Impacts and damages ~~of the~~to European ~~multi-year~~ forests from the 2018-2022 heat and drought ~~and heat event 2018 - 2022 on forests - a review~~events

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Abstract~~.~~

Drought and heat events in Europe are becoming ~~more~~increasingly frequent ~~in Europe~~ due to human-induced climate change, ~~affecting many aspects of~~ impacting both human well-being and ecosystem functioning. ~~However, the~~The intensity and effects of these ~~drought and heat~~ events ~~is not spatially and temporally uniform. Understanding the spatial variability of drought impacts is important information~~vary across the continent, making it crucial for decision~~-~~-makers~~, supporting both planning and preparations~~ to ~~cope with the changing climatic conditions. Currently, data relating to the~~understand spatial variability in drought impacts. Data on drought-related damage ~~caused by extended drought episodes is scattered across languages and sources such as~~ are currently dispersed across scientific publications, ~~governmental~~government reports, and ~~the~~ media~~. In this review paper, we gathered~~ outlets. This study consolidates data ~~of damage caused by~~on drought and ~~high temperatures~~heat damages in European forests from 2018 ~~until~~to 2022 ~~in forest ecosystems and combined our data with~~, using Europe-wide ~~data sets such as (1)~~ datasets including crown defoliation, ~~(2) damaged wood by insects, (3)~~ insect damage, burnt forest areas, and ~~(4)~~ tree cover loss. ~~We partitioned the~~The data ~~stemming from~~, covering 16 European countries ~~into~~, were analysed across four regions: Northern, Central, Alpine, and Southern~~.~~, and compared with a reference period from 2010 to 2014.

~~During the 2018-2022 period,~~Findings reveal that forests ~~across~~in all ~~four~~ zones ~~exhibited diminished~~experienced reduced vitality due to drought and elevated temperatures, ~~albeit~~ with varying severity. ~~We identify several trends affecting more than one climate zone: (1) Conifers have no significantly higher defoliation rates within the Northern zone or individual countries within it, but higher rates are observed in the~~ Central Europe showed the highest vulnerability, impacting both coniferous and deciduous trees. The Southern ~~zones. Broadleaves exhibit significantly higher defoliation rates across the three zones, (2) There~~ 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 ~~significant increase in general~~protective effect of altitude.

Key trends include: (1) Significant tree cover loss in the Northern, Central, and Southern ~~zone. Although in several regions 2021 was~~zones; (2) High damage levels despite 2021 being an average year ~~high levels of damages were still observed~~, indicating ~~strong legacy~~lasting effects from ~~the events in 2018- 2020, (3) The Northern and the Alpine zones showed comparatively lesser impacts, and (4) Central Europe and Sweden experienced notable damage to wood from bark beetles.~~ previous years; (3) Notable ~~zone-specific trends were: (1) The Central zone experienced notable~~ challenges ~~exacerbated by~~in the Central zone and Sweden due to bark beetle infestations~~, (2) While wildfires pose a colossal challenge for~~; and (4) No increase in wildfire severity in Southern Europe~~, their impact during this specific timeframe is not pronounced and (3) while some adaptive responses to heat and~~ despite ongoing challenges.

Based on this assessment, we conclude that: (i) European forests are highly vulnerable to drought ~~were discernible in the Southern zone. Overall, given the projected increase in future occurrences of drought and heat, these results emphasise the~~

~~critical necessity for implementing~~and heat, with even resilient ecosystems at risk of severe damage; (ii) tailored strategies ~~to alleviate the detrimental impacts of~~are essential to mitigate climate change ~~on European forests.~~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 (~~Toreti et al., 2019, ~~Brás et al., 2021; Bento et al., 2021), and unprecedented forest mortality events (Schuldt et al., 2020). Extreme drought is often closely linked with extreme heat, which in turn increases heat-related mortality and morbidity (Watts et al., 2020). Vicedo-Cabrera et al., (2021) found that up to 30% of heat-related deaths globally in the last 30 years can be attributed to anthropogenic climate change. Mitchell et al~~.,~~. (2016) found the risk of heat-related 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 ~~heat episodes.~~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~~Northern hemisphere midlatitudes (Rousi et al., 2022). Central and Southern Europe are affected by a longer-term drying trend, in line with expectations from theory and climate model simulations (Ionita et al., 2022). This trend includes also consecutive multi-year meteorological summer droughts, such as those of 2018 to 2022 in Central and Western Europe, which are characterised by two or more summers of lower~~-~~-than~~-~~-normal precipitation and higher than normal evaporative demand, resulting in a larger reduction of soil moisture content in the second year of the drought, and therefore to potentially more extreme drought impacts (Van Der Wiel et al., 2022). Worryingly, climate models project a strong increase of dry spells (Rousi et al., 2021) and multi-year droughts in Western Europe in response to further global warming (Van Der Wiel et al., 2022; Suarez-Gutierrez et al., 2023).

1.2. Scope, aims and research approach

In this ~~review~~study we present the impacts documented in European forests during the years 2018-2022, ~~some of~~among the warmest and driest on record over Europe~~.~~ (Figure 1). We focus on forest ecosystems ~~because they are not irrigated and thus~~to reduce the risk of bias that could arise from variations in irrigation practices, allowing us to better observe the effects of climate extremes~~ are clearer, and we avoid a potential bias in the interpretation of results due to variation in irrigation levels. Forests~~

~~play a fundamental role in~~. Furthermore, forests are essential to our livelihoods~~ and supply~~, they provide wood~~,~~ as a renewable raw~~-~~ material and ~~other essential~~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 ~~review~~study refer to political boundaries (at country-level), we assigned those sources to ~~whichever geographical zone was~~ the most appropriate~~.~~ geographical zone. An exception was ~~that four~~made for countries ~~were assigned to~~ that fall within two zones~~ because~~, as they ~~are~~ partly ~~in~~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 ~~compound~~ drought and heat ~~event~~events between 2018 and 2022, along with ~~its~~their impacts, were derived using an interdisciplinary ~~study~~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 ~~before~~prior to 2018 ~~where it is needed~~ to provide a better context for our focal period ~~of~~ 2018-2022. Following this, we focus on the heat and drought ~~and heat~~ impacts on forests~~.~~ and its legacy effects. We collected the ~~different~~damage estimates ~~of damages~~ from research papers, reports, and even media coverage when no ~~better~~other source was available. We focus our ~~review~~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 ~~source~~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~~ areas~~. However, for some countries, only statistics on ~~wildfires (~~all~~-~~-vegetation and uncontrolled ~~vegetation fires)~~ wildfires were available. ~~Also~~Additionally, the online ~~available data on number and burnt areas~~data from the European Forest Fire Information System (EFFIS) ~~shows~~ provides information on the number of wildfires and the total affected vegetation area. To resolve these issues, we used data ~~about~~on forest fires ~~where~~(when available) and ~~pointed out~~clearly indicated when ~~we present~~the information ~~about~~pertains to wildfires. ~~This~~Although this study examines forest damage spanning 2018-2022, ~~only~~ the exceptional forest fire damage ~~in~~of 2017 in Southern Europe ~~is~~was also included~~, as it provides~~ 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 ~~of~~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~~ in Europe~~, we considered ~~the years 2010-2014 as~~ a reference period~~. We note that the year~~ spanning five years from 2010 to 2014. Year 2015 was ~~characterised~~regarded as an extraordinary drought ~~period~~year in Europe (e.g. Hoy et al., 2017, Laaha et al., 2017~~)~~), and ~~therefore we did~~thus not ~~include 2015~~included in our reference period. Compared to other periods in the ~~new~~current millennium, ~~the period~~years between 2010 ~~to~~and 2014 ~~was~~were characterised by fewer climate extremes, ~~such as intense heat waves, widespread~~large scale droughts or severe floods~~, e.g.~~. For example, in Germany, the water balance levels ~~in Germany~~ show only small deviations from the climatological mean during that ~~pperiod~~period (*cf*. DWD Dokumentation SPEI). The period ~~of~~ 2010-2014 ~~had~~experienced below-average to average annual mean temperatures ~~(~~across Europe, relative to the 1991-2020 average~~) across Europe, in particular during~~, 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.

~~In the following sections, we take a closer look at the climatic situation during those five critical years in four European zones (Northern, Central, Alpine, and Southern). Table 1 lists the countries and regions present in this review.~~

Countries were selected based on exposure to heat and drought during 2018-2022, ~~but also based~~as well as on data availability and language barriers~~. Out~~ (Table 1). Therefore, out of the 44 European countries (UN 2024~~)~~), 28 countries ~~were~~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 ~~as broadly as possible~~extensively across Europe over several months ~~of work~~ by a working~~-~~ group in the ClimXtreme project (https://www.climxtreme.net/index.php/en/~~)~~), with additional experts beyond the project contributing their expertise.

Table 1: ~~Four~~The four climate zones and ~~the~~ associated 16 countries in ~~total, the~~this study. The countries of the Alpine zone ~~are~~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 ~~above average temperatures and extreme deficits in precipitation~~drought conditions characterised the ~~summers~~spring and summer seasons during 2018-2022 ~~(Fig 1)~~ across Europe~~, one of~~ as shown by the Standardised Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2012, 2013, Beguería et al., 2013~~worst consecutive drought periods that~~) (Figure 1). These prolonged droughts co-occurred in ~~the continent. The extreme climatic conditions~~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~~, especially in late spring and summer 2018. It was found that a~~. A persistent positive North Atlantic Oscillation~~, a pattern defined by higher-than-average atmospheric pressure over the subtropical North Atlantic and lower-than-average pressure over the North Atlantic (~~ (NAO) was found before the heatwave (Drouard et al., 2019; Li et al., 2020~~), combined~~). This pattern was further associated with a double jet stream configuration~~, with~~ and two ~~instead of one single current of~~ high-~~speeds winds~~speed wind currents in the upper atmosphere ~~affecting~~that influenced the intensity and persistence of atmospheric ~~patterns~~conditions in the inter-jet region~~, were present before the initiation of the heatwave (~~ (Rousi et al., 2023).

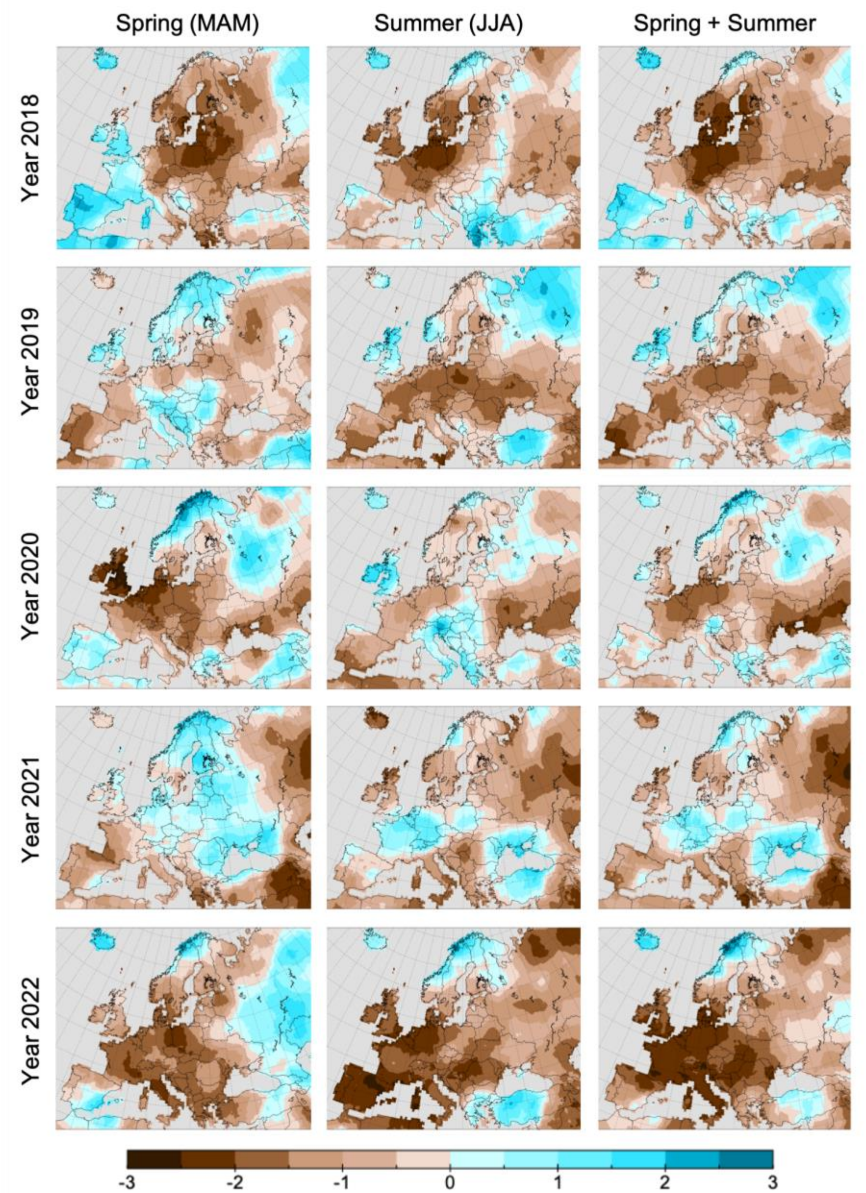


Figure 1. SPEI (Standardized Precipitation Evaporation Index) for spring (MAM - March to May), summer (JJA - June to August) and the entire growing season (March to August) during the 2018 (top row) to 2022 period (bottom row). SPEI results are shown in units of standard deviation from the long-term 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).

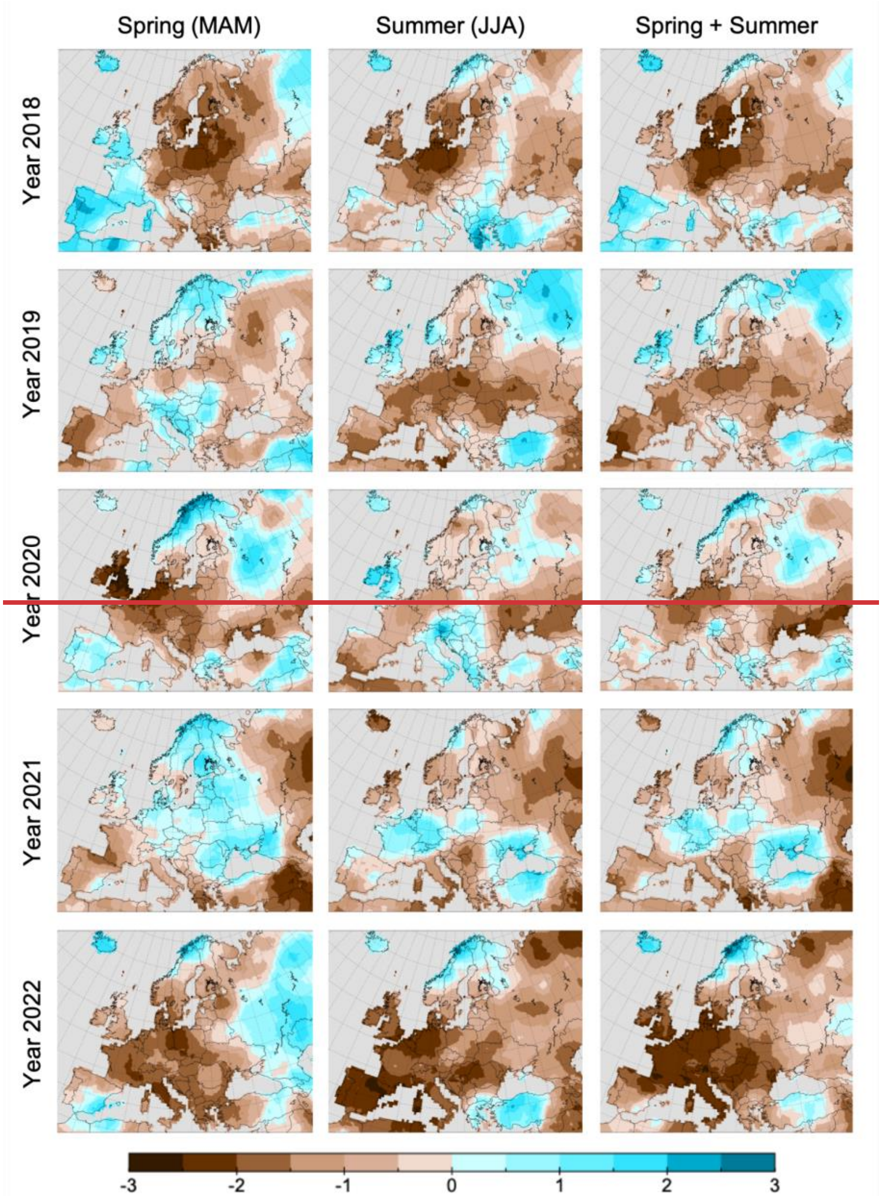


Figure 1. SPEI (Standard Precipitation Evaporation Index) for spring (March to May), summer (Hari et al. (2020) useJune to August) and the entire growing season (March to August) during the 2018 (top row) to 2022 period (bottom row). SPEI results are shown in units of standard deviation from the long-term mean of the standardised distribution. SPEI includes precipitation, effects of temperature and hence evapotranspiration. SPEI uses a climatic water balance D obtained at various time scales (i.e. over three and six months). E.g. for a 6-month SPEI, first a time series is constructed by the sum of D values from five months before to the current month. For a SPEI series comparable in space and time, the D series is transformed using equal probability

