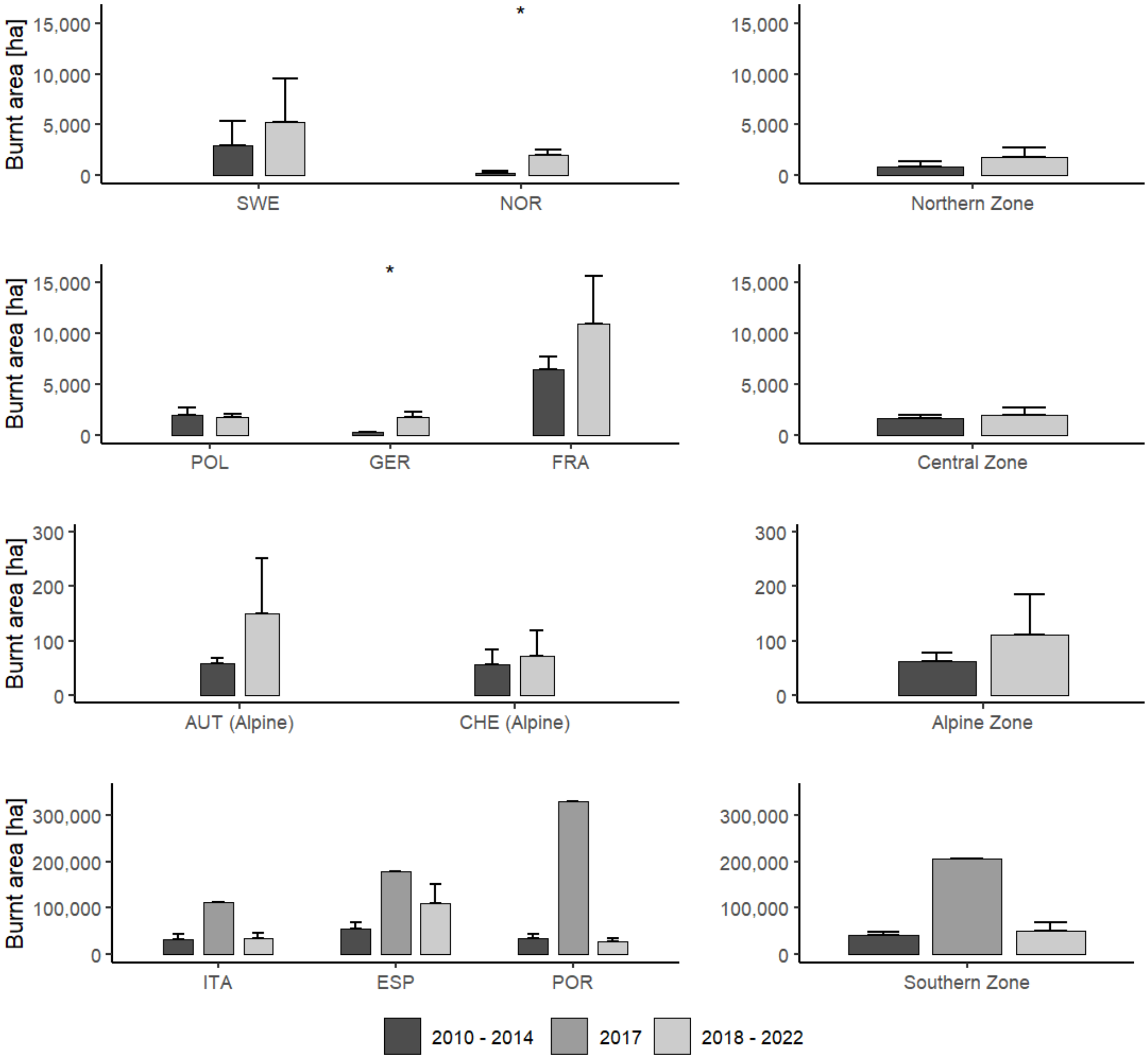

Figure 6. Burnt forested area (mean for the two periods under consideration) in selected European countries. Italy and Portugal had large fires in 2017 (accordingly, value for 2017 is given for the Southern zone). All data from JRC Technical Reports of the years Forest Fires in Europe, Middle East and North Africa of the years 2010 to 2022 (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). The data utilised here stem from the EC-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.

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. Notably, very highly significant disparities between the dry period (2018-2022) and the reference period (2010-2014) were observed in the Northern zone (Figure 7).

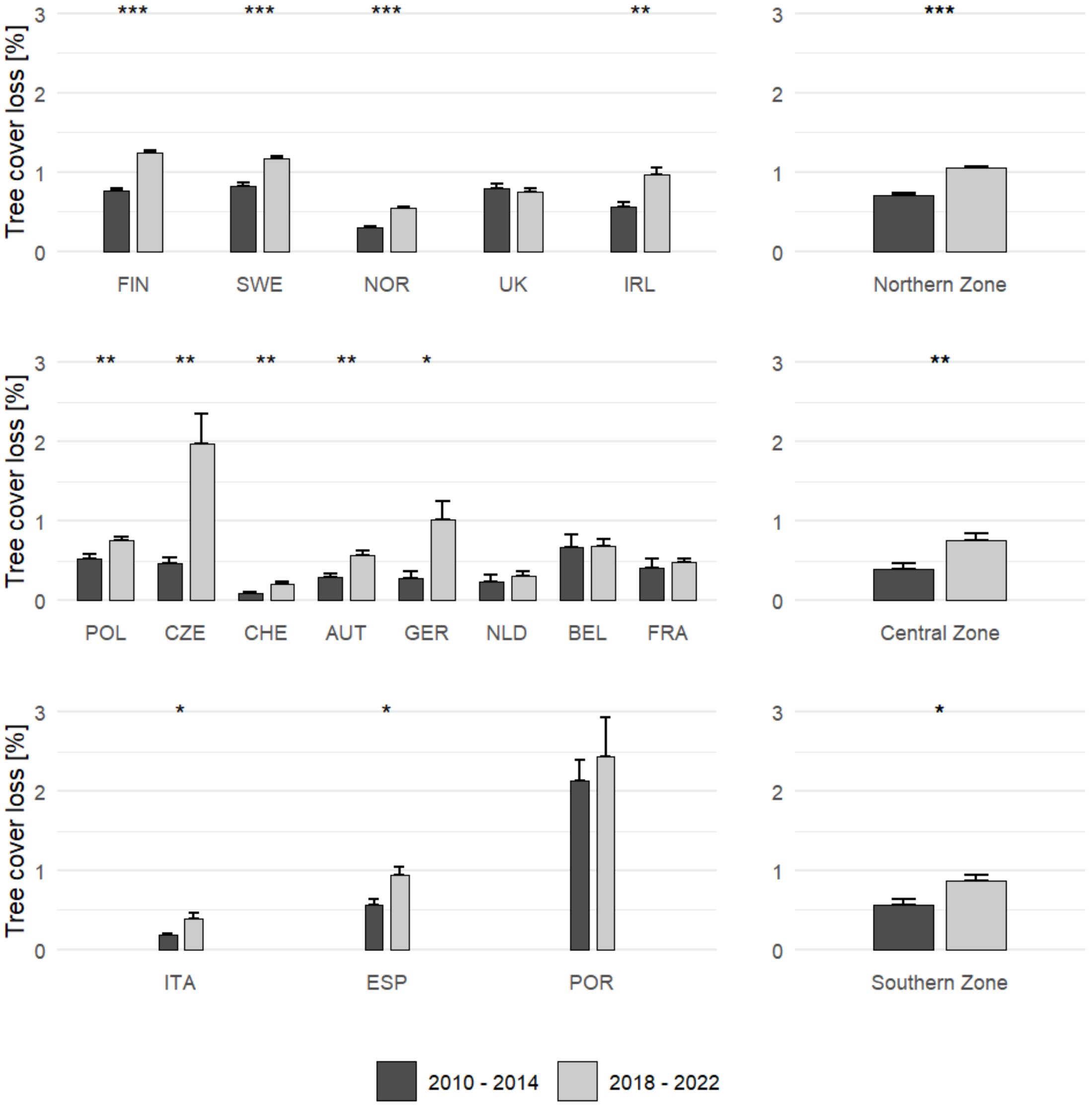

Figure 7. Relative tree cover loss (mean for the two periods under consideration); data from GlobalForestWatch.

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. Direct Forest damage in Finland directly coming from drought and heat 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., 2022; Melin et al., 2022; Terhonen et al., 2023). These numbers are high for Finland given that the accumulated forest drought damage in years 2009-2015 was 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, for example, to snow and moose-based damage (Nuorteva, 2019; Nuorteva et al., 2022, 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 to 20,800 ha and 18,000 ha in 2021 and 2022, respectively. 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 higher 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). 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 damaged by forest fires was roughly 500 ha, in 2020/2021 slightly over 1,000 ha and in 2022 only slightly over 265 ha (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% for conifers in 2018-2021 (data for 2022 and for broadleaved trees were not applicable; Michel et al., 2022). In Sweden bark beetles damaged 3–4 million m^3 of spruce in 2018, 7 million m^3 in 2019, and 8 million m^3 in 2020 and 2021, more than 20 folds 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, which allowed for rapid beetle population growth (Öhrn et al., 2021). In Sweden, the dry and warm period of summer 2018 led to the most severe outbreak of forest fires, estimated at around 25,000 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 more than 166 million €. This is a similar estimate as if the forest fires in Sweden in 2014 (14,000 ha, costs: 1 billion Swedish Krona) were upscaled to 2018: 160-200 million €.

Norway has a total forested area of more than 12 million ha, of which 8.6 million ha are suitable for forest production (SSB, 2022). On a national level, the drought did not yield a serious impact on Norwegian forestry. In 2017, there was a total of 965 million m^3 of standing forest, which increased to 987 million m^3 in 2020 (SSB, 2022). Physiological damage, expressed as moderate to severe crown defoliation, ranged from 14.9 to 17.2% for conifers in 2018-2021 (data for 2022 and for broadleaved trees were not applicable; Michel et al., 2022).

Norway's annual roundwood production is about 11 million m^3 (ICP 2022). Numbers from NIBIO’s 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 although concerning, these levels remain below outbreak levels.

The forest area affected by fires in Norway was more than 2,000 ha in 2018 and decreased to less than 1,000 ha in 2019 and 2020 (NIBIO, 2023). A record number of 1,906 forest fires occurred between January and August 2018. Wells and drinking water resources were almost empty, low water levels in rivers led to fish dying, and electricity production was at times20% below normal production levels (-23 TWh), leading to higher electricity costs (MET Norway, 2019). Favourable wind conditions meant that the total area affected 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. The 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 has led to an increase in tree felling: 1.1 million m^3 in 2018, 1.23 million m^3 in 2019 and 1.1 million m^3 in 2020, despite low timber prices especially in 2020. In comparison, the average felling in the 2010-2014 reference period was 896.000m^3/annum. To mitigate the consequences of the 2018 fires, 296,599 saplings were planted in 2019, and another 250,000 in 2020, compared to an average planting of 131,000 in the reference period. While there have been some short-term effects, the drought in Norway has not yet had a lasting negative impact. However, there are indications of increased beetle attacks and more deadwood because of periods with heavy snow in winter, and forest authorities are concerned about the future (e.g. forskning, 2019; Wataha, 2021).

In the **UK**, woodlands cover approximately 3.24 million ha, with an almost equal distribution between conifers (1.65 million ha) and broadleaves (1.59 million ha) (Forest Research, 2022a, b). Drought events have significantly impacted these woodlands in recent years. In 2018, early leaf senescence was observed in southern regions due to drought (Michel et al., 2019). Although

2019 was wetter and milder, thus mitigating severe drought impacts (Michel et al., 2020), challenges persisted in subsequent years. The 2020 weather extremes exacerbated ash dieback (*Hymenoscyphus fraxineus*), with widespread future mortality expected (Michel et al., 2021). By 2021, *Phytophthora pluvialis* was affecting mature trees, and 2022's severe drought led to widespread defoliation (Michel et al., 2022; Forest Research, 2022c).

Wildfire activity has varied, with significant events in 2018 (17,689 ha burned), 2019 (28,754 ha), 2020 (13,793 ha), and 2022 (20,362 ha). The average annual burned area from 2011 to 2022 was around 10,000 ha (EFFIS Annual Statistics for UK, 2023).