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

~~Using~~ pattern climatology data for Europe and ~~linking it with~~ long-term observations ~~over the last 120 years, Hari et al., (2020)~~ to claim that ~~alone~~ the consecutive droughts of 2018~~-~~ and 2019 ~~drought was~~were unprecedented ~~during~~in the last 250 years. ~~Including also~~Adding 2020 in ~~their~~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. ~~From a spatial perspective, the~~The authors ~~found~~identified the 2018–2020 drought event having an unprecedented intensity that ~~approximately~~ persisted for more than 2 years, exhibiting a mean aerial coverage of 35.6% of Europe~~ was affected during the first two most severe years of the drought.~~. Following the 2018-2020 extreme drought years, 2021 marked a rather normal to wet year. However, persistent hot and dry conditions ~~returned in~~ prevailed during spring and summer 2022, ~~leading~~which led to ~~similarly~~ depleted soil water levels ~~as in~~(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 ~~were subject to~~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** ~~had~~experienced a series of unusually warm and dry ~~year in~~years. In 2018~~. The summer was long with many days over 30°C temperatures~~, prolonged heat and ~~rainfall levels were at a~~ record~~-~~-low ~~in some areas. In Central Finland, the all-time lowest~~rainfall caused significant groundwater ~~table levels were measured in small~~depletion, algal blooms, fish and ~~shallow aquifers~~mussel deaths, and a 20% crop yield reduction (Veijalainen et al., 2019~~). Furthermore, the summer of 2018 saw uncommonly large algal blooms and the death of fish and mussels and a 20% reduction in crop yields (~~; Winland-project Policy Brief VII, 2019). ~~Summer 2019 was not as severe as 2018, but with significant impacts, for example, on the ground water levels, which were very low already from the previous year. Summertime temperatures were about 1°C higher than normal in Southern and Western Finland, but slightly lower in eastern and northern parts. Summer 2019 was drier than normally, especially in~~ Groundwater levels remained low in 2019, with Central and Eastern Finland~~, where such~~ experiencing the worst dryness ~~was last experienced in~~ since 1955 (Ilmastokatsaus, 2019). The year 2020 ~~was a~~saw record~~-~~-breaking ~~warm-year in Southern and Central Finland. Summer and autumn were exceptionally warm, but also many~~ warmth and rainfall ~~records were broken~~, particularly in Southern and Central Finland (Ilmastokatsaus, 2020). ~~Year 2021 was not overall~~

~~exceptional, but ~~June and July ~~were warmer than normally. June temperatures were in many parts of the country higher than ever recorded before. Summer was also unusually dry, although only in June and July~~of 2021 were exceptionally hot and dry (Ilmastokatsaus, 2021). ~~The year~~In 2022~~ was warmer than normal and summertime~~, summer temperatures were ~~almost~~nearly 2°C ~~higher than normal. Southern and Western Finland experienced less rainfall than normally, whereas Central and Northern Finland experienced more rain ~~above normal, with varying rainfall patterns across the country (Ilmastokatsaus, 2022).

Sweden experienced ~~prior to 2018 two rather ~~dry years in 2016 and 2017~~. Especially~~, particularly in Southern Sweden~~,~~, where streamflow was 28% below normal~~ and many regions issued~~, prompting local water use restrictions (Geological Survey of Sweden, 2017). This drought ~~continued~~persisted and ~~culminated~~peaked in 2018, leading to the most severe wildfires in modern Swedish history (Swedish Board of Agriculture, 2019~~), which ultimately led to the most serious wildfires in modern times in Sweden (~~; Teutschbein et al., 2022~~). Fires like those in 2018 were~~ a, b). Current climate conditions made such fires approximately 10% more likely ~~in Sweden under current climate conditions ~~compared to pre-industrial ~~climate~~times (Krikken et al., 2021). Drought conditions eased in ~~the following~~subsequent years, with ~~the return of ~~slightly drier conditions returning in 2022~~.~~ (SMHI, 2023).

Norway ~~also ~~experienced ~~periods of drought in the years~~significant droughts from 2018~~-~~ to 2022. In ~~the ~~spring and summer ~~of ~~2018, temperatures were up to 4.7~~ ~~°C above normal~~ levels. Precipitation between May~~, and ~~September 2018 was only between 18-46% of the average ~~precipitation ~~level for the years ~~from May to September was only 18-46% of the 1991-2020 average (Norwegian Center for Climate Services, 2023). ~~The summer of 2018 had~~This year marked the longest ~~consecutive~~ drought period in ~~the past ~~five years~~, but~~ 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 ~~for the country being August 2021 ~~(Norwegian Center for ~~climate services~~Climate Services, 2023). ~~This led to a reduction in groundwater~~Ground-water (GW) levels ~~down~~below the tree line dropped to 75% of ~~the ~~average ~~levels in most of South-eastern~~in southeastern Norway ~~below the treeline ~~in August 2018 and August 2022, ~~causing problems for~~impacting agricultural production ~~in the region ~~(NVE, 2023). ~~As predicted by climate~~Climate models ~~(projection for 2031-2060, RPC 4.5. Reference period 1971-2000), precipitation is becoming~~predict more concentrated precipitation, leading to ~~periods of ~~floods ~~(during~~in early spring and ~~on certain days in~~some summer~~)~~ days, followed by ~~periods of drought (~~droughts in late spring to summer~~)~~ (Hanssen-Bauer et al., 2017).

In 2018~~, most parts of~~ the **United Kingdom (UK)** ~~suffered a~~experienced combined ~~heatwave~~heatwaves and ~~drought~~droughts (Holman et al., 2021). ~~In some parts of the UK a protracted dry spell~~This extended into late 2018 and 2019 in some areas (Turner et al., 2021). ~~Nonetheless, humid weather conditions in the period from ~~From June 2019 to February 2020~~ led to~~, humid conditions caused harmful ~~flood events~~floods (Sefton et al., 2021). The year 2020 ~~was~~saw a hot~~ with a~~, dry spring ~~but~~followed by a wet summer (Kendon et al., 2021~~) and the year~~). In 2021~~ continued this trend with temperature ~~, temperatures and rainfall ~~reaching~~were slightly below the long-term average (Met Office, 2021). ~~The year~~In 2022~~ was~~, the UK recorded its first ~~with an ~~annual average temperature ~~across the UK ~~exceeding 10°C~~ for the first time~~, while ~~the UK's ~~total rainfall ~~accumulation has ~~remained~~ persistently~~ below average (Met Office, 2022~~,~~; Royal Meteorological Society, 2023). ~~At~~The areas of Coningsby~~,~~ and Lincolnshire~~, a temperature above 40°C was~~ recorded temperatures over 40°C for the first time in ~~the weather record~~UK history~~ of the UK~~ (Met Office, 2022).

2.3 Drought and heat in the Central zone 2018-2022

Due to its geographical location and unfavourable hydrological conditions, **Poland** has relatively few natural water resources ~~relative to~~compared to the rest of central/eastern? Europe (Ministry of Climate and Environment, 2023~~,~~; SUSZA, 2023). ~~The relative scarcity of water resources is illustrated by the fact that almost~~Almost 40% of Poland's arable and forested land ~~in Poland~~ is permanently threatened by drought (Polish Supreme Chamber of Control, 2021). Drought ~~in~~impacts Polish agriculture ~~typically occurs~~approximately every five years, ~~and~~but recently it has ~~covered significant areas of the country almost every year – in~~ affected large areas nearly annually, including 2015, 2016, 2018, 2019, and 2020. In 2018, ~~the~~severe soil drought ~~was severe with regions having more than~~ resulted in over 50 days of no plant-available water ~~(~~in regions like Wielkopolska and Kujawy ~~Region;~~ (Wawrzoniak et al., 2019). ~~In recent years, soil~~ Soil droughts have also been observed ~~also~~ in ~~large parts of~~extensive forested areas in recent years (Lech et al., 2021).

The 2018 severe drought ~~event of 2018 was~~ centred over southwest **Germany**, the **Benelux countries,** and ~~northeast~~northeastern **France**~~, the centre of the~~. The 2019 drought ~~was further~~shifted east, ~~with~~impacting Eastern Germany and neighbouring countries~~ most affected. The severity of~~. Although the 2019 ~~summer~~ drought was not ~~exceptional in itself, but the fact that it was a second~~exceptionally severe, consecutive drought ~~year led to a worse~~years exacerbated the water ~~deficit than 2015~~deficits in ~~many parts of~~ Germany (soil moisture impacts, Xoplaki et al., 2023) and France~~ (as 2015 was the worst drought until 2018). Also, the spatial extent of the 2019 drought exceeded that of previous years. Using~~. GRACE data~~, Boergens et al., (2020) found~~ indicated severe drought conditions ~~were most severe~~ in ~~the~~ western ~~part of~~ Germany in autumn 2018, ~~while drought conditions were most severe in~~shifting to Eastern Germany and Poland in summer 2019~~.~~ (Boergens et al., 2020). Germany and France~~ (with exception of~~, excluding Southern Germany~~)~~, experienced continued drought ~~conditions till~~ until late summer 2020. Summer 2021 ~~brought a relief in terms of~~ saw heavy precipitation~~, leading to~~ and a severe flooding event in Central Europe (Mohr et al., 2023). ~~The summer of~~In 2022~~ saw a return to~~, extreme drought conditions ~~in~~affected Germany and France~~. These dry conditions were related to persistent lack of~~ due to low precipitation ~~combined with~~ amounts, and occurrence of early heatwaves in May and June. ~~Overall, the extent of drought~~ Drought-affected areas in Germany reached ~~almost~~ 40% of the country in 2022, followed by ~~2019 (~~30~~%), 2018 (~~% in 2019, 19~~%)~~% in 2018, and 16% in 2020~~ (16%).~~ .

2.4 Drought and heat in the Alpine zone 2018-2022

In 2018, **Switzerland**~~, 2018 included~~ experienced the fourth warmest spring ~~(March, April, May)~~ and ~~the~~ third warmest summer ~~(June, July, August)~~ since ~~the start of~~ instrumental measurements began in 1864 (Bader et al., 2019). ~~While summer~~Summer 2018 received only 70% of the long-term mean precipitation (1981–2010), though above-normal winter rainfall ~~(including snowfall) was above normal, which~~ helped ~~alleviate~~mitigate the summer's worst impacts~~ of the summer.~~

~~Between~~. From 2019 ~~and~~to 2021, frequent summer heat episodes occurred ~~during the summer seasons, but mean~~, with normal winter precipitation ~~during winter was about normal. This changed in~~. However, winter 2021/2022~~, when~~ saw anomalously warm and dry conditions ~~persisted~~, especially in Southern Switzerland and Northern Italy. Summer 2022 ~~saw~~had record-breaking temperatures~~.~~, with July ~~2022 was~~being one of the hottest months since ~~measurements began in~~ 1864, ~~beating some of the records set only four years earlier. The heat was accompanied by~~ and low rainfall~~, which~~ led to record~~-~~-low levels ~~for~~in many lakes in Eastern and Central Switzerland.

Austria ~~with~~, despite its ~~Alpine topography is~~ generally ~~considered as a~~ water-rich ~~country with freshwater resources that exceed demand even in relatively dry years. However, Austria did experience~~Alpine areas, faced exceptional heat and drought ~~episodes in recent years, particularly~~ in 2018 and 2022, raising concerns about water availability (Stelzl et al., 2021). ~~One factor is a~~A significant decline in ~~observed~~ snow depth in the ~~wider~~ Alpine region, ~~which is required to~~that could balance the increased summer evaporative demand ~~in summer~~, exacerbated these impacts (Matiu et al., 2021). ~~While the~~The summer of 2019 was less dry ~~in Austria, it tied for the~~but record-breakingly hot (Olefs et al., 2021). Summer 2022, the fourth warmest ~~summer~~ on record ~~with 2003 (since at least 250 years). Summer 2022 was the 4th warmest in recorded history, taking place right after a rather~~, followed a dry and mild winter, and while ~~several heavy~~ rainfall events occurred, they ~~barely alleviated the~~ 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 ~~was affected by~~ experienced less impact from the 2018 drought ~~to a lesser extent~~ compared to Central and Northern ~~European countries. For instance, there were~~ Europe, with no significant soil moisture anomalies ~~and~~or forest ~~disturbance during 2018 in Italy (see Fig. 1 in~~ disturbances reported (Senf ~~and~~& Seidl, 2021a). ~~Drought~~

However, drought conditions persisted ~~during~~into the summers of 2021 and 2022 ~~summer~~ (Toreti et al., 2022a~~). The~~), exacerbated by a winter rainfall deficit ~~during winter 2021 to 2022 exacerbated drought conditions across the peninsula~~ (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 ~~continued to be rather~~ remained relatively dry (Toreti et al., 2023).

In **Spain**, precipitation in the 2020/2021 water year ~~precipitation~~ was 5% below ~~the~~ normal ~~value. Between the start of the next hydrological year on 1~~. From October 2021 to ~~the next reporting date on 8~~ early March 2022, ~~the national average value of~~ accumulated rainfall was 38.2% below ~~the normal value~~ average (BOE, 2022). As of ~~8~~early March 2022, the peninsular water reserve ~~stood at~~was 40.5%, ~~significantly lower than~~markedly below the 5-year average ~~for the last 5 years (of~~ 52.5~~%)~~% and the 10-year average ~~for the last 10 years (of~~ 60.8~~%).~~%. The water reservoir ~~network in Spain was conceived to sustain~~system, designed to manage demand during dry ~~years~~periods using ~~the~~ reserves from ~~prior wet~~wetter years, has been strained by consecutive years~~. The succession~~ of ~~years with~~ below~~-~~-average precipitation ~~experienced in the region~~ since ~~the~~ 2012/2013 ~~water year, with the sole exception of~~, except for 2017/2018~~, led to low to depleted water reserves compounding~~

the extremely persistent . The 2021/2022 hydrological and meteorological drought conditions in the years 2012-2022 (BOE, 2022). The hydrological year 2021/2022 ended as one ofyear was among the three driest years on record, with precipitation 25% less precipitation thanbelow average and water reservoirsreservoir levels at around 35%, the lowest in 27 years (Greenpeace, 2022).

The last Over the past 20 years have been particularly dry in, mainland **Portugal** has experienced significant drought, with 6 of the 10 driest years occurring after post-2000, including 2017-2018, 2019, and 2021/2022. The average value of the amount of precipitation in the 2021/2022 hydrological year 2021/2022 (recorded 488.3 mm), shows of precipitation; a precipitation deficit of -393.8 mm, compared to the normal accumulated precipitation for 1971-2000. Compared to previous years of drought, 2021/2022 it is average. It ranks as the 3rd driest hydrological year after 2004/05 andsince 1944/1945, presenting a sharp deficit in relation to the average value throughout the yearfollowing 2004/2005 (APA, 2023).

For the period From 2018 to 2020, drought in Portugal was affected by drought to a lesser extent, and mostly inless severe, predominantly affecting the southern part of the countryregions (Figure 1). TheDuring 2019/2020, drought conditions impacted water storage, with monthly storage deviations from the average in the last hydrological years, showing that in 2019/2020 the hydrological drought waswere more severepronounced, with five of the eleven hydrographic basins in Portugal maintainingshowing negative monthly storage deviations throughout the year. The 2020/21 hydrological2021 year ended with onlysaw four watershedsbasins with below-average storage levels (APA, 2023).