In England, woodlands span 1.32 million ha of which 26% are conifers and 74% are broadleaves (Forest Research, 2022a, b). Notably, 2018 saw severe wildfires in Greater Manchester, which burned 3,600 ha and predominantly affected broadleaved woodlands (Telegraph, 2018, BBC, 2018). In 2022, the English fire services managed nearly 25,000 wildfires (BBC, 2022). Wales, with 310,000 ha of woodland equally divided between conifers and broadleaves, faces frequent fires, especially in the south. In the spring of 2020, fires in the Afan Valley and Seven Sisters forests caused over €115,000 in damage and destroyed nearly 140 ha (NRW, 2020).

Scotland 1.49 million ha of forest, 74% of which are conifers and 26% are broadleaves. The region's forests, including Sitka spruce plantations, are particularly vulnerable to drought (Kirkpatrick et al., 2021). Although no insect damage data were available, the great spruce bark beetle (*Dendroctonus micans*) is now established in southern Scotland (Scottish Forestry, 2023a), and has expanded northwards from 2018 to 2022 (Scottish Forestry, 2023b). Sitka spruce is Scotland's most important commercial tree species and the primary host of this pest. The 2018 drought hindered forest regeneration, while wildfires in April 2018 and 2019 affected significant areas (Copernicus, 2023; The Herald, 2021). In March and April 2022, 95 wildfires were recorded (Highland Council, 2023). Key industries such as whisky production and forestry are heavily reliant on stable water supply (Kirkpatrick et al., 2021).

Northern Ireland, with 118,000 ha of woodland (54% conifers, 46% broadleaves), experienced wildfires in spring 2022, damaging approximately 720 ha (DAERA, 2022). Ireland's forest area ranges from 551,110 ha (EFFIS, 2023) to 770,020 ha (Forest Statistics Ireland, 2020), with a predominance of conifers (three-quarters, including 51% Sitka spruce) and broadleaves (one-quarter). Forest health remains generally good, with high defoliation rates reported only in 2020 and 2021 (Michel et al., 2022). Ireland's strict pest regulations and island status protect against many forest pests (O'Hanlon et al., 2021). Approximately 3,000 ha of forest burned annually from 2018 to 2022, which is moderate compared to record years (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 over an area of 43.500 ha. In the same year, forest damage was observed on 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 the analysis of three parameters: average defoliation, the proportion of healthy trees (up to 10% defoliation), and the proportion of damaged trees (more than 25% defoliation), and it 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 due to drought, were reported in 253 out 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 was played by the following pests: bark beetle (*Ips acuminatus*), mistletoe (*Viscum spec.*), Sphaeropsis blight (Sphaeropsis sapinea), steelblue jewel beetle (*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 forest trees species: the most severely infested were fir and pine trees, and to a lesser extent birch, as well as a mixture of deciduous species and spruce (Lech et al., 2019). In addition, well-known forest pests such as the European spruce bark beetle (*Ips typographus*) continue to pose a major threat to Polish forests. The dieback of Norway spruce stands was already increasing in Central and Eastern Europe in the 1970s and 1980s (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).

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 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 GW table, as well as decrease in tree growth, stand vitality, and resistance to pathogens and pests (Kwiatkowski et al., 2020). Among the species affected by this process are oaks, where the impact of declining GW has been observed since the late 1980s (Przybył, 1989). Current GW fluctuations further weaken oak trees and accelerate their decline (Jakoniuk, 2022), e.g. on the Krotoszyn Plateau (Danielewicz, 2016).

Furthermore, the prolonged drought has increased the risk of forest fires. Despite the high number of fires, the situation in Poland is relatively good. The average forest fire in the state forests is only 0.25 ha, which indicates a high efficiency of fire protection systems. According to official statistics, between 2011 and 2020, almost 25,000 fires with a total area of 6,049 hectares occurred in the areas managed by the State Forests, causing losses of approximately PLN 39 million. However, the year 2020 was marked by a large fire (6,000 hectares) in the Biebrza National Park in northeastern Poland.

In the **Czech Republic**, forest disturbances, mainly by pests, were triggered by drought and high temperature. 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 mean in annual air temperature in the current year (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 bark beetle-sensitive trees 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, resulting in 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 is infected by insects (WII). In 2018, 25.6 million m³ were harvested and 13 million m³ were WII; in 2019—32.5 million m³ were harvested with 22.8 million m³ of WII, and in 2020, the estimate ranges between 40 and 60 million m³ of WII (Fernandez-Carrillo et al., 2020). The timber damage was almost exclusively caused by European spruce bark beetle infestations (*Ips typographus* L.). The largest forest fire in Czech history broke out in Bohemian Switzerland in the northern Czech Republic and spread to 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 million m³ of solid timber has been harvested and 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 extracted since 2017, and 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 (2015-2019), with growth reductions in five major species due to drought conditions that were observed when compared to the reference period 2005–2009 (Jiang et al., 2024).

In the **German** forestry sector, 2018 to 2020 and 2022 are considered dry years (e.g. DFWR, 2021; NW-FVA, 2022). Monthly data from the Earth observation satellites Sentinel-2 and Landsat-8 show dramatic canopy losses in Germany, with coniferous forests in the central part of the country particularly affected: from Saxon-Switzerland in the east, through Thuringia to the Harz Mountains, into the Sauerland region and finally to the Eifel region 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. On a regional scale, results show the same, e.g. the forest condition survey in the German federal state of Lower Saxony shows that defoliation values are at their highest level in the time series since 1984 (NW-FVA 2022). High water availability enabled trees to maintain growth in the Leipzig floodplain forest during summer 2018, but the consecutive drought in 2019 caused significant reduction in tree growth, even in a forest ecosystem with a comparably high water supply demonstrating the cumulative effect of consecutive drought years (Schnabel et al., 2021).