2.6 Drought 2.6 European droughts from past to future: an attribution challenge

As discussed earlier in the general introduction, aA long-term drying trend has been observed in Central and Southern Europe in recent years and, with climate- simulations projectprojecting these trends to continue (Stagge et al., 2017,; Ukkola et al., 2020,; Bakke et al., 2023). There is high confidence that both temperature increaseincreases, and precipitation decrease hasdecreases have already led to increased aridity in the Mediterranean region (IPCC, 2021a). According to the lastlatest IPCC report (IPCC, 2021b), thethis combined warming and drying trend is already attributable to human causes. This trend is less clear in Western and Central Europe (Germany, Northern France, Southern UK), which is not surprising given the fact that , but there is high confidence ofin decreased aridity in response to a meanincreased precipitation increase in Northern Europe (Scandinavia, Scotland, Ireland) in a warmer climate (IPCC, 2021a). Nonetheless, using summer However, Christidis and Stott (2021) found increased drought risk in France and Germany based on summer SPEI trends between 1950-2018, Christidis and Stott (2021) found that there is an increased drought risk also in France and Germany, both in observations and in CMIP6 model simulations.. South-eastern Europe is also affected, following an analysis based on rainfall and precipitation--minus evaporation potential evapotranspiration (P-PET) reanalysis data (1950-2018; Christidis and Stott, 2021). A similar result is found when analysing longerLonger-term SPEI trends (1902-2020), where) indicate drying hotspots in terms of drying were found in Spain, Portugal, Southern France, Italy, Eastern Germany, the Czech Republic, Poland, Hungary, Slovenia, and Croatia, with the opposite trend in Norway (Ionita et al., 2021a). The same authors hypothesise that those observations might be linked to changesChanges in large-scale atmospheric circulation in the North Atlantic region may be linked to these drying conditions (Ionita et al., 2022). Others have highlighted that the changes in the North Atlantic circulation may in turn be linked2022) and possibly to the slowdown of the Atlantic Meridional Overturning Circulation (AMOC; Caesar et al., 2018). Hence, the question remains to whatThe extent the observedto which these trends are directly (thermodynamically) or indirectly (dynamically) attributable to anthropogenic factors. There are two ways impact remains a question.

Two approaches have been widely used to address this question more broadly: (1) The: i) the paleo-climatic perspective based on proxy data (climate indicators like pollen, tree rings, etc) and (2and 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.

(1) Looking at climate reconstructions based on proxy data that are typical for summer conditions over the Czech Republic and neighbouring regions in Poland, Germany, Austria, Hungary, and Slovakia, Büntgen et al., (2021) found that the most recent drought extremes between 2015 and 2018 are not only unprecedented during the period of proxy-target overlap, but also in the context of the past approximately 2,000 years. In other words, the most recent drought episode is beyond the variability seen in proxy data from paleoclimatic records that reach as far back as two millennia. These results are in contrast to findings by Ionita et al., (2021b), who claim that mega-droughts during the 15th and late 18th/early 19th century were longer and more severe compared to recent drought events. It is noteworthy, that both studies used summer scPDSI (self-calibrated Palmer Drought Severity Index) data which are not entirely comparable with SPEI, but they should at least be consistent against one-another. We can thus only conclude that neither the location (central part of Europe in case of Ionita et al., (2021b)), the method (the latter based on the Old World Drought Atlas; Cook et al., 2015), nor the spatial extent considered may be different. What the results do highlight though is that it remains difficult to draw definite conclusions as far as current drought intensity in a historic or paleo-climatic context is concerned.

(2) Climate model projections based on the latest CMIP6 assessment broadly confirm the historical trends deduced from observations. As shownobserved in ICCPdrought conditions. According to the IPCC (2021b), the rainfall deficit is projecteddeficits are expected to be most pronounced during the summer season (by the end of the 21st century vs current conditions).in Central and Southern Europe. While increased winter and spring precipitation may offset some summer water deficits (i.e. a negative hydrological balance some of the summerly water deficit,), this is unlikely to be the case in for France and, Germany (, and certainly not in the Mediterranean region). Given that trends. Trends in evapotranspiration are, already negative with regard to the annual mean, the negative trend is only going to intensify in summer for the time being. In this context, it is important to note that annualannually, are projected to worsen in summer. Annual mean rainfall changes are not informative when it comes to for drought attribution. In fact,, as drought and heavy precipitation is often occurringevents can occur in the same season, leading tocreating adverse conditions for the agriculturalagriculture and forest sectorforestry despite a climatologically balanced mean rainfall amount. In tandem with the rainfall deficit, it is very likely that meteorological.

Meteorological drought conditions will occur muchare likely to become more often thanfrequent under recentcurrent climate conditions (e.g. projections (Mömken et al., 2022 for the Iberian Peninsula). It is highly unlikely that the 2022). The current stringseries of extreme drought years is an exception, rather it islikely a harbinger of what will soon be theprecursor to a new normal in large parts of Europe. That said, theseThese projections are valid only forapply to transient warming conditions. If we stop emitting ; if carbon toemissions cease, the atmosphere, the planetclimate will slowly transition from its current transient warming state and enter the to an equilibrium warming phase following an e-folding trajectory. Thermodynamically, the transient warming state is characterised by a maximised , reducing the land-ocean temperature contrast between land and ocean (land masses warming much faster than ocean waters), causing the water deficit over land to increase even more than it would under (hypothetical) uniform land and ocean warming conditions. Given that the water vapour supply from oceans is limited due to relatively cooler ocean SSTs, the relative humidity over many land areas decreases and potentially altering the drying trend (Byrne and O’Gorman, 2013). While not relevant for the near future, it should be kept in mind that the current drying trend is unlikely to continue if the climate system is allowed to return to a new equilibrium state, which has recently been highlighted by; Dittus et al., (2024) as well.).

How do these two lines of evidence compare with actual attributionAttribution studies of individual extreme drought events? While it is generally straight-forward to attribute are complex due to the low signal-to-noise ratio. While heat waves are easily attributed to anthropogenic climate change (e.g. Vogel et al., 2019; IPCC, 2021a), the fact that the signal-to-noise ratio for drought events is still low despite attributable global warming of 1.2-1.3°C, which leaves the attribution community in a limbo as far as robust results are concerned. For example,remain challenging to attribute robustly. Van der Wiel et al.,. (2022) concludesfound that drought eventsdroughts like those from 2018-2020 are part ofwithin the realm of current climate possibilities in the present-day climate, that is, a comparable event was expected to occur based on the average frequency or return period as eventually , with the signal will emergeemerging from natural variability with the detrimental effects forover time, impacting biodiversity and human health in general. .

As it is difficult to reconcile the existing lines of evidence, only a few drought attribution studies have tried to quantify the role of humans thus far. A prominent rapid event attribution of the intense 2022 drought in Central and Western Europe showed that human-induced climate change made the root zone soil moisture drought about 3-4 times more likely, and the surface soil moisture drought about 5-6 times more likely (Schumacher et al., 2022). The authors concluded that while the magnitude of historical trends vary between different observation-based soil moisture products, they all agree that the dry conditions observed in 2022 would have been less likely to occur at the beginning of the 20th century. One study on the 2015 European summer drought concluded that the attribution results depend on the methodology used (Hauser et al., 2015). OnlyHuman influence on the increased likelihood of Central European droughts could only be detected when using the largest possible forcing difference in CMIP5 models, were they able to detect a human influence for an increased likelihood of Central European droughts.. García-Herrera et al.,. (2019) analysed the drought that affected France and western Germany from July 2016 to June 2017, stating that recent trends, including those in human-induced higher temperature, have exacerbated the severity of the drought event. Finally, Philipp et al.,. (2020) investigated the hydrological drought of 2018, stating that the trend is driven by strong trends in temperature and global radiation rather than a trend in precipitation, resulting in an overall trend in potential evapotranspiration. Given that these trends match results from climate model simulations, the authors conclude that the observed trend in agricultural drought can at least in part be attributed to human-induced climate change.

3. Damages to forests

~~Drought and heat are environmental factors that can have harmful impacts on forest ecosystems.~~ Drought events compounded by heat waves can fundamentally transform the composition, structure, and biogeography of forested ecosystems (Allen et al., 2010, 2015). Overall, the consequences on forests can be summarised in three major impact categories: (i) physiological stress, (ii) insect outbreaks, and (iii) forest fires (e.g. Brodribb et al., 2020, Seidl et al., 2020, Mezei et al., 2022, ~~Salomon~~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, ~~The reduced water availability can also strongly affect the carbon cycle by limiting photosynthesis and nutrient uptake and lead to decreased growth rates and reduced carbon storage in forests. Heat and drought can also disrupt forest ecosystem dynamics and alter community composition~~

~~(Hicks et al., 2018), as tree species differ in their vulnerability to drought stress, leading to shifts in species abundance and distribution (Morin et al., 2018). These changes can also have cascading effects on other organisms that depend on forest ecosystems, such as mammals, birds, reptiles, amphibians or invertebrates such as insects and microorganisms (Liebhold et al., 2017).~~making their quantification challenging.

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

Heat and ~~dry conditions~~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~~EUROSTAT 2023). Furthermore, the value of forest areas is likely to decrease, if economically valuable tree species decline (Hanewinkel et al., ~~2012~~2013), and the cultural and recreational qualities of forests can suffer (Winkel et al., 2022). ~~Finally,~~

Heat and drought can ~~have consequences particularly for biodiversity, since forests provide habitat for a wide range of plant and animal~~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 ~~during 2018 have~~ increased ~~5-fold in large parts~~significantly across much of Europe ~~when compared with the average levels over the past three decades,~~in 2018, particularly in Central and ~~disturbances~~ Eastern regions, and remained above average ~~also~~ in both 2019 and 2020 (Senf ~~et al., 2021~~& Seidl., 2021a). However, there are opportunities to better understand the damage~~, offering opportunities~~ and to mitigate future harm.

3.1. Europe-wide damages to forests 2018-2022

~~To comprehensively assess the diverse effects of drought and higher temperatures on forests, we gathered Europe-wide data where applicable (Table 2). This multifaceted approach allowed for a comprehensive view of the multifarious impacts of drought and temperature elevation on forest ecosystems. Our objective was to elucidate the impacts by comparing the consequences of the drought period spanning 2018-2022 with a reference period from 2010-2014. Physiological stress indicators, specifically crown defoliation data segregated into conifers and broadleaves, were sourced from ICPTechnical reports (http://icp-forests.net/page/icp-forests-technical-report). Information regarding insect pests was obtained by analysing the extent of wood damage caused by insects, drawing from various reliable sources. Forest fire data were derived from the JRC Technical reports (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). To broaden our understanding, we incorporated tree cover loss data from Global Forest Watch (https://www.globalforestwatch.org/). Significant differences between the study period (2018-2022) and the reference period (2010-2014) were discerned utilising a t-test conducted with RStudio 2022.12.0.~~

~~**Table 2:** Differences between the study period 2018-2022 (18-22) to reference period 2010-2014 (10-14), where available. Denoted next to the higher average value ($\bar{x}$) in each cell are the results of the statistical tests: n.a. (not applicable), n.s.~~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.

~~(not significant), * significant (p<0.05), ** highly significant (p<0.01), *** very highly significant (p<0.001).~~

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

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

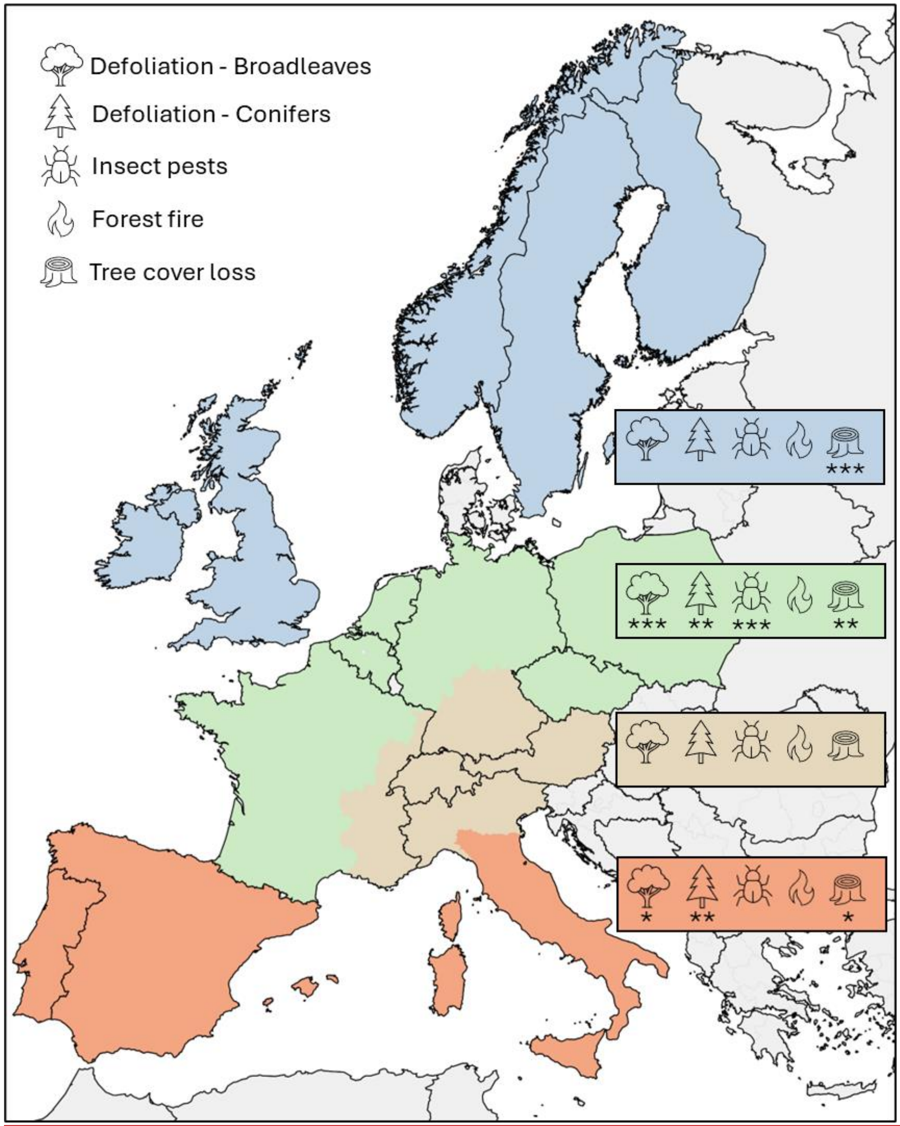


Figure 2: Differences in impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period (2018-2022) and the reference period (2010-2014). * significant ($p<0.05$), ** highly significant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

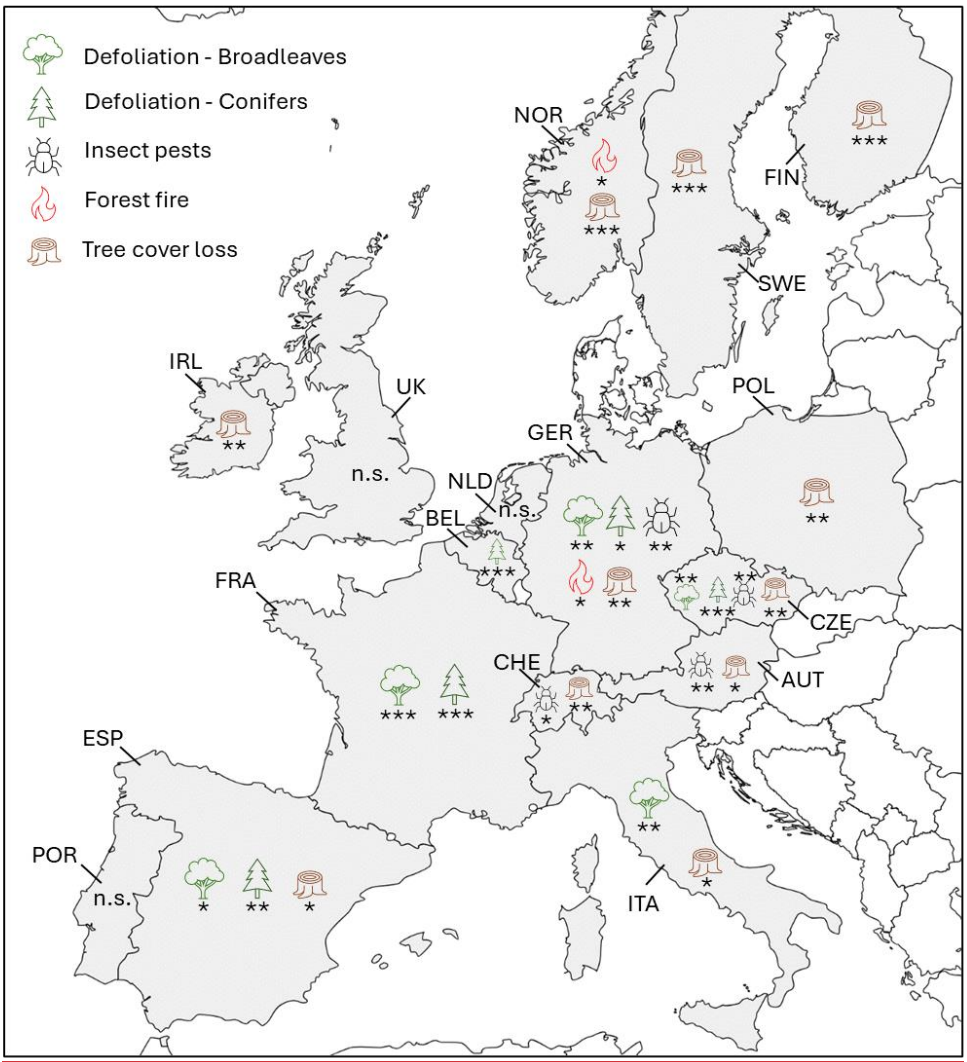
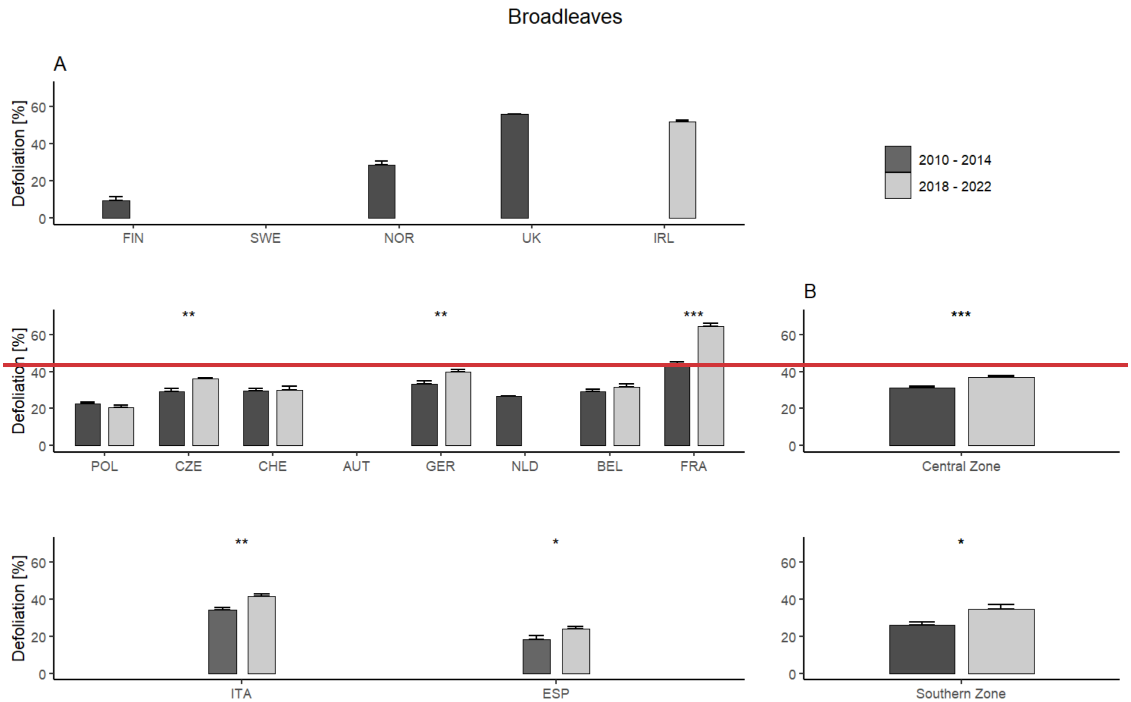
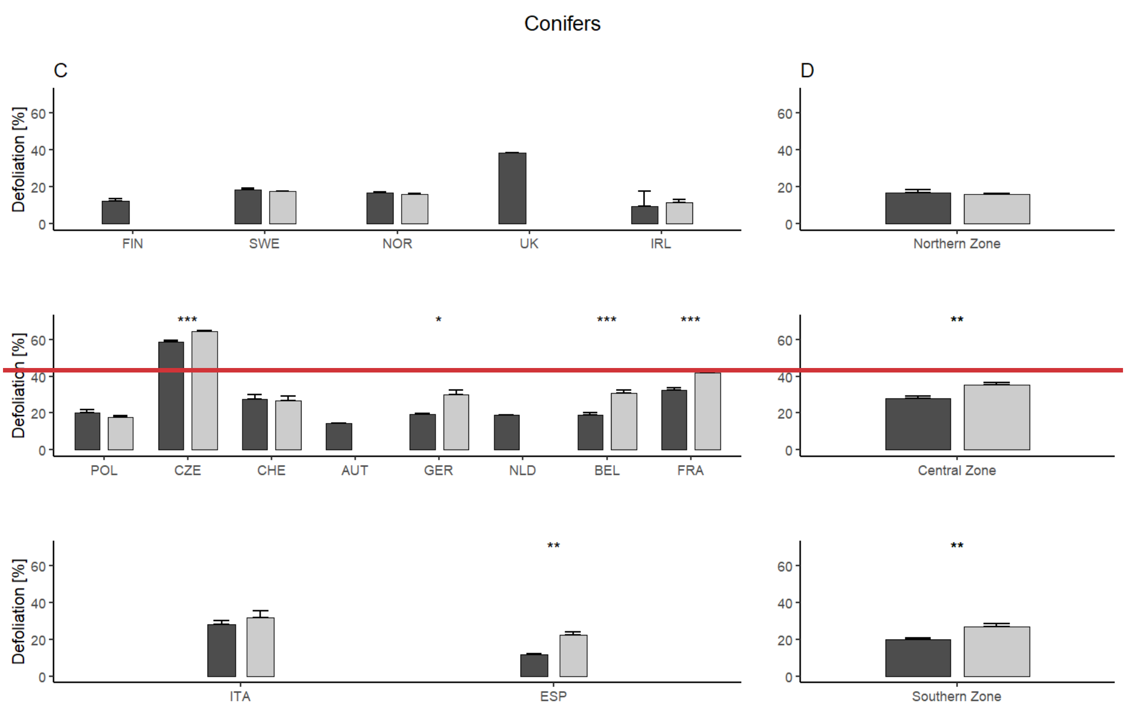
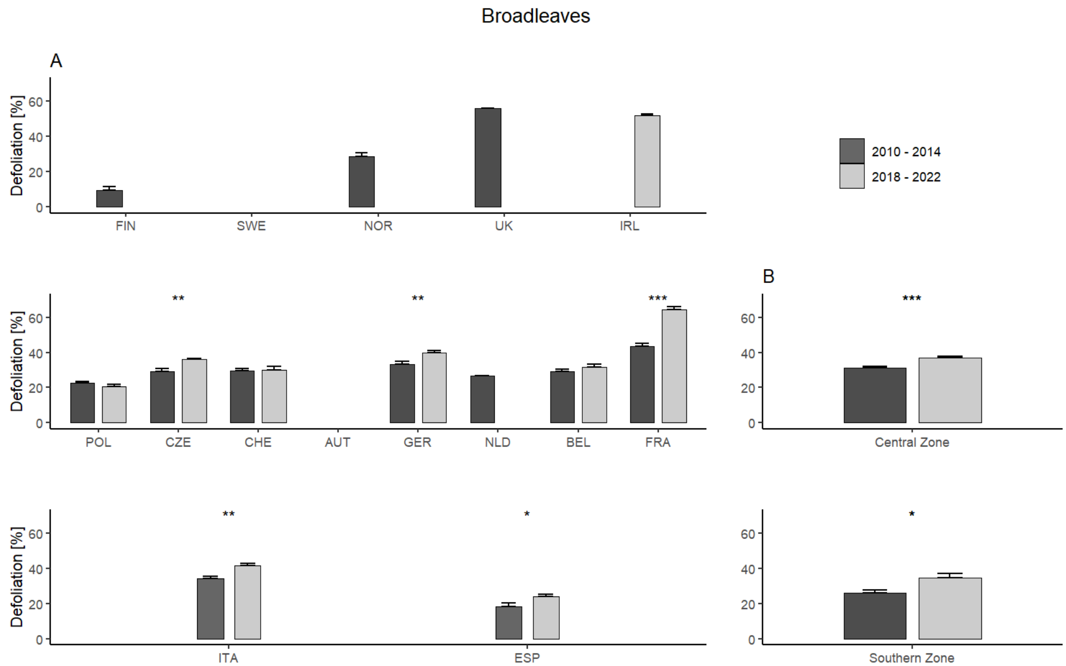


Figure 3: Significant differences in the 16 countries regarding impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period 2018-2022 and a reference period (2010-2014); n.s. (not significant),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





~~Figure 2.~~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
Central Zone
ITA
ESP
Southern Zone
**
***
*

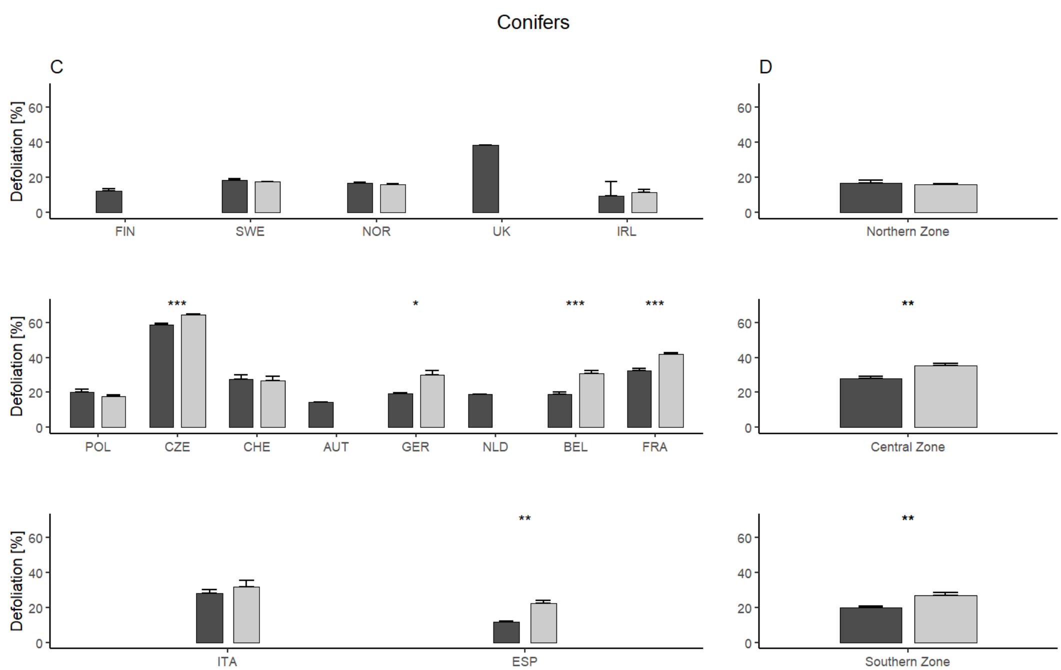

Conifers
C
D
Defoliation [%]
0
20
40
60
FIN
SWE
NOR
UK
IRL
Northern Zone
POL
CZE
CHE
AUT
GER
NLD
BEL
FRA
Central Zone
ITA
ESP
Southern Zone
***
**
*

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.

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

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

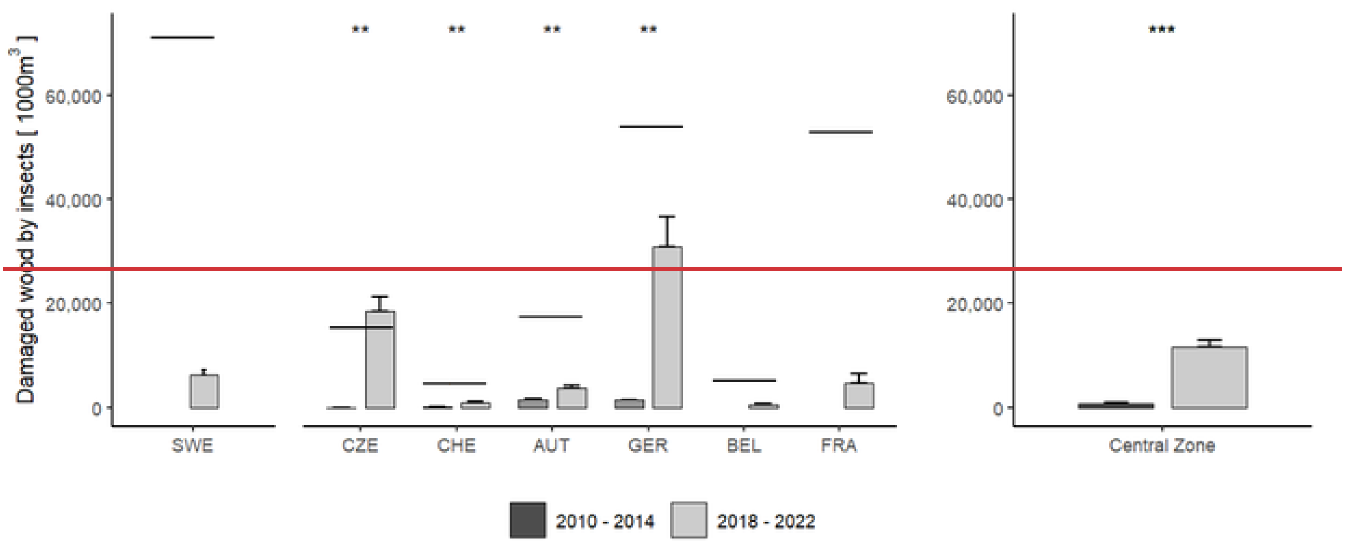


Figure 3. Damaged roundwood (1000 m³) by insect pests in Europe in the period 2018-2022, partly in comparison with the reference period 2010-2014. The black lines show the Total roundwood production average per year 2010-2014. Wood data derived from different sources (EUROSTAT 2016, Wulff and Roberge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

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

Damaged wood caused by insect infestation was significantly higher across Central Europe in the study period of 2018-2022 than the reference period (2010-2014), being particularly evident in countries such as the Czech Republic, Switzerland, Austria, and Germany (Figure 3).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.

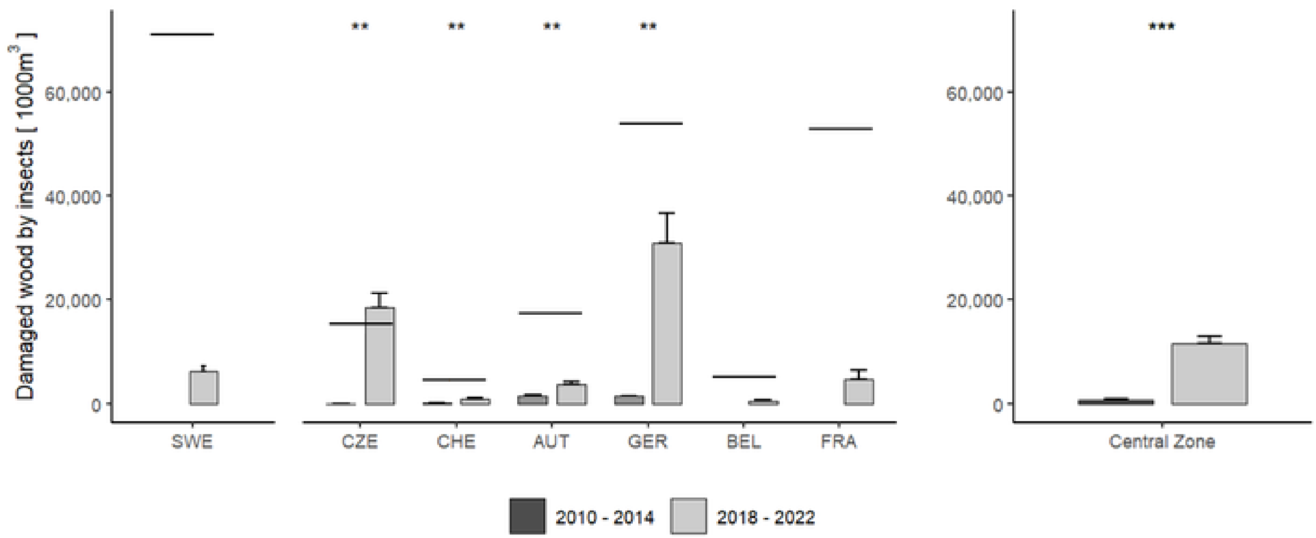


Figure 5.