Even if in Germany deciduous forests 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) in 2020, a record high number of dead trees was documented across all examined tree species. The survey revealed that only 20% of trees exhibited no crown thinning, with European beech showing an even more pronounced decline—only 11% of these trees were unaffected. Specifically, older trees (exceeding 60 years of age) and those growing in drier sites experienced notably reduced growth rates and increased mortality. These findings are corroborated by additional studies (e.g. Leuschner (2020); and Weigel et al. (2023)), which highlight the ongoing stress and vulnerability faced by European beech. Even tree species that are considered to be relatively drought-resistant, such as Scots pine (*Pinus sylvestris*), experienced massive mortality since 2018 (e.g. Kunert 2019, 2020). 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 caused widespread damage to forests, particularly during periods of heat and drought. In many cases, there was a need for emergency felling and even deforestation to prevent the pest from spreading (e.g. Thonfeld et al., 2022; Bork et al., 2024). In Thuringia almost 21 million m³ of deciduous (mainly beech) and coniferous (mainly spruce) deadwood occurred between 2018 and end of September 2022, of which around 65% due to insect infestation 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) were registered due to 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). It is estimated that around 500,000 hectares, or 4.4% of Germany's forest area, have been damaged by climate impacts, fires and bark beetles. These areas will need reforestation to mitigate the impacts of the drought from 2018 to 2022 (BMEL 2023c). For the approximately 13.3 million m³ of damaged wood by bark beetles, 95.6% are due to activities of the European spruce bark beetle and 2.8% to the Spruce wood engraver (*Pityogenes chalcographus*). Although the latter still plays a subordinate role, it could gain increasing importance given that it specialised on younger spruce stands. This is a large-scale threat in the future in terms of reforestation means or rejuvenation with conifers (TMIL 2022).

The years 2018, 2019, and 2022 were also above average for forest fires in Germany (DWD, 2022; UBA, 2023a). The burnt area in 2022 is more than five times the annual average of almost 776 ha (since 1991) 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 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 the forestry sector at more than 12.7 billion €, which is ten times the annual net profit of the entire German forest industry.

In the **Netherlands**, there are clear signs that trees suffered from the drought and heat of2018, with deciduous species in particular experiencing stunted or no growth (Salomón et al. 2022). On a national level, the average volume of living and dead wood increased during 2017-2021, although at a slower rate due to the dry summers in 2018-2020 (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 on 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 mortality of mature deciduous trees, as well as Norway spruce and larch, was observed. 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, 2023) 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 (as of the time this text was written, data for 2022 had not yet been 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 m³ of spruce were infested by bark beetles, compared to 5-10,000 m³ in normal years. This number increased to approximately 1 million m³ in the years 2019 and 2020 (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, were 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).

The share of harvested wood of all tree species declared as accidental (often related to storm damage) and sanitary (often related to drought damage or insect pests) products in metropolitan France increased from 0.8% in 2017 to 1,5% in 2018 (MAA 2019a) to 5.5% in 2019 (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 the figures were 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 to date 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 regions most affected by drought and heat are primarily in the lowlands, particularly in the east (Vienna, Lower Austria, Burgenland), as well as in the southeast (Styria) and the northern foothills of the Alps (Upper Austria, Northern Salzburg). The country experienced severe bark beetle infestations between 2018 and 2022, resulting in significant timber losses, especially in 2018 (5,210,000 m³), 2019 (4,690,000 m³), and 2022 (3,750,000 m³, see Figure 3). In 2022, forest damage in Austria, primarily attributed to climate change, was estimated at approximately 28 million € (Bundesforste 2023). Around 940,000 m³ of wood was damaged, representing about 59% of the total wood harvested in 2021. The primary cause of this damage was a significant increase in bark beetle infestations, with these pests now spreading up to the tree line at approximately 2,000 m above sea level due to climate change (Bundesforste 2023). Additionally, in March 2022, a massive wildfire in Allentsteig, Lower Austria, burned approximately 800 ha, including 400 ha of forest, making it one of the largest forest fires in Austria's history (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, 2024). A study based on NDVI data confirms that drought impacts decrease with elevation: especially above 1,500 m (Rita et al., 2020).

Damage caused by forest insects in Austria was only sporadically detected, such as in East Tyrol during 2022 (CIPRA 2022). In March 2022, a significant wildfire occurred in Tyrol, near the German border, where around 35 ha of mountain forest were destroyed in Pinswang (SZ 2022, Merkur 2022). The total direct costs for firefighting and necessary measures on burnt areas in the Alpine region, excluding preventive actions, are estimated to be around 75 million € per year (Müller et al., 2020).

In **Switzerland**, in both 2018 and 2022, the canopy 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% of the swiss forests were classified as 'naturally disturbed', most of them (59%) by wind, 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). 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 were found at high altitudes in Switzerland, as for example on a regional increase of bark beetles in the Alps in 2020 (e.g. Schreiner Zeitung, 2020; SRF 2020).

In **Italy**, following the Vaia windstorm in 2018, pest activity was initially moderate. However, a significant heat wave in early June 2021 triggered a massive swarming of the spruce bark beetle (Agrar-&Forstbericht Südtirol, 2021). By 2022, around 5,000 ha of the 350,000 ha of forest in South Tyrol were infested with the bark beetle (Tagesschau 2022). The pest then rapidly spread in Tyrol from mid-May 2022 (CIPRA 2022), with approximately 105,000 m³ of wood affected in 2021 and around one million m³ in 2022. The total amount of damaged wood from 2018 to 2022 is roughly equivalent to 15 times the normal annual harvest (Dolomitenstadt 2023).

Additionally, a prolonged drought during the 2017 growing season led to the most extensive outbreak of simultaneous fires in the Alpine region in the past 30 years. In the Piemonte region, 11 large fires occurred in the autumn of 2017, burning nearly 10,000 ha of mostly broadleaved forests within a week (Müller et al., 2020). Furthermore, in October 2018, one of Italy's largest forest fires occurred in Monte San Lucano, Veneto, burning 632 ha (Müller et al., 2020).

3.5 Damages to forests 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 extratropical 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).

In general, during 1998-2021 there was an increase in defoliation, forest mortality and leaf discoloration in Italian forests, especially in montane conifer forests, with peaks reached in 2021 (Bussotti et al., 2022) and leaf discoloration mainly observed 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 large accumulation of dead wood in the forests (Bussotti et al., 2022).

The summer of 2022 was affected by severe-to-extreme meteorological drought (Toreti et al., 2022a). Northern Italy was strongly affected, facing the warmest and driest winter on record in the last 30 years (Toreti et al., 2022b), resulting in strong hydrological drought and unusually low streamflow of the Po River, also related to the lack of snow 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 in the evergreen Mediterranean tall woodlands and in the aged coppices (on holm oaks), 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**, during 2018-2019, due to an increase in precipitation there was some recovery or stabilisation in terms of forest defoliation and discoloration following the drought of 2017 (AIEF 2019). However, more recent reports over parcels in North-eastern Spain reveal a deterioration in defoliation during 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, the country 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 6).

Although **Portugal** 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 and damaged wood by insects in Portugal is unavailable since 2006 (ICP Forests 2007).