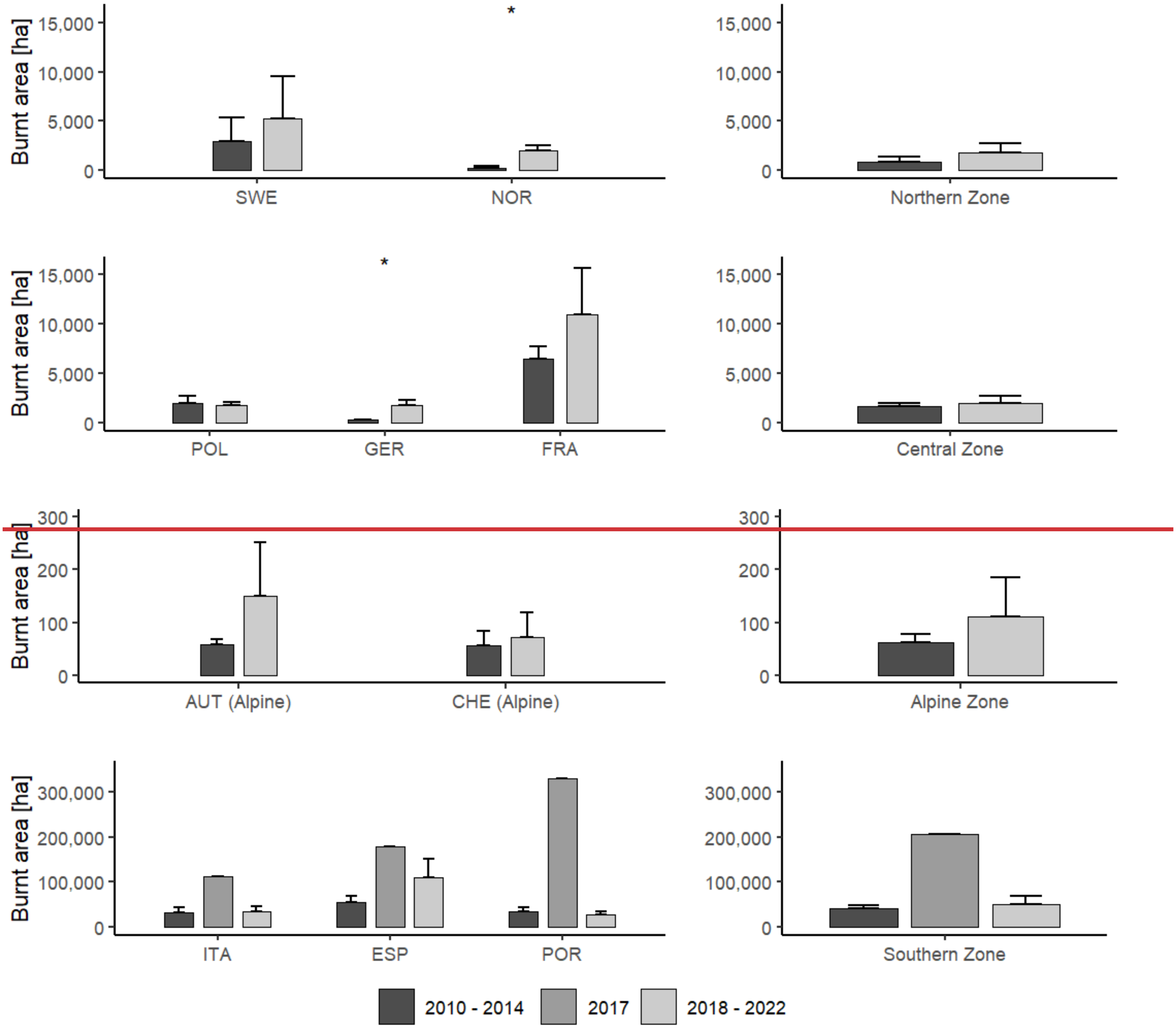


Figure 4. Damaged roundwood (1000 m³) by insect pests in Europe in the period 2018-2022, partly in comparison with the reference period 2010-2014. The black lines show the total roundwood production average per year 2010-2014. Wood data derived from different sources (EUROSTAT 2016, Wulff and Roberge 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.

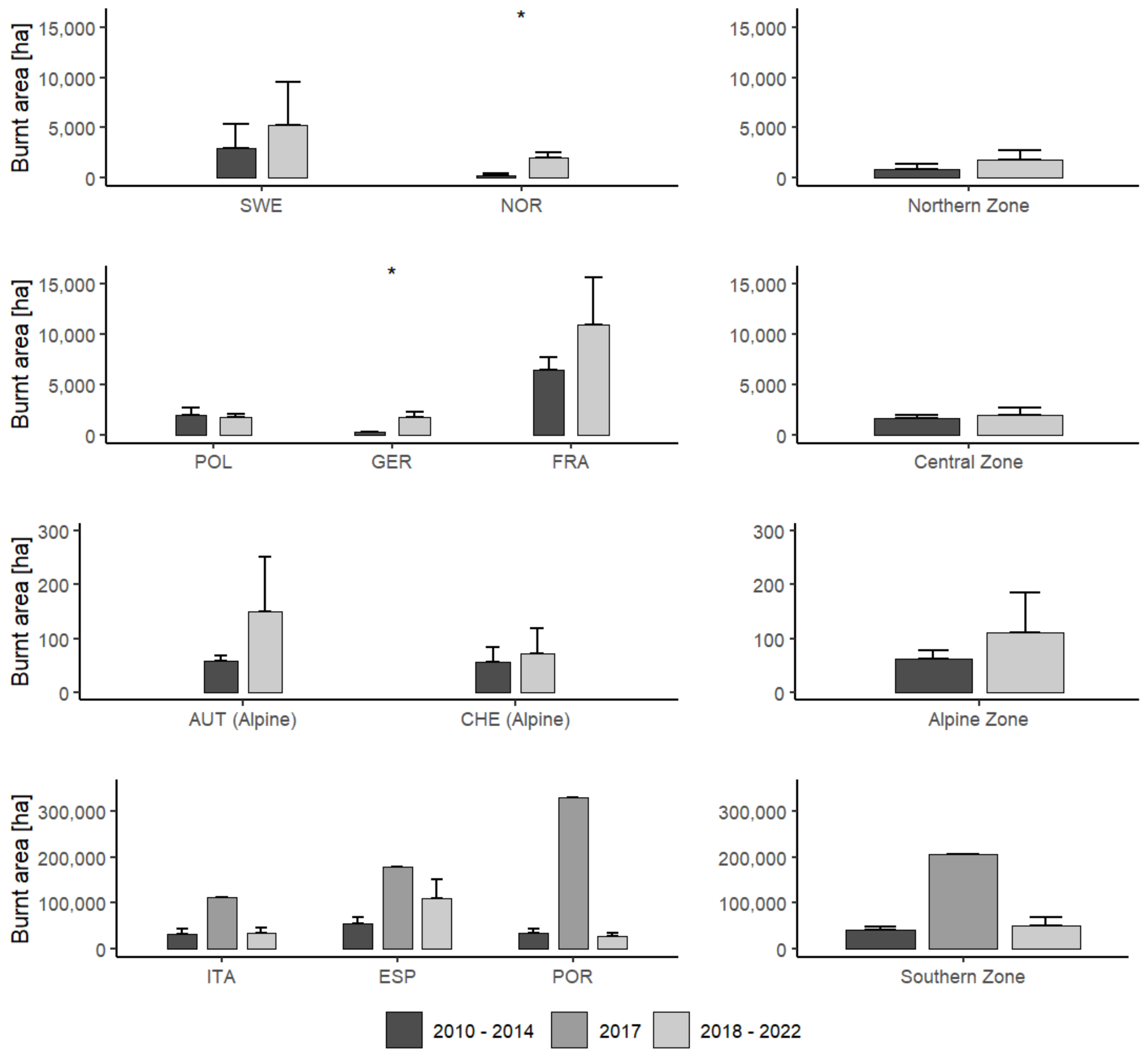


Figure 6. Burnt forested area (mean for the two periods under consideration) in selected European countries. Italy and Portugal had large fires in 2017 (accordingly, value for 2017 is given for the Southern zone). All data from JRC Technical Reports of

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 ~~stems~~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.

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

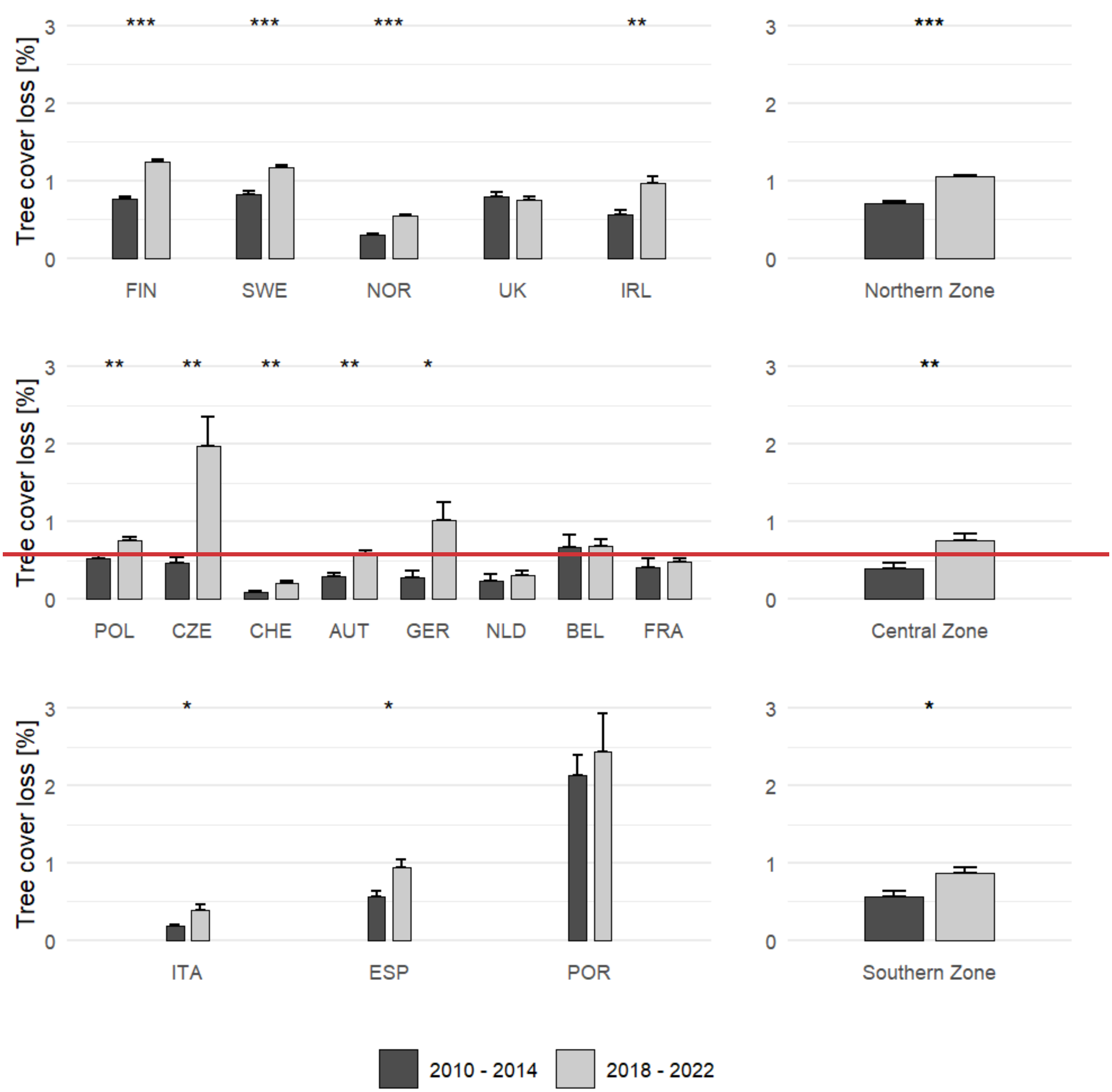


Figure 5. ~~Relative tree cover loss (mean for the two periods under consideration); data from GlobalForestWatch.~~

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

noted for Germany. Turning to the Southern zone, significant differences were evident, with Italy and Spain also showing significant differences. (Figure 7).

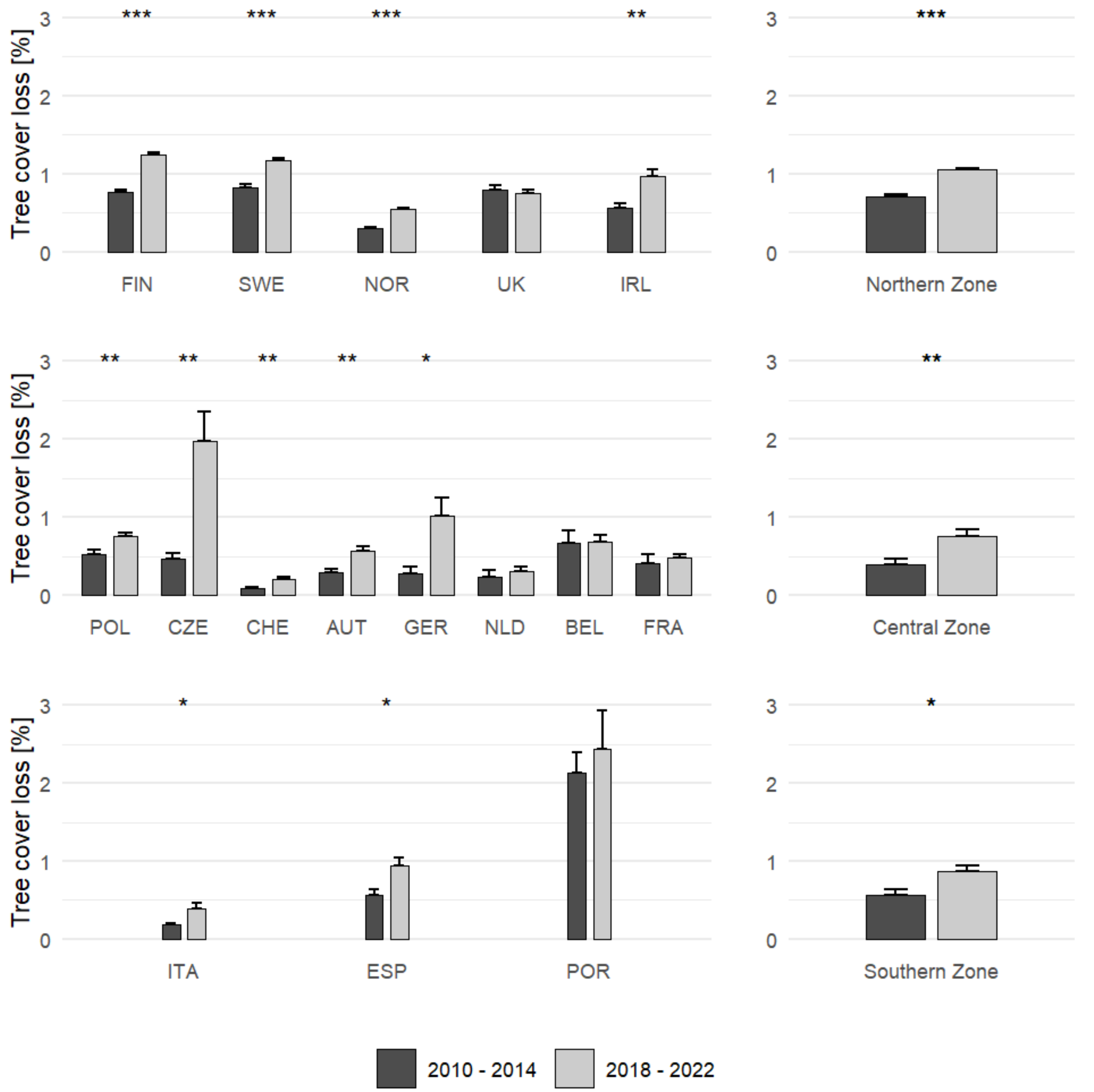


Figure 7. Relative tree cover loss (mean for the two periods under consideration); data from GlobalForestWatch.

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 ~~the~~ 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., ~~2022a, 2022b~~2022; Melin et al., 2022~~,~~; Terhonen et al., 2023). These numbers are high for Finland~~, because~~ given that the accumulated forest drought damage ~~previously for~~in years 2009-2015 ~~were~~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 ~~to~~, for example, to snow and moose-based damage (Nuorteva, 2019; Nuorteva et al., ~~2022a, 2022b;~~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 ~~in 2021~~ to 20,800 ha and ~~in 2022 to~~ 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 ~~more~~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~~) and forest~~). Forest damage could be influenced by the overall well-being of the trees. Additionally, the efficiency of collecting the fallen trees influences the bark beetle spread and outbreaks, since they provide prime habitat for the beetle population to grow (Hroššo et al., 2020).

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

In **Sweden**, about 90 million m^3 are felled every year (UNECE 2022) and the total forested area is 30 million ha (EFFIS 2023). Physiological damage, expressed as crown defoliation, was between 17.1 and 17.8% ~~in~~for conifers in ~~the years~~ 2018-2021 (data for ~~the year~~ 2022 and for broadleaved trees ~~was~~were not applicable; Michel et al., 2022). In Sweden ~~during 2018,~~ 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, ~~thus over 20~~

~~folds~~ more than ~~in~~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, ~~enabling a~~which allowed for rapid beetle population growth (Öhrn et al., 2021). In Sweden, the dry and warm period of summer 2018 led to ~~a~~the most severe outbreak of forest fires, ~~with estimates reaching roughly~~estimated at around 25,000 ha ~~(the total forested area in Sweden is 28 million ha)~~ and 3 million m^3 of wood damaged (Forestry 2018). Using the estimate of Venäläinen et al., (2016~~)~~), the costs for the year 2018 are ~~over~~more than 166 million ~~€ in Sweden.~~€. This is a similar estimate as if the ~~2014~~ forest fires in Sweden in 2014 (14,000 ha, costs: 1 billion Swedish Krona) ~~would be~~were upscaled to 2018: 160-200 million €.

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

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

The forest area ~~influenced~~affected by fires in Norway was ~~over~~more than 2,000 ha in 2018 and ~~reduced~~decreased to less than 1,000 ha in 2019 and 2020 (NIBIO, 2023). ~~During 2018,~~ A record number of 1,906 forest fires occurred between January and August ~~occurred 1906 forest fires, a new record.~~2018. Wells and drinking water resources were almost ~~emptied~~empty, low water levels in rivers led to fish dying, and electricity production was ~~down 20% compared to~~at times20% below normal production levels (-23 TWh~~) at times, which led~~), leading to higher electricity costs (MET Norway, 2019). Favourable wind conditions meant that the total ~~affected~~ 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~~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~~ in both 2018, with felling of~~: 1.1 million ~~m^3, 2019, with~~ m^3 in 2018, 1.23 million m^3 in 2019 and ~~2020, with~~ 1.1 million m^3 in 2020, despite low timber prices ~~on timber~~ especially in 2020. In comparison, the average felling in the 2010-2014 reference period was 896.~~000m3/~~000m^3/annum. To mitigate the consequences of the 2018 fires, 296,599 saplings were planted in 2019, and ~~a further~~another 250,000 in 2020, compared to an average planting of 131~~.~~,000 in the reference period. While there ~~were~~have been some short-term ~~consequences, there have not been lasting negative~~ effects~~ of~~, the drought in Norway ~~so far.~~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 ~~**United Kingdom (**~~**UK**~~),~~ ~~the area of woodland is estimated to be~~, woodlands cover approximately 3.24 million ha, with an almost equal distribution between conifers (1.65 million ha ~~(51%) conifers~~) and broadleaves (1.59 million ha ~~(49%) broadleaves ()~~ (Forest Research, 2022a~~).~~, b). Drought events have significantly impacted these woodlands in recent years. In 2018, early leaf senescence ~~due to drought~~ was observed ~~across much of the Southern UK~~ in southern regions due to drought (Michel et al., 2019). ~~In~~Although 2019~~, trees were not strongly affected by drought, since it~~ was ~~both warmer and~~ wetter ~~than average~~ and milder, thus mitigating severe drought impacts (Michel et al., 2020~~). Merely 3% of UK native woodlands are in unfavourable condition due to pests and diseases, but problems with oak health have been identified in the South and West of the UK (Quine et al., 2019, Michel et al., 2020). In 2020, a year of~~), challenges persisted in subsequent years. The 2020 weather extremes ~~(wet and hot),~~exacerbated ash dieback (*Hymenoscyphus fraxineus*~~) continues to spread across the UK. Accordingly, it is~~), with widespread future mortality expected ~~that the majority of ash trees will subsequently die from or be significantly affected by the disease in the coming years~~ (Michel et al., 2021). ~~The fungus-like pathogen~~ By 2021, *Phytophthora pluvialis* was ~~discovered in climatically average year 2021, where it was found to be~~ affecting mature ~~western hemlock and Douglas-fir trees~~ trees, and 2022's severe drought led to widespread defoliation (Michel et al., 2022; Forest Research~~ 2023c). In the very hot and dry year 2022, the trees lost their leaves in August over a large area due to the drought (e.g. Cheshire 2021). A comparison between 2015 and 2020 surveys reveal that 79% of woodland owners in UK observed an increase in pathogen in the last five years (Hemery et al., 2020). To counteract the damages associated with drought about 14,000 ha of new woodland were generated in the UK in 2020-2021, and there was a 4% increase in new planting and a 9% increase in restocking in the UK in 2021-2022 (Forest Research 2022b). In UK, there were large wildfires in the years~~ , 2022c). Wildfire activity has varied, with significant events in 2018 (17,689 ha burned ~~area~~), 2019 (28,754 ha), 2020 (13,793 ha~~)~~), and 2022 (20,362 ha~~), while over 2021 there were only 6,236 ha~~). The average annual burned area from 2011 to 2022 was around 10,000 ha (EFFIS Annual Statistics for UK, 2023). ~~The mean burnt area from 2011 to 2022 was 10,000 ha.~~

~~The area of woodland in~~In England ~~is estimated to be~~, woodlands span 1~~,323~~.32 million ha~~, with 343,000 (~~ of which 26~~%) ha Conifers~~% are conifers and ~~980,000 ha (~~74~~%)~~% are broadleaves (Forest Research, 2022a~~). In England, just over 79,000 ha land burnt throughout the twelve-year period 2009-10 to 2020-21 (2017-18: 2,352ha~~, b). Notably, 2018~~-19: 26,047, and 2019-20: 3,686ha, 2020-21: 6,251, 2022 was not applicable, data from Forestry Commission 2023). In 2018, England witnessed the worst wildfires in recent history (Turner et al., 2021). In the two major fires in the~~ saw severe wildfires in Greater Manchester ~~region, an area of~~, which burned 3,600 ha ~~burned, which could only be extinguished after more than a month: In Saddleworth Moor, seven square miles (i.e. 1,800 ha) of moorland burned (telegraph 2018), in Winter Hill also 1,800 ha (BBC 2018). Surprisingly, the overwhelming majority of wildfires have been in~~ and predominantly affected broadleaved ~~woodland (10.4%) and not conifer woodland (1.8%). The rest of the wildfires took place across all other land covers including built-up areas,~~

gardens, and grassland. According to the BBC (2022),woodlands (Telegraph, 2018, BBC, 2018). In 2022, the English fire services in England dealt with almost managed nearly 25,000 wildfires during the summer 2022, with more than 800 recorded wildfires on one single day (19.7.2022).

The area of woodland in(BBC, 2022). Wales is estimated to be , with 310,000 ha, with 152,000 ha (49%) Conifers and 152,000 ha (51%) of woodland equally divided between conifers and broadleaves (Forest Research 2022a). South Wales suffers from about 3,000 blazes a year and there is a strong possibility that this will continue to increase (e.g. BBC 2021a, BBC 2021b). Fires in , faces frequent fires, especially in the south. In the spring of 2020, fires in the sections of the Afan Valley and Seven Sisters forests have caused damage of more than over €115,000 (£100,000), in damage and destroyed almostnearly 140 ha of Natural Resources Wales (NRW) managed forestry including 80,000 newly planted trees (NRW 2020). , 2020). In Scotland, Forests and woodlands cover about 1,486.49 million ha, with 1.092 million ha (of forest, 74%) Conifers% of which are conifers and 395,000 ha (26%)% are broadleaves (Scottish Government 2019, Forest Research 2022a).. The region's forests, including Sitka spruce (*Picea sitchensis*) dominated major plantations along the east coast as well as Scottish rainforests along the west coast, are particularly at risk, since both are vulnerable to ariditydrought (Kirkpatrick et al., 2021). At a clear-cut area in Harwood Forest, Northumberland, the 2018 drought prevented the development of a SitkaAlthough no insect damage data were available, the great spruce orchard that would have formed from a clear-cut area in the second year after replanting (Xenakis et al. 2020). Inbark beetle (*Dendroctonus micans*) is now established in southern Scotland, wildfires are generally more likely to spread through grassland or peatland, however Scotland's forests - which are among the most productive in Europe - provide an abundance of flammable biomass ((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. and Land Scotland 2023). SeveralThe 2018 drought hindered forest regeneration, while wildfires were reported in April 2018 in the north of Scotlandand 2019 affected significant areas (Copernicus 2023). Wildfire severely affected 11,700 ha in 2019 (, 2023; The Herald, 2021). Statistics from the Scottish Fire and Rescue Service (SFRS) show that during In March and April 2022, 95 wildfire incidents (involving an area of more than 1,000 m^2) were wildfires were recorded across Scotland (Highland Council, 2023). Several Scottish keyKey industries are dependent on water supplies, which can be disrupted by droughts: e.g. such as whisky production (valued with £5.5 billion) and forestry (valued with £1 billion) GVA per year respectivelyare heavily reliant on stable water supply (Kirkpatrick et al.., 2021).

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

Ireland has a Ireland's forest area ofranges from 551,110 ha (EFFIS, 2023) orto 770,020 ha (Forest Statistics Ireland, 2020)), with a predominance of conifers (three -quarters conifers (, including 51% Sitka spruce alone) and one quarter broadleaves.. Physiological damage expressed as moderate to severe crown defoliation was only applicable for 2020 and 2021, where it was

~~very low for conifers (9.8 and 13.0%), but surprisingly high for broadleaves (53.4 and 52.0%; Michel et al., 2022). Furthermore, national reports about forest conditions state for Ireland that forest~~ (one-quarter). Forest health remains generally good, with high defoliation rates reported only in ~~2019 and~~ 2020 and 2021 (Michel et al., ~~2020,~~2022). Ireland's strict pest regulations and~~2021). Regarding tree pests, Ireland is generally known to have a good plant health status due to its~~ island status ~~and high plant protection regulations~~ protect against many forest pests (O'Hanlon et al., ~~2021),~~ 2021). Approximately 3,000 ha of forest burned annually from 2018 to 2022, which ~~provides protection from pest such as the eight-toothed spruce bark beetle (*Ips typographus*), which is absent from Ireland (Forest Health 2021). Around 3,000 ha of forest burned in each of the years 2018-2022 (see Table Fire). Compared to the~~ is moderate compared to record years ~~2011 (16724 ha) or 2017 (7219 ha), this is a moderate level of damage~~ (EFFIS Annual Statistics for Ireland, 2023).

3.3 Damages to forests in the Central zone 2018-2022

Poland has a forest area of 9,242,000 ha (Central Statistical Office, 2017). In 2018, the drought significantly weakened the condition of the forests ~~in~~over an area of 43.500 ha. ~~The~~In the same year, forest damage was observed ~~in~~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 ~~an~~the analysis of three parameters: average defoliation, the proportion of healthy trees (up to 10% defoliation), and the proportion of damaged trees (~~above~~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 ~~by~~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: ~~The~~ 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 ~~species of~~ forest trees~~:~~ species: the most severely infested ~~by mistletoe~~ were fir and pine trees, and to a lesser extent birch, ~~and~~as well as a mixture of deciduous species and spruce (Lech et al., 2019). ~~Also~~In addition, well-known forest pests such as the European spruce bark beetle (*Ips typographus*) continue to pose a ~~huge~~major threat to ~~the~~ Polish ~~Forests~~forests. The dieback of Norway spruce stands ~~increased~~was already ~~through the 1970s and 1980s~~ 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).

~~Surface losses occurred in recent years on State Forest land in Poland (source: DGLP, Dyrekcja Generalna Lasów Państwowych) in terms of drought (2018: 40,852 ha, 2019: 60,356 ha, 2020: 58,056 ha, 2021: 34,673 ha, and 2022: 20,258 ha). Surface losses in terms of high temperatures were relatively small (burns, wilt and dieback) were (2018: 80 ha, 2019: 340 ha, 2020: 2574 ha, 2021: 197 ha, and 2022: 244 ha).~~ Recent years have seen significant surface losses on Poland's State Forest land due to drought and high temperatures (Source: DGLP, Dyrekcja Generalna Lasów Państwowych~~):~~). Drought-related losses were ~~specified with~~ 40,852 ha (2018), 60,356 ha (2019), 58,056 ha (2020), 34,673 ha (2021), and 20,258 ha (2022). High temperature losses (burns, wilt, dieback) were reported with 80 ha (2018), 340 ha (2019), 2,574 ha (2020), 197 ha (2021), and 244 ha (2022). Long-lasting drought in Poland has also led to a lowering of the surface and ~~groundwater~~GW table, ~~and a~~as well as decrease in ~~the~~tree growth~~ of trees, the~~, stand vitality~~ of stands~~, and~~ their~~ resistance to pathogens and pests (Kwiatkowski et al., 2020). Among the species affected by this process are ~~oak trees~~oaks, where the impact of declining ~~groundwater~~GW has been observed since the late 1980s (Przybył, 1989). Current ~~groundwater~~GW fluctuations ~~are~~ further ~~weakening the~~weaken oak trees and ~~accelerating~~accelerate their decline (Jakoniuk, 2022), e.g. on the Krotoszyn Plateau (Danielewicz, 2016).

Furthermore, the prolonged drought ~~increases~~has increased the ~~fire hazard in forests. Although~~risk of forest fires. Despite the high number of fires~~ is high~~, the situation in Poland is relatively good. ~~As the~~The average forest fire in the state forests is only 0.25 ha, ~~indicating~~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~~ between 2011 and 2020, ~~, causing ~~a loss~~losses of approximately PLN 39 million. However, the year 2020 was marked by ~~an extremely~~a large fire (6,000 hectares) in the Biebrza National Park in ~~Northeastern~~northeastern Poland~~ (see Figure 3).~~.

In the **Czech Republic**, forest disturbances, mainly by pests, were triggered by drought and ~~higher temperatures:~~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 ~~current year's average~~mean in annual air temperature in the current year (Pirtskhalava-Karpova et al., 2024). In the Bohemian ~~forest~~Forest, it was observed that the surface temperature in stands subsequently attacked was higher in the year preceding pest colonisation when compared to intact stands (Kozhoridze et al., 2023). At the beginning of the massive bark beetle attacks, spruce accounted for 50.5% of stands, and pine for 16.4% respectively (Zahradník & Zahradníková 2019). This abundance of ~~trees sensitive for the~~ bark beetle-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, ~~leading to~~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 m^3 were harvested with 22.8 million m^3 of WII, and ~~for the year~~in 2020, the estimate ~~is ranking~~ranges between 40 and 60 million m^3 of WII (Fernandez-Carrillo et al., 2020). The timber damage was almost exclusively caused by ~~infestations with~~ European spruce bark beetle infestations (*Ips typographus* L.). The largest forest fire in Czech history broke out in Bohemian Switzerland in the ~~Northern~~northern Czech Republic and ~~spilled over into~~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 ~~mio.~~million m^3 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 ~~mined~~extracted since 2017~~. In the Czech Republic~~, 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 ~~in the Czech Republic (in this study~~ (2015-2019), ~~where~~with growth reductions in five major species due to drought conditions that were observed when compared to the reference period ~~of~~ 2005–2009 (Jiang et al., 2024).