Since 1980, the mean annual burnt area has been around 115,000 ha, with a large interannual variability and with 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, which are influenced by the amount of precipitation during and before 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 totalled around 1 billion € (between 1 billion and 1.2 billion USD), and the local insurance sector declared it as the costliest natural disaster in the country's history with pay-outs exceedingly around 270 million € (295 million USD) (Global Fire Monitoring Center, 2018; AON, 2018).

According to Global Forest Watch, Portugal experienced significant TCL from 2001 to 2021, totalling approximately 1.13 million ha. A notable portion of this loss occurred in 2017 alone, with 226,000 hectares lost primarily due to wildfires. In comparison, the cumulative tree cover loss from 2018 to 2022 amounted to 188,000 hectares. The loss during this period was predominantly driven by deforestation, with permanent deforestation mainly attributed to urbanisation and shifting agriculture.

4. Drought legacy

4.1. Drought legacy effects

Drought and heat impact vegetation not only immediately but can also have long-term effects that persist for years. Short-term damage assessments often underestimate the overall impact on forest ecosystems. Recovery times vary; for instance, carbon cycle recovery and compositional changes may span several years (Müller & Bahn, 2022). Severe droughts in temperate forests have led to growth reductions lasting up to 6 years, depending on tree species (Orwig & Abrams, 1997). Furthermore, long-term damage assessment is complicated by vegetation adaptation to persistent conditions. For example, pre-existing structural changes in tree hydraulic traits can either mitigate or exacerbate damage, influenced by shifts in plasticity (López et al., 2016). Trees in drier environments often show greater drought resistance (Orwig & Abrams, 1997).

Assessing the impact of consecutive drought years involves disentangling the effects of specific events from ongoing conditions that may influence hazard levels. This task includes evaluating long-term changes in water availability due to extreme droughts and understanding the legacy damage to forest ecosystems from the 2018-2022 drought events. While this section focuses on damage, it is important to recognize that long-term positive effects can also arise following extreme climate events (Müller & Bahn, 2022).

4.2 Linking vegetation drought legacy with groundwater drought legacy

GW is a key component of the terrestrial water cycle, contributing dynamics and feedback with vegetation processes on time scales far beyond the weather and seasonal time scales (Aeschbach-Hertig and Gleeson, 2012), which are especially important for the development and persistence of droughts. The vegetation water supply under meteorological and hydrological drought is determined by the redistribution of moisture in the shallow subsurface (soil) and its hydraulic connection with 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 GW 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 GW 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 rooting 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 processes. 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 (Loon, 2015; Hellwig et al. 2020), one can expect a strong connection to shallow moisture redistribution and drought legacy over very large time scales in regions of critical GW depths.

To assess the connection of drought legacy with GW 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 database exists over Europe or for specific countries. Thus, the data remains fragmented and dispersed across many political and private institutions, and it is not publicly available. This renders a formal analysis of the connection infeasible within the scope of this study, and only the general principles can be discussed here.

In Northern and Central Europe, dispersed bore hole observations of GW levels revealed that the 2018 drought was indeed one of the most severe in decades and comparable with the drought of 1976 (Bakke et al., 2020; Hellwig et al., 2020). In 2018, in many observation wells, GW 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 severe drought stress, even beyond the year 2018 (Schuldt et al., 2020). For example, Süßel and Brüggemann (2020) studied tree water relations in 2018 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 GW 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 showed distinct spatial patterns, 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 GW processes, specifically GW discharge and recharge, respectively. Under drought conditions, along river corridors, GW discharges as baseflow toward the stream constituting essentially an outcrop of the GW table, thus leading to shallow GW 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 GW 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 GW 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 GW convergence zone. In the future, a merger of in-situ, remotely sensed, and model data with ensuing in-depth analyses will be required to identify potential tree and forest legacy effects induced by GW 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

Drought events can leave longer-lasting impacts on forests, depending on which tree demographic processes are most affected (Müller & Bahn 2022; Rukh et al., 2023). Adult tree mortality can create gaps in forests, altering carbon and water cycles, species composition, and long-term profitability. These gaps also increase understory solar radiation, temperature, and soil dryness, which can lead to further damage through soil hydrophobicity and nutrient loss (Grünzweig et al., 2022). Similarly, the death or weakened vitality of saplings can hinder forest recovery, leaving trees vulnerable to future droughts, storms, fires, and pests (Gliksman et al., 2023). A study from Matías Resina et al. (2020) showed that the impact of drought on tree-level resilience was not strongly dependent on its latitudinal location, but rather on the type of sites the trees were growing on and their growth performances (i.e., magnitude and variability of growth) during the pre-drought period. Examples of drought damage during 2018-2022 in European forests highlight these impacts. The most pronounced legacy effects involved saplings and young trees, with long-term seedling establishment varying by location and species (Salomón et al., 2022). In Central Eastern Germany, the 2018 drought caused 65% defoliation in saplings across multiple species, with some species suffering over 85% defoliation. Despite some recovery, 25-32% of saplings still showed damage in 2020 (Beloiu et al., 2022). In Scotland, the droughts of 2018 and 2020 caused significant losses, including 50,000 seedlings at a Sitka spruce orchard in Galloway, and notable mortality rates in privately managed young forests (Locatelli et al., 2021). In Poland’s Brodnica Forest District, 20% of planted trees died leading to replanting costs of approximately 33,000 € (LASY, 2023). Similar damage was observed in young spruce and beech trees across Germany (BMEL, 2020). Growth reductions occurred in Northern Germany following the 2018 drought, exacerbated by insufficient winter water recharge, with similar reductions in 2019 and 2020 (Beloiu et al., 2022). In Switzerland, forest gross primary productivity recovered in about 50% of forested area by 2019, while 49% remained at 2018 damage levels, indicating a strong legacy effect (Sturm, 2022).

5. Discussion

Overall, the findings of this study emphasise that the Central zone of Europe is the most vulnerable to drought years, like those between 2018-2022, due to its specific forest composition, climate conditions, and susceptibility to secondary effects like pest infestations. The Southern zone, although significantly affected in TCL, exhibited less severe impacts compared to the Central zone. The relatively smaller impact in the Southern zone could be attributed to the region's long-term exposure to drought, which may have fostered adaptive mechanisms and built resilience over time. At the same time, the varying occurrence of drought conditions along the Southern zone may have also contributed to the moderate impact. In the Northern zone, the first impacts of drought and heat start to emerge, although severity is not yet pronounced. The presence of site-adapted boreal forest tree species is likely to contribute to the region's overall resistance. The Alpine zone displayed the least impact, which may highlight the potential protective role of altitude in mitigating the effects of climate extremes.