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

Even if in Germany deciduous forests ~~in Germany~~ are not dying off to the same extent as coniferous stands, they are also strongly affected by climate change. In the forest condition survey (BMEL) in 2020~~), more~~, a record high number of dead trees ~~were recorded than ever before,~~was documented across all examined tree species ~~examined. Only about~~. The survey revealed that only 20% of ~~the~~ trees ~~did not show any~~exhibited no crown thinning, ~~for~~with European beech ~~it is only~~ showing an even more pronounced decline—only 11~~%,~~% of these trees were unaffected. Specifically, older ~~beeches (>~~trees (exceeding 60 years of age) and ~~trees at~~those growing in drier sites ~~show especially a~~ experienced notably reduced growth rates and increased mortality~~ (BMEL 2020,~~. These findings are corroborated by additional studies (e.g. Leuschner ~~2020).~~(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 ~~in Germany~~ (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 ~~inflicted~~caused widespread damage ~~on~~to forests, particularly during ~~episodes~~periods of heat and drought. In many cases,~~ the harvest was lost and~~ there was a need for emergency felling and even deforestation to prevent the pest from spreading (e.g. ~~HessenForst 2022;~~ Thonfeld et al., 2022; Bork et al., 2024). In ~~the German federal state~~ Thuringia almost 21 million m³ ~~in the period 2018 until 30.9.2022~~of deciduous (mainly beech) and coniferous (mainly spruce) ~~dead wood incurred~~deadwood occurred between 2018 and end of September 2022, of which around 65% due to insect infestation ~~fall~~ and 35% due to drought and storms (TMIL 2022). In 2022, around 344,000 m³ of damaged wood (202,000 m³ of hardwood and 142,000 m³ of coniferous) were registered ~~by~~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). ~~The estimates are~~It is estimated that ~~about~~around 500,000 ~~ha (~~hectares, or 4.4% of ~~the German~~Germany's forest area~~) forest~~, have been damaged by ~~drought~~ climate impacts, fires and bark beetles~~ and~~. These areas will need ~~to be afforested in order~~reforestation to ~~offset~~mitigate the ~~damages~~impacts of the drought from ~~the drought years~~ 2018~~-~~ to 2022 (BMEL 2023c). For the ~~approx.~~approximately 13.3 million m³ of damaged wood by bark beetles, 95.6% ~~goes back~~are due to activities of the European spruce bark beetle and 2.~~76~~8% to the Spruce wood engraver (*Pityogenes chalcographus*). Although the latter still plays a subordinate role, ~~this~~it could gain increasing importance ~~since the engraver~~given that it specialised on ~~weaker dimensions, which~~younger spruce stands. This is a large-scale threat in the future ~~regarding~~in terms of reforestation means or rejuvenation with conifers (TMIL 2022).~~ 2018, 2019, and 2022 were above average years for forest fires in Germany.~~ The years 2018, 2019, and 2022 were also above average for forest fires in Germany (DWD, 2022; UBA, 2023a). The burnt area ~~of~~in 2022 is more than five times the annual average ~~(since 1991)~~ of almost 776 ha~~, the pure wood damage~~ (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 ~~a field like~~ the German forestry sector, which generates about ~~€~~170 billion € annually and employs directly and indirectly more than 1.1 million people (Popkin 2021). Möhring et al., (2021) estimated the economic damage caused by the extreme weather events of 2018 to 2020 in the forestry ~~with an amount of~~sector at more than 12.7 billion ~~Euro – this corresponds to~~€, which is ten times the annual net profit of the entire German forest ~~economy in Germany~~industry.

In the **Netherlands**, there are clear signs that trees suffered from the drought and heat ~~in 2018, where especially~~of2018, with deciduous ~~tree~~ species ~~had~~in particular experiencing stunted or no growth (~~measurements by dendrometers, see Lerink~~Salomón et al~~., 2019~~. 2022). On a national level, the average volume of living and dead wood ~~continued to increase for the period~~increased during 2017-2021, although at a slower rate due to the dry summers in 2018-2020 (~~the seventh systematic~~

~~national forest inventory;~~ NBI-7, 2022). There are several indications of tree mortality: the volume of standing dead wood compared to the NBI-6 (2012-2013) shows an increase from 6.1 to 10.0 m^3 ha^{-1} from 2012-2013 (NBI-6) to 2017-2021 (NBI-7), respectively, and lying dead wood increased from 6.6 to 9.2 m^3 ha^{-1} for the same periods. However, there is no information ~~about~~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 ~~dying~~mortality of mature deciduous trees~~ was also observed, and also~~, as well as Norway spruce and larch~~ trees~~, 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~~. Information~~ (as of the time this text was written, data for 2022 ~~is~~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 m^3 of spruce were infested by bark beetles, compared to 5-10,000 m^3 in normal years. This number increased to approximately 1 million m^3 in the years 2019 and 2020 (Saintonge et al., 2021). During the colder and wetter year 2021, the newly infested timber volume has dropped again to about 500,000 m^3 (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 m^3 of wood, ~~are~~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 m^3 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 m^3 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 m^3 in 2021 (Saintonge et al., 2021), although this year was the only one in the period 2018-2022 that was not particularly hot and dry. The French government has allocated 150 million € for the period 2021-2022 to regenerate and adapt the impacted surfaces (Gouvernement Français 2020).

~~Another indicator to measure the impact of drought is the share of wood declared as accidental or sanitary products. This indicator only refers to commercially used timber, which could explain the lower numbers compared to the numbers on killed forest areas, which are often based on remote sensing data. The accidental products are often related to storm damage, while the sanitary products, which are responsible for the bulk of the total damage, relate to drought damage or to pest infestation and thus indirectly mostly to drought as well (MAA 2021a). The share of harvested wood of all tree species declared as accidental and sanitary~~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 (~~Beaufils 2022,~~ MAA 2021a), to 10.6% or 3.8 million m^3 in 2020 (MAA 2022a) and 4.1 million in 2021 (MAA 2023). Spruce is particularly impacted with more than 2 million m^3 in 2020 (MAA 2022a).

In addition, higher defoliation rates have been observed since 2015, which is probably largely due to the droughts and heat waves and a resulting increase of pests. While in 1997 only 2.2% of the deciduous trees and 1.8% of the conifers were affected, in 2019 ~~it is already~~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 ~~so far~~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 ~~centres of~~ regions most affected by drought and heat are primarily in the lowlands, ~~especially~~particularly in the east (Vienna, Lower Austria, Burgenland), ~~but also~~as well as in the southeast (Styria) and ~~in~~ the northern foothills of the Alps (Upper Austria, Northern Salzburg). ~~Austria was hit hard by~~ The country experienced severe bark beetle ~~attacks~~infestations between 2018 and 2022~~. In particular, in~~, resulting in significant timber losses, especially in 2018 (5,210,~~000m~~000 m^3), 2019 (4,690,~~000m~~000 m^3), and 2022 (3,750,~~000m~~000 m^3, see Figure 3~~) the wood losses were large. Overall,~~). In 2022, forest damage in Austria~~ 2022, which is~~, primarily ~~caused by~~attributed to climate change, ~~is~~was estimated at ~~around~~approximately 28 million ~~euros~~€ (Bundesforste 2023). Around 940,000 m^3 of wood was damaged~~ in 2022, which corresponds to around~~, representing about 59% of the total ~~amount of~~ wood harvested in 2021. The ~~main reason for~~primary cause of this ~~is an~~damage was a significant increase in bark beetle ~~damage. Due to climate change, Austria's largest forest pest has already spread~~infestations, with these pests now spreading up to the tree line at ~~around~~approximately 2,000 ~~meters~~m above sea level due to climate change (Bundesforste 2023). ~~In~~ Additionally, in March 2022, a ~~huge~~massive wildfire ~~raged~~ in Allentsteig~~ in~~, Lower Austria~~. With a burnt area of about~~, burned approximately 800 ha, ~~of which~~including 400 ~~hectares were forested,~~ha of forest, making it ~~was~~ one of the largest forest fires ~~that have ever occurred in Austria~~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~~). A study based on NDVI data confirms that drought impacts decrease with elevation: especially at above 1,500m (Rita et al., 2019). Damage caused by forest insects could only be detected sporadically, as during 2022 in East Tyrol (cipra 2022). In Tyrol, there was a bigger fire in the Alps in March 2022, directly across the border to Germany around 35 ha of mountain forest burned down in Pinswang in Tyrol (SZ 2022, Merkur 2022). An EUSALP study, initiated by the Austrian ministry, highlighted that the total direct costs for firefighting and for necessary measures on burnt areas (without preventive measures) in connection with forest fires are currently estimated at around 75 million € per year in the Alpine region. (Müller~~, 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**, ~~during~~in both 2018 and 2022, the ~~canopies~~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,~~ but only~~ 16% by insects (predominantly bark beetle), 1.2% by fire and 1.6% by drought (Scherrer et al., 2022). The interim results of the fifth state forest inventory (NFI5) over the survey years 2018 to 2022 clearly show that there is an increase in dead and damaged trees (WSL 2023b~~);~~). Spruce has declined in the Jura, the Mittelland and the foothills of the Alps, and the sweet chestnut on the southern side of the Alps. The decline of ash trees, attributed to ash dieback caused by the fungus *Hymenoscyphus fraxineus,* spread rapidly and reached the inner Alpine valleys within a few years, with East Tyrol being affected in 2010 at the latest (Heinze 2017). ~~The annually growing amount of wood is lower than five years ago.~~ In addition, fewer young trees are growing in a quarter of all forests throughout Switzerland. The Alps and especially the southern side of the Alps are particularly affected. Besides the interim results of NFI5, only a few reports ~~could be~~were found at high altitudes in Switzerland, as for example ~~about~~on a regional increase ~~in~~of bark beetles in the Alps in 2020 (e.g. Schreiner Zeitung, 2020; SRF 2020).

In **Italy**, ~~after~~following the Vaia windstorm in 2018, ~~the number of pests~~pest activity was ~~rather~~initially moderate~~, but at the beginning of June 2021, there was~~. However, a ~~pronounced~~significant heat wave~~, which~~ in early June 2021 triggered a massive swarming of the spruce bark beetle (Agrar-&Forstbericht Südtirol, 2021). ~~In~~By 2022, around 5,000 ha of the 350,000 ha of forest in South Tyrol were infested with the bark beetle (~~Tagessschau~~Tagesschau 2022). ~~From mid-May 2022, the bark beetle~~The pest then ~~spread~~ rapidly spread in Tyrol ~~(cipra~~from mid-May 2022 (CIPRA 2022~~). In 2021 around~~), with approximately 105,000 m³ of wood ~~were~~ affected~~, while~~ in ~~2022~~2021 and around one million m³ ~~were affected.~~in 2022. The total amount of damaged wood ~~in the years~~from 2018~~-~~ to 2022 ~~corresponds~~is roughly equivalent to ~~around~~ 15 times the ~~amount of~~ normal ~~use in a year~~annual harvest (Dolomitenstadt 2023).~~ In 2017~~

Additionally, a ~~long-term~~prolonged drought during the 2017 growing season led to the ~~largest fire~~most extensive outbreak ~~regarding~~of simultaneous fires ~~of the last 30 years~~ in the Alpine region~~:~~ in ~~autumn 2017, there were 11 simultaneous large fires in~~ the past 30 years. In the Piemonte ~~Region, Italy, that burned almost~~region, 11 large fires occurred in the autumn of 2017, burning nearly 10,000 ha ~~in a week, consuming mainly~~of mostly broadleaved forests within a week (Müller et al., 2020). ~~In~~ Furthermore, in October 2018, one of ~~the~~Italy's largest forest fires ~~ever with 632 ha~~ occurred in Monte San Lucano, ~~in the~~ Veneto~~ region in Italy~~, burning 632 ha (Müller et al., 2020).

3.5 ~~Forest damages~~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 ~~extra-tropical~~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).

~~More generally, for the period~~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 ~~the~~ peaks reached in 2021 (Bussotti et al., 2022~~),~~) and leaf discoloration mainly ~~occurring~~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 ~~the~~ large accumulation of dead wood in the forests (Bussotti et al., 2022).

The summer of 2022 ~~Italy~~ was affected by severe-to-extreme meteorological drought (Toreti et al., 2022a). Northern Italy was strongly affected, facing the warmest and driest winter ~~in~~on record ~~of~~in the last 30 years (Toreti et al., 2022b), resulting in strong hydrological drought and unusually low streamflow ~~in~~of the Po River, ~~which is~~ also related to the lack of snow~~ drought~~ in the Italian Alps that winter (Koehler et al., 2022). A study looking at the impacts of the 2017-2022 drought and heatwaves in forest areas of Tuscany found that the most severe impacts were observed ~~on~~in the evergreen Mediterranean tall woodlands and in the aged coppices (on holm ~~oak trees~~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**, ~~in the period~~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 ~~due to an increase in precipitation~~ (AIEF 2019). However, more recent reports over parcels in North-eastern Spain reveal a deterioration in defoliation ~~in the period of~~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, ~~Spain~~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 ~~3~~6).

Although **Portugal** ~~(Western Iberia)~~ has recently shown increasing frequency of drought conditions coupled with heatwave events (Bezak and Mikoš, 2020; Vogel et al., 2021; Ribeiro et al., 2020), leading to exacerbated limiting climatic conditions for plant growth, the situation of Maritime pine (*Pinus pinaster*, one of the most frequent species) is according to Kurz-Besson et al., (2016~~),~~) not completely discouraging. Detailed information regarding defoliation and damaged wood by insects in Portugal is unavailable since 2006 (ICP Forests 2007). ~~Also, data of damaged wood by insects was not available.~~
Since 1980, the mean annual burnt area has been around 115,000 ha, with a large interannual variability~~,~~ and ~~including~~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 ~~as a result from~~, which are influenced by the amount of precipitation during and ~~prior~~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 ~~in Portugal~~ totalled ~~almost~~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 ~~exceeding~~ exceedingly around 270 million € (295 million USD ~~(~~) (Global Fire Monitoring Center, 2018; AON, 2018).

~~Following the information from the~~ According to Global Forest Watch ~~(GFW, 2023, Figure 4), from 2000 to 2020~~, Portugal experienced ~~a reduction of 104,000 ha (-3.4%) in tree cover. From~~ significant TCL from 2001 to 2021, ~~Portugal lost~~ totalling approximately 1.13 million ha ~~of tree cover, equivalent to a 49% decrease in tree cover since 2000, with 10% of the loss occurring between 2018 and 2021. For the same period, 0.57% of~~. 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 ~~occurred in areas where the dominant drivers of~~from 2018 to 2022 amounted to 188,000 hectares. The loss ~~resulted in~~ during this period was predominantly driven by deforestation, ~~which in case of~~with permanent deforestation ~~was dominated by~~ mainly attributed to urbanisation and shifting agriculture.

4. Drought legacy

4.1. Drought legacy effects

~~Beyond the immediate damage caused by drought~~ Drought and heat ~~to~~impact vegetation~~, there~~ not only immediately but can ~~be~~also have long-term effects that ~~can~~ persist for ~~many~~ years. ~~Therefore, the short~~Short-term ~~assessment of~~ damage ~~can strongly underrepresent~~assessments often underestimate the overall ~~damage caused by an event in~~ impact on forest ecosystems. ~~The duration of a legacy damage can~~Recovery times vary ~~between different aspects of the observed ecosystem. For example, the~~; for instance, carbon cycle recovery and compositional ~~change can take~~changes may span several years (~~Mueller~~Müller & Bahn, 2022). ~~More specifically, long recovery periods were found in a~~ Severe droughts in temperate ~~forest, in which severe droughts caused~~ forests have led to growth ~~reduction~~reductions lasting up to 6 years, depending on tree species (Orwig ~~and~~& Abrams, 1997). ~~Further complicating the~~ Furthermore, long-term damage assessment is ~~that over long periods the target~~ complicated by vegetation ~~adapts~~adaptation to ~~the~~ persistent conditions. For example, pre-existing structural changes ~~related to~~in tree hydraulic traits ~~in trees before an extreme climate event can~~can either mitigate or ~~enhance the damage caused during an extreme event, depending on the direction of the shift~~exacerbate damage, influenced by shifts in plasticity (López et al., 2016~~), and an interspecies comparison showed that trees growing~~). Trees in drier ~~sites were more~~environments often show greater drought ~~resistant~~resistance (Orwig & Abrams, 1997).

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

4.2 ~~The connection of~~Linking vegetation drought legacy with groundwater drought legacy

~~Groundwater~~GW is a key component of the terrestrial water cycle~~ and contributes~~, contributing dynamics and ~~feedbacks~~feedback with vegetation ~~process at~~processes on time scales far beyond the weather and seasonal time ~~scale (Aesbach~~scales (Aeschbach-Hertig and Gleeson, 2012), which are especially important for the ~~evolution~~development and persistence of droughts. The vegetation water supply under meteorological and ~~hydrologic~~hydrological drought is determined by the redistribution of moisture in the shallow subsurface (soil) and its hydraulic connection with ~~groundwater (~~GW~~)~~ (Yu et al., 2017). Thus, the impact and legacy of drought strongly depends on the local and regional distribution of soil moisture, infiltration and ~~groundwater~~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 ~~groundwater~~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 ~~routing~~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 ~~process~~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 (~~Aesbach-Hertig and Gleeson, 2012;~~ 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 ~~groundwater depths. While there is a dependence on climate, and local and regional terrestrial conditions, the basic physical principles of the processes described above are universal.~~GW depths.