5.1 Central zone

The Central European forests experienced severe impacts during the drought years 2018-2022, with both coniferous and deciduous species suffering significant damage. Notable crown thinning, particularly among broadleaved species, was observed in France, with similar trends in the Czech Republic and Germany. These observations indicate that broadleaved trees across Central Europe are increasingly vulnerable to climate change-related stressors. Conifer defoliation was especially pronounced in the Czech Republic, Belgium, France, and Germany. The region also witnessed high levels of forest damage from pest infestation, underscoring the susceptibility of Central European forests to secondary drought effects, such as increased pest activity. The significant rise in TCL and bark beetle-infested wood highlights the profound impact of prolonged water deficits on these ecosystems, suggesting that the resilience of Central Europe's forests is being severely tested by climatic stressors.

The intense drought of 2018, characterised by an exceptionally hot summer, led to early wilting in about 11% of Central European forests, with Central and East Germany and the Czech Republic being the most affected (Brun et al., 2020; Buras et al., 2021). These drought conditions, combined with above-average water vapor pressure deficits in subsequent years, were primary drivers of forest disturbances affecting around 4.74 million ha between 2018 and 2020, particularly in Germany, the Czech Republic, and Austria (Senf et al., 2021). The physiological damage from 2018, marked by reduced greenness in Austria, Germany, and Switzerland, significantly contributed to forest mortality, and the reduced greenness persisted into 2019 (Schuldt et al., 2020; Brun et al., 2020). The record-hot summer of 2022 further exacerbated this trend, with forest greenness decreasing more sharply than in any other summer since 2002, surpassing even the 2018 drought record (Hermann et al., 2023; Buras et al., 2023).

The prevalence of spruce bark beetles in Central Europe has increased over recent decades (Fernandez-Carrillo et al., 2020). From 2018 to 2022, drought and heat triggered an unprecedented outbreak, severely affecting standing timber, particularly in the Czech Republic, Germany, and Austria (Hlásny et al., 2019, 2021; Nardi et al., 2023; Kautz et al., 2023). In 2019, over 50% of timber harvests in Austria and Germany, and over 90% in the Czech Republic, were associated with salvage logging due to bark beetle damage (Senf and Seidl, 2021a). The vulnerability of Norwegian spruce monocultures significantly contributed to this damage. Projections suggest a potential sevenfold increase in bark beetle disturbances by 2030 compared to 1971-1980 (Seidl et al., 2014), with a possible twofold increase throughout the 21st century depending on climate conditions and forest management practices (Dobor et al., 2020a, b). The cumulative growing stock affected by bark beetles is expected to rise significantly under moderate climate change scenarios, with even greater impacts under more extreme conditions (Sommerfeld et al., 2020).

In addition to drought, storm impacts must also be considered. While there is no definitive evidence of a significant increase in storm frequency in Germany, windthrow damage notably increased during 2018-2022 (BMEL, 2023a). The trend towards milder winters and increased precipitation outside the growing season in parts of Central Europe may contribute to greater windthrow susceptibility, as heavy rainfall can weaken root systems, and drought-stressed stands are more prone to wind damage (Středová et al., 2020, UBA 2023b).

Economic losses in Central Europe's forestry sector during 2018-2022 were substantial, though precise estimates are challenging due to an incomplete understanding of the full economic impacts (Knoke et al., 2021). While direct damages, such as the loss of immature trees can be quantified, more complex factors like stand destabilisation, market price fluctuations, and impacts on forest workers and machinery are difficult to assess.

5.2 Southern zone

In the Southern zone, crown thinning in deciduous trees was particularly pronounced in Italy and Spain. This indicates that even regions well-adapted to dry conditions, which have fostered the development of various adaptive mechanisms in both plant species and forest ecosystems, experienced unprecedented stress during these years. Mediterranean vegetation in the Southern zone seems to cope better with seasonal droughts through physiological and structural adaptations, such as deep rooting systems and reduced leaf area. Access of roots to deep water reserves enables hydraulic redistribution, whereby plants transport water from moist deep to dry shallow soil layers through their root system along a water potential gradient (Prieto et al., 2012). This mechanism improves plant nutrition, extends root lifespan and preserves hydraulic conductance in the xylem during dry periods, and occurs frequently in the Southern zone (Kurz-Besson et al., 2006, Peñuelas and Filella, 2003).

The observed damage attributed to increasing temperatures and drought conditions in the Southern zone shows that forests are encountering significant repercussions. Data on damage caused by wood-boring insects are unavailable, suggesting that insect pests may not have posed a major threat between 2018 to 2022. Nevertheless, a significant increase in TCL compared to the reference period was observed. Assessing the incidence of wildfires during the period of 2018-2022 was not possible. However, the exceptionally severe wildfires in 2017, particularly in Portugal, with staggering losses necessitated its inclusion in this study. The devastation caused by wildfires presents a continuously growing challenge for Southern Europe, despite wildfires being generally part of the South-western European ecosystems. Italy was strongly affected by the windstorm Vaia in 2018. We found no increase in insect infestation during the period from 2018 to 2022, nor in the years prior. Up to 2018, 3 million ha of forest have been reported to be converted into shrublands or grasslands in the European Union Mediterranean countries. Fire and drought are the main drivers underlying this deforestation (Karavani et al., 2018). In Spain, forest health showed some recovery between 2018 and 2019, contrasting with greater damage in Central Europe (AIEF, 2019; Blunden & Arndt, 2019). The situation for Maritime pine (*Pinus pinaster*, one of the most common species) in Iberia 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, stringent prevention and rapid response measures have been implemented in the area. When comparing the periods 2007-2017 and 2018-2022, the total number of fires has decreased by half, particularly on days of high fire danger. Larger fires have occurred less frequently since 2017. The average number of fires burning more than 1,000 hahas decreased from 19 events to just 8 in recent years. Although forest losses are decreasing in the last period, Portugal experienced an increasing trend in forest area loss due to fires between 2001 and 2019 (Tyukavina et al., 2022). Without the unique events of 2017, the decline in fire incidents might not have been as apparent. This highlights the challenges of interpreting long-term fire trends, as exceptional circumstances can significantly impact annual statistics. Furthermore, the effective implementation of prevention strategies and rapid response efforts in the Iberian Peninsula has played a substantial role in mitigating fire damage (e.g. REA, 2024).

5.3 Northern zone

The relatively low impact observed in the Northern zone suggests that it has not yet experienced the full extent of climate extremes, or that its forests are more resilient. Nonetheless, the data indicate potential vulnerability to future drought impacts, highlighting the need for ongoing monitoring and conservation efforts. It is important to note that the lack of data on crown defoliation for broadleaves limits a comprehensive assessment of the situation.

The Northern zone's forests might benefit from a reduced severity of climate extremes i.e. more consistent precipitation patterns and cooler temperatures, which reduce evapotranspiration rates and alleviate drought stress. Several indices supporting this assumption were that Europe-wide data show that the Northern zone was still affected during the 2018-2022 drought period. Specifically, evidence from Sweden reveals significant insect damage to coniferous wood, with high levels recorded in 2018, and even higher levels in subsequent years (2019-2021). Additionally, TCL increased markedly from 0.7% to over 1%.

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 may be more vulnerable to climate extremes. For conifers, however, no significant differences in defoliation were observed in the Northern zone or within individual countries within this zone. This suggests a relative stability of conifer health in this region, despite variations in environmental conditions. 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.

The example of Norway may make it clear that Fennoscandia is probably the area where climate change has had yet less 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 particular during dry seasons. So far, the effects seem to cancel each other out (miljødirektoratet, 2023; Bardalen et al., 2022) . For example, while winter, spring and summer in 2021 were dry, Norway experienced an autumn and winter with more rain than usual, with GW levels that went above normal. 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 rainfall leading to passing floods.

In the British Isles, the damage during the study period was not exceptional. Indirect signs of previous drought impacts were noted, with 77% of UK respondents agreeing on the need for protective measures against pests and diseases (Forest Research, 2021). An earlier spatial modelling study (Forest Research, 2008) even predicted an improvement in 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 the European spruce bark beetle (*Ips typographus*) has now become established in South-east England, likely 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 ranked third, while impacts on freshwater ecosystems and water quality ranked higher (Turner et al., 2021). Future tree growth in Scotland might benefit from a warmer climate, especially in Southern and Eastern Scotland (Forest Research, 2008).

5.4 Alpine zone

The Alpine zone exhibited minimal impact, with no statistically significant differences observed in any forest health or damage indicator used in this study. This limited impact may be attributed to the region's higher altitudes, which might provide mitigating effects such as cooler temperatures or reduced evapotranspiration, potentially buffering the area from extreme drought conditions. 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, reduced precipitation and shorter cold periods can lead to reduced snow cover and trigger the distribution of harmful organisms or alien and invasive species that have an 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, as long as there is sufficient access to water, as confirmed by previous studies (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 conducted by Stephan et al. (2021) reveals that pre-Alpine areas experience more significant effects compared to higher elevations. The majority of reported impacts are related to agriculture and public water supply, with less focus on forestry and terrestrial ecosystems. Drought impacts are found to be most severe during summer and early autumn, likely due to the mitigating effect of spring snowmelt on water shortages. The analysis also highlights spatial variability across the Alps, with notably greater impacts observed in the Northern Alpine regions. Eriksen & Hauri (2021) mentioned that forest fires have traditionally been more common on the southern side of the Alps and that these countries have better forest fire management.

5.5 Forest fire and tree cover loss

Contrary to our expectations, no significant differences in forest fire outbreaks were observed between the dry period of 2018-2022 and the reference period of 2010-2014. This trend was consistent across the Northern, Central, Alpine, and Southern zones. Additionally, consultations with local offices, such as those in Austria, confirmed that there were neither more fires nor larger burnt areas during 2018-2022 compared to the reference period. The absence of significant differences in wildfire damage across all zones suggests that implemented fire prevention measures, such as enhanced forest and fire management, monitoring, rapid detection and response, as well as international collaboration, might play a more substantial role than drought conditions alone (e.g. REA, 2024). In Nordic countries, for example, differences in early detection, forest road density, and the number of local fire brigades contribute to variations in forest fire incidence and damage (Lehtonen and Venäläinen, 2020). Wildfires in the Alps are influenced by a range of factors, including the high level of human activity driven by recreational activities (Garbarino et al., 2020, Müller et al. 2020). Consequently, there is a complex interplay of elements affecting fire activity, including climatic conditions, forest management practices, preventive measures, public awareness, and the effectiveness of firefighting efforts. The countries in the Southern zone experienced severe impacts from forest fires, and not just during the 2018-2022 period. 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, especially 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 to develop effective strategies to mitigate the impacts of forest fires in vulnerable regions. For Alpine forests, data availability was limited to

Austria and Switzerland for both periods, showing no significant differences in fire damage. Identifying trends in fire risk in the Alps is challenging due to differences in forest fire documentation systems between Alpine countries (Müller et al., 2020). Based on the available data for 2018-2022, the occurrence of forest fires in the Alps appears consistent with the long-term average. Although our study found no increase in forest fires in Europe during the hot and dry period of 2018- 2020, research in the USA has clearly linked the rising frequency and severity of forest fires to climate change. For instance, Northern and Central California experienced a fivefold increase in summer burned forest area from 1996 to 2021 compared to 1971-1995 (Turco et al., 2023). In the western United States, climate change and other factors have doubled the cumulative forest fire area since 1984 (Abatzoglou & Williams, 2016). Global projections for the 21st century suggest that climate change will worsen fire weather conditions, affecting a significant portion of the burnable land worldwide (Abatzoglou et al., 2019). The significant disparities in TCL 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. 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, underscoring the urgent need for proactive measures to address these challenges. Further research is needed to better understand the specific drivers behind the disparities in reporting, and to develop targeted interventions for sustainable forest conservation and management.

5.6 Future trends and biophysical feedback and impacts on forests

Future global warming is expected to lead to more frequent and intense periods of hot 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 coming decades than in recent years (Suarez-Gutierrez et al., 2023). For example, Hari et al. (2020) found a sevenfold increase in the occurrence of consecutive drought events as of 2018-2019 in Europe under SSP5-8.5. 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 with increasing proximity to the Mediterranean, linked to roughly similar spatial changes in surface runoff (IPCC 2021a, b). At the same time, evapotranspiration increases the further east in Europe one gets (IPCC 2021a, b). Combined, those two meteorological aspects lead to a pronounced surface soil moisture deficit, which increases the (hydrological) drought risk substantially (IPCC 2021a, b). Accordingly, forest disturbance regimes are expected to intensify with continuing global warming, leading to increasing forest biomass losses due to windthrow, fires and insect outbreaks (Forzieri et al., 2021, Patacca et al., 2023).