To assess the connection of drought legacy with ~~groundwater~~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 ~~data base~~database exists over Europe or for specific countries. Thus, the data remains fragmented and dispersed across ~~a large number of~~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 ~~Mid~~Northern and Central Europe, dispersed bore hole observations of ~~groundwater~~GW levels ~~reveal~~revealed that the 2018 drought was indeed one of the most severe in decades and comparable with the drought of 1976 (~~Schuldt~~Bakke et al., ~~2018).~~2020; Hellwig et al., 2020). In 2018, in many observation wells, ~~groundwater~~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 ~~server~~severe drought stress~~ also~~, even beyond the year 2018 (Schuldt et al., 2020). For example, Süßel and Brüggemann (2020) studied tree water relations in ~~2028~~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 ~~groundwater~~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 ~~also~~ showed distinct spatial patterns~~ from observations~~, with limited stress along river corridors and extreme stress in the upper parts of hillslopes along ridges (Cartwright et al., 2020). These patterns are directly related to ~~groundwater~~GW processes~~ that are the groundwater~~, specifically GW discharge and recharge, respectively. Under drought conditions, along river corridors, ~~groundwater~~GW discharges as baseflow toward the stream constituting essentially an outcrop of the ~~groundwater~~GW table, thus~~,~~ leading to shallow ~~groundwater~~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 ~~groundwater~~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 ~~groundwater~~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 ~~groundwater~~GW convergence zone. In the future, a merger of in-situ, remotely sensed, and model data with ensuing in-depth analyses ~~are~~will be required ~~in order~~ to identify potential tree and forest legacy effects induced by ~~groundwater~~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

~~Legacy of a drought event in~~ Drought events can leave longer-lasting impacts on forests~~ can take many forms (~~, depending on which tree demographic processes are most affected (Müller & Bahn 2022~~,~~; Rukh et al., 2023~~), depending on the tree demographic processes that are most affected (See Section 1.4 for more on soil moisture deficit and Rousi et al., 2023). The~~). Adult tree mortality ~~of adult trees~~ can create gaps in ~~a forest, influencing the~~ forests, altering carbon and water cycles, species composition, and long-term profitability~~ of an economic forest but also the carbon and water cycle and species composition. Forest~~. These gaps also increase understory solar radiation, temperature, and soil dryness~~ in the understory and the soil~~, which ~~may~~can lead to further damage ~~caused by~~through soil hydrophobicity ~~aggravating soil dryness, horizontal translocation of water, nutrients and soil, and additional dryland mechanisms of ecosystem functioning~~ and nutrient loss (Grünzweig et al., 2022). Similarly, the ~~mortality~~death or ~~diminished~~weakened vitality of saplings can ~~impede these processes, slowing down the overall recovery of the forest. Additionally, damage that does not cause mortality may weaken~~ 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 ~~and make them more susceptible for future droughts or to a different type of extreme events, e.g. storms (Gliksman et al., 2023) or fires and pests as described in detail in previous sections. We present several examples for the damage of drought~~ 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 ~~period on forests in Europe. However, we expect that future literature will examine this topic more in depth in the years to follow 2022, as either examination of recovery rates if the drought will come to an end, or, if the drought will continue for several years longer, then it would be possible to study the ongoing adaptation to drought. Below, we offer examples mostly relating to~~in European forests highlight these impacts. The most pronounced legacy effects involved saplings and young trees~~ as the more reliant aspects of legacy that can be observed during this drought period.~~

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

~~In Scotland, Locatelli et al., (2021) observe notable mortality rates among younger forest stands managed by the private sector, encompassing both restored sites and newly planted forests.~~

, 2020). Growth reductions ~~were also observed~~occurred in ~~North~~Northern Germany following the 2018 ~~due to~~drought, exacerbated by insufficient winter water recharge ~~during the winter of 2018/2019 (Scharnweber et al., 2020), and similarly in Germany~~, with similar reductions in 2019 and 2020 (Beloiu - et al., 2022). ~~Additionally, relating to growth reduction due to 2018, the GPP of the forests in~~In Switzerland, forest gross primary productivity recovered ~~during 2019 (due to normal amount of precipitation but with heat waves)~~ in about 50% of ~~the~~ forested area ~~but~~by 2019, while 49% remained ~~damaged~~ at ~~the~~2018 damage levels ~~of 2018, showing~~, 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 ~~the~~ individual countries ~~situated in it (Figure 2).~~within this zone. This suggests a relative stability ~~in~~of conifer health in this region, despite variations in environmental conditions. ~~Conversely, the Central zone exhibited a substantial and statistically significant increase in defoliation levels during the period of 2018-2022 compared to the reference period. This discrepancy was particularly evident in the Czech Republic, Belgium, and France, where the differences were highly significant. Additionally, significant differences in defoliation were noted in Germany, indicating a widespread trend of deteriorating conifer health in this region. In the Southern zone, notable deviations during the dry period of 2018-2022 compared to the reference period were observed, with Spain also registering significant differences.~~ Overall, our findings suggest that conifers in the Northern zone exhibit a greater resilience to drought and heat stress compared to those in other regions.

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

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

~~bark beetle disturbance, contingent upon the level of climate forcing and forest conditions (e.g., Dobor et al., 2019; Dobor et al., 2020b). The cumulative growing stock affected by bark beetles is projected to increase substantially under moderate climate change scenarios, with even greater impacts anticipated under hot and wet climate change scenarios compared to baseline conditions (Sommerfeld et al., 2020).~~

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, ~~we did not find~~no significant differences in forest fire outbreaks were observed between the dry period of 2018-2022 and the reference period of 2010-2014~~ (Figure 4).~~. This trend ~~is observed consistently~~was consistent across the Northern, Central, Alpine, and Southern zones. ~~Also, on request to individual~~Additionally, consultations with local offices~~ (e.g.~~, such as those in Austria~~), it was found~~, confirmed that there were neither more fires nor larger burnt areas ~~in the years 2018 - 2022 compared to the reference period. These findings indicate~~ 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 ~~factors influencing~~elements affecting fire activity, including climatic conditions, ~~prevention measures,~~ forest management~~,~~ practices, preventive measures, public awareness~~ raising~~, and ~~firefighting~~the effectiveness~~, which may vary across regions. However,~~ of firefighting efforts. The countries in the Southern zone experienced severe impacts from forest fires, and not ~~only~~just during the ~~period of~~ 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, ~~particularly evident in~~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 ~~highlights the need~~Switzerland for ~~effective~~ both periods, showing no significant differences in fire ~~management strategies. However~~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 unequivocally attributedclearly linked the rising frequency and severity of forest fires to climate change: In. For instance, Northern and Central California experienced a fivefold increase in the summer burned forest area betweenfrom 1996 andto 2021 compared to 1971–-1995 was reported (Turco et al., 2023). AcrossIn the western United States, climate change and other driversfactors have led to a doubling ofdoubled the cumulative forest fire area since 1984 (Abatzoglou and& Williams, 2016). Global projections for the twenty-first21st century indicatesuggest that climate change heightenswill worsen fire weather conditions, impactingaffecting a substantialsignificant portion of the burnable land surfaces worldwide (Abatzoglou et al., 2019).

The significant disparities in **tree cover loss**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 (Figure 5).. The escalating frequency and intensity of extreme weather events, such as storms, droughts, and wildfires, pose significant threats to forest health and resilience. However, forests are under increasing pressure, not only from climate extremes, but also from human activities such as logging, deforestation, and urbanisation. Notably, the three zones Northern, Central, and Southern experienced losses of 0.34% of forest land during the analysed period, with varying degrees of significance, underscoring the urgent need for proactive measures to address these challenges. Further research is needed to better understand the specific drivers behind thesethe disparities in reporting, and to develop targeted interventions for sustainable forest conservation and management.

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

Overall, in Fennoscandia, the forest management during the last decades has favoured conifer monocultures, leading Norway spruce and Scots pine to be the dominant species (Huuskonen et al., 2021). This means that the large forest ecosystems are likely to be more vulnerable to climate extremes. However, the example of Norway may make it clear that Scandinavia is probably the area where climate change has had the least consequences for forest ecosystems. In Norway, larger seasonal differences in precipitation/drought and temperature are expected. Periods of drought are replaced by periods of heavy rains and flooding. The consequences are moderate for forestry – but can be severe for agriculture in particularly during dry seasons – and also for hydroelectric dams. So far, the effects seem to cancel each other out. For example, winter, spring and summer 2021 were dry, but then Norway had an autumn and winter with more rain than usual, groundwater levels went above normal and hydroelectric dams were filled. Insect attacks after the 2018 drought could have become severe, but cold and wet preceding years probably mitigated this. Overall, the major concern in Norway is periods of drought followed by periods of heavy rains leading to passing floods.

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

Also in the British Isles, the amount of damage was not exceptional during the investigation period. Only some indirect signs were detectable: a survey published by Forest Research (2021) shows that the effects of the previous years of drought damage were clearly noticeable for forest visitors: 77% in the UK (76% in England) agreed that 'action should be taken by authorities and woodland managers to protect trees from damaging pests and diseases'. Regarding insects, no damage data was found. However, the great spruce bark beetle (*Dendroctonus micans*) is today an established pest in Southern Scotland (Scottish Forestry 2023a). Sitka spruce is Scotland's most important commercial tree species and the primary host of this pest. The '*D. micans* distribution map in Scotland' clearly shows its expansion northwards in the period 2018 until 2022 (Scottish Forestry 2023b). A synopsis of spatial modelling research (Forest Research 2008) even expects an improvement of tree growth due to a warmer climate in Scotland in the future: particularly in Southern and Eastern Scotland for high-quality broadleaved trees on suitable deep, fertile soils and for conifers on sites where water and nutrients are not limiting. However, a breeding population of European spruce bark beetle (*Ips typographus*) has now become established in South-east England probably arriving by flight across the English Channel following a large-scale dispersal from continental Europe due to extreme weather in 2021-2022 (Inward et al., 2024). This poses a future threat to the spruce in the UK, which is the dominant timber species. It should also be noted that when it comes to drought damages recorded in England and Scotland in 2018, wildfires only came in third place, while impacts on freshwater ecosystems and water quality ranked higher (Turner et al., 2021).

The observation of harm that are clearly due to rising temperatures and drought in the **Central zone**, make it evident that these forests are facing significant impacts and challenges. The severity of the situation in the Central zone is underscored by pronounced increases in crown defoliation observed in both coniferous and broadleaved trees, alongside an extraordinary rise in bark beetle-infested wood and an overall increase in tree cover loss. These findings paint a concerning picture for the Central zone's forest resilience, highlighting the vulnerability of its forests to climatic stressors. The cumulative effects of rising temperatures and prolonged drought periods have evidently taken a toll on the forest ecosystems in Central Europe. The less drought-adapted ecosystems of Central and Northern Europe experienced a record hot drought (Buras et al., 2020) that caused early wilting during summer 2018 in about 11% of the Central European forested area. The most affected forests were in

Central and East Germany, and in the Czech Republic (Brun et al., 2020). The drought and heat of 2018 were the prerequisites for the forest damage caused in Central Europe in the period 2019-2020, while the main driver was an above-average water vapour pressure deficit (Senf and Seidl, 2021a). The low soil moisture content in 2018 and the higher-than-normal water vapour pressure deficit of the following two years were viewed as the main drivers for the forest disturbances of about 4.74 million ha during 2018-2020, mainly in Germany, the Czech Republic and Austria (Senf et al., 2021). The main cause for tree mortality in 2018 is likely due to physiological damage as greenness was strongly reduced in Austria, Germany, and Switzerland during 2018 (Schuldt et al., 2020). Reduced greenness was also observed in the spring of 2019 when compared to the greenness before the drought in spring 2018 (Brun et al., 2020). During the hottest summer on record in Europe in 2022, large parts of the temperate forest regions were negatively affected, and forest greenness decreased more strongly than any other summer since 2002 by breaking the former record drought in 2018 (Hermann et al., 2023, Buras et al., 2023). These observations of changes in forest greenness are based on satellite-derived Normalised Difference Vegetation Index (NDVI).

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

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

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

Regarding the **Alpine zone**, it must be noted that accessing data was particularly challenging. We were unable to precisely identify which datasets specifically pertained to Alpine areas. Concerning fires in Alpine forests, we could only obtain data from Austria and Switzerland for both periods, where we did not observe any significant differences. Based on this research, we did not observe a significant increase in the impacts of drought and heat in the Alps during the period of 2018-2022. But it should be noted that mountain forests are particularly under pressure from climate change impacts due to their temperature limitation and high exposure to warming (Albrich et al., 2020). Such impacts can vary greatly with elevation and topography (e.g. Lindner et al., 2010, Thrippleton et al., 2020) and require a careful study addressing the target species and the abiotic conditions. The main tree species in central European mountain forests are Norway spruce, European beech and silver fir. All of them are late-successional and shade-tolerant (Dyderski et al., 2023) and sensitive to drought stress. Additionally, drought can also destabilise mountain forests and result in soil erosion, landslides, and rock-falls. Warmer temperatures and a shortening of cold periods can lead to reduced snow cover and trigger the distribution of harmful organisms or alien and invasive species and therefore can have a strong impact on biodiversity (Eriksen & Hauri 2021). Since the length of the growing season decreases with altitude, a warmer climate could also lead to more growth so long as there is enough access to water. This was confirmed by a study that measured tree aboveground biomass increment in temperate mountain forest (e.g. Thom and Seidl 2022, Dyderski et al., 2023). Tree lines will shift upwards over a longer period and tree species from the lowlands will establish at higher altitudes. A simulation of forest dynamics in the Northern Alps predicts for the first half of the current century a probability for increasing gains in stem density, structural complexity, and tree species diversity (Thom et al., 2022). An inventory of Alpine drought impact reports by Stephan et al., (2021) shows that the pre-Alpine areas are more affected than those at higher elevations. Additionally, most reported impacts were categorised as agriculture and public water supply, while impacts on forestry and terrestrial ecosystems were less mentioned. According to that study, drought impacts occur mostly in summer and early autumn, likely due to snowmelt in spring, which mitigates water shortages. At the same time, that study also observed a spatial heterogeneity across the Alps with, surprisingly, more impacts in the Northern Alpine regions. Eriksen and Hauri (2021) mention that forest fires have traditionally been more common on the southern side of the Alps and that those countries have an improved handling of forest fires.

Fire is one of the major natural disturbances in the European Alpine forests and shows heterogeneity in frequency, spatial extent and seasonality, driven by climatic, environmental and anthropogenic factors (Morresi et al., 2020). However, if there is an increased danger of forest fires in Alpine regions, it is not so easy to identify such a pattern, because each Alpine country has its own forest fire documentation system with different attributes, criteria, and accuracies (Müller et al., 2020). According to the values compiled for this review for the period 2018 to 2022, it does not appear that the occurrence of forest fires in the Alps are very different from the long-term average (Table 3).

A supra-regional body would be required to unify the different data sources for the Alps In order to understand the impact of climate change on the Alps, a larger context needs to be considered across national borders, since many systems do not stop at national borders (e.g. river basins such as the Danube or the Rhône). Cooperation across national borders and disciplines (climate research, ecology) is necessary.

Observing the obvious damage attributed to increasing temperatures and drought conditions in the **Southern zone**, it becomes apparent that forests are encountering significant repercussions. The gravity of the situation in the Southern zone is accentuated by marked increases in crown defoliation, particularly noticeable in broadleaved trees. While data on damage caused by wood-boring insects are unavailable, it suggests that insect pests might not pose a major threat during the investigated drought years from 2018 to 2022. Nevertheless, there is a significant increase in tree cover loss compared to the reference period. Assessing the incidence of wildfires, it's not possible to assert that the situation worsened significantly during the period of 2018-2022. However, the exceptionally severe year of 2017, particularly in Portugal, with staggering losses, necessitates its inclusion in this study. The devastation caused by wildfires presents a challenge for Southern Europe. However, wildfires are also generally part of the South-western European ecosystems. Italy was also strongly affected by the windstorm Vaia in 2018. Based on our research, we could not find an increase in impacts on forest ecosystems with regard to insect infestation or physiological damage such as defoliation between the period 2018 and 2022 examined here and the years before. Up to 2018, 3 million hectares of forests have been reported to be converted into shrublands or grasslands in the Mediterranean countries of the European Union. Fire and drought are the main drivers underlying this deforestation (Karavani et al., 2018).

In Spain, over the period 2018-2019, there was even some recovery in forest health in Spain which contrasts with the larger levels of damage recorded across Europe, in particular in Central Europe, which experienced both drier conditions and larger levels of vegetation damage (AIEF 2019, ESOTC 2019).

The situation for Maritime pine (*Pinus pinaster*, one of the most common species) in Iberia is according to Kurz-Besson et al., (2016) is not completely discouraging. According to Kurz-Besson et al., (2016), wood radial growth and density highly benefit from the strong decrease of cold days and the increase of minimum temperature. Yet, the benefits are hindered by long-term water deficit, which results in different levels of impact on wood radial growth and density. Despite the intensification of long-term water deficit, tree-ring width appears to benefit from the minimum temperature increase, whereas the effects of long-term droughts significantly prevail on tree-ring density. Since the particularly extreme year of 2017, severe measures have been applied and comparing the periods 2007-2017 and 2018-2022, the total number of fires decreased in half, particularly