Biophysical feedback 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 of 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 (FPS LUCAS) investigated the effects of extreme forest cover changes on local and regional climate in Europe (Rechid et al., 2017). Davin et al. (2020) found significant biophysical effects of re-/afforestation on regional and local climates seasonally, with RCMs showing consistent winter warming due to albedo changes but differing summer temperature responses due to varying evaporative fractions. Summer temperature changes are mainly driven by land processes, while atmospheric processes dominate winter responses. 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 cooler daytime and warmer nighttime summer surface temperatures, aligning with other observational 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 soil temperature cycle using the LUCAS RCM ensemble, finding a general reduction in the annual amplitude across Europe, though not all models showed this trend. Observations at paired FLUXNET sites confirmed summer ground cooling in forested areas compared to open areas. While most models align with this trend, variability in change magnitude exists. Daloz et al. (2022) explored the snow-albedo effect of FPS LUCAS RCMs in Sub-polar and Alpine climates, and Mooney et al. (2022) examined extreme forest cover changes within FPS LUCAS simulations. Their findings suggest that re-/afforestation reduces the snow-albedo sensitivity index, enhancing snowmelt, with robust direction but uncertain magnitude of change. The FPS LUCAS Phase 1 simulations highlight the significance of biophysical feedback from forest cover changes in Europe, with potential for intensification under further climate change through regional and local processes.

5.7 Conclusions

Our main conclusions from this study are as follows:

1. European forests are highly vulnerable to heat and drought, with even currently resilient ecosystems at significant risk of severe damage in the decades to come.
2. The geographical variability in the distribution of forest damage needs to be integrated into Europe-wide strategies to effectively mitigate future impacts.
3. The study underscores the challenges in data collection and highlights the necessity for harmonised data and enhanced monitoring to address future environmental challenges effectively.

European forests are critically vulnerable to the combined effects of increasing heat and drought, which threaten even those ecosystems currently deemed resilient. This vulnerability is likely to escalate, leading to severe consequences such as heightened tree mortality, shifts in species composition, increased risk of insect pests and wildfires, and diminished forest productivity and carbon sequestration. These potential impacts are far-reaching, undermining the goals of reforestation and climate-smart management efforts (Verkeerk et al., 2022; Albrich et al., 2022) and potentially exacerbating local and regional climate extremes (Lejeune et al., 2018).

As extreme heat and drought are projected to intensify and persist longer each year (Hundhausen et al., 2023) and become more frequent (Suarez-Gutierrez et al., 2023), the impacts on forest ecosystems are likely to increase. Central Europe is already facing considerable stress from these conditions, and other regions are expected to experience heightened impacts as well. Global warming is forecasted to prolong thermal summers and shorten winters in Northern Europe (Ruosteenoja et al., 2020). The European Alps are anticipated to undergo substantial warming throughout the twenty-first century, accompanied by a marked decrease in snow cover at lower elevations (Kotlarski et al., 2023). Additionally, regions such as the Iberian Peninsula may confront persistent drought conditions by the late 21st century (Moemken et al., 2022). These projected changes highlight the urgent need for comprehensive adaptation and mitigation strategies to address the increasing frequency and severity of extreme climate events.

While the extent of damage might have been anticipated, the surprising element is the pronounced heterogeneity in its distribution across different regions. This variability underscores the necessity for Europe-wide strategies that accommodate regional differences. Effective mitigation and adaptation efforts must integrate these diverse regional impacts to comprehensively address and reduce future damage. Overcoming language barriers and improving information accessibility are essential not only for mitigating climate impacts but also for raising public awareness of the severe effects of drought and heat. Forest managers must be better equipped to tackle these challenges through adaptive management techniques and the selection of climate-resilient tree species, mixtures, or provenances. Tailored climate information, such as that demonstrated by Bülow et al. (2024) for the Karlsruhe municipal forest, is crucial for this purpose. Thus, a comprehensive, transdisciplinary approach to managing forest vulnerability should include robust forest management practices—such as species choice, thinning, or prescribed burning—alongside climate adaptation measures, early warning systems, and wildfire risk reduction strategies. Enhancing forest resilience through these measures on a regional scale will be pivotal in addressing future environmental challenges effectively.

The assessment and management of forest damage are significantly complicated by substantial challenges in data collection and reporting. This study highlights notable inconsistencies in impact reporting across sectors and countries, characterised by delays and gaps in data availability. For example, Spain’s National Forest Damage Inventories were outdated at the time of this study (AIEF, 2020), and comprehensive data for the Alpine zone were particularly scarce. For instance, the Swiss stone pine (*Pinus cembra*), crucial to Alpine forests, grows in small, fragmented populations across Switzerland, Germany, Austria, and Italy (EUFORGEN, 2024). Many natural systems extend across national borders and understanding the impact of climate change on the Alps, as well as other regions, necessitates a broader, cross-national perspective. Additionally, while a description of heat and drought damage to grasslands was planned, limited data availability restricted this assessment, despite the critical ecosystem services provided by grasslands. These inconsistencies in data availability impede the ability to rapidly assess multi-country drought impacts and develop effective responses. Addressing these challenges requires the establishment of harmonised data collection and enhanced forest monitoring. A unified, accessible platform for drought damage data and improved cross-linguistic and cross-sectoral communication are essential for effective impact assessment and response formulation.

To effectively address the complex challenges posed by recurrent heat waves and droughts, a comprehensive and collaborative approach is essential. The impacts of these extreme climate events extend beyond forests, affecting water resources, air quality, recreation, wood supply, and overall human well-being, and can also heighten risks such as political instability through forest fires and climate feedback. Recent extreme weather has highlighted deficiencies in current preparedness and the critical need for enhanced information accessibility for forest managers. Developing adaptive management techniques and climate-resilient forest strategies requires the joint efforts of researchers, policymakers, and forest managers. Integrating forest management, climate change adaptation, and global greenhouse gas reduction strategies is crucial for mitigating future environmental impacts and ensuring broader ecological and societal stability.

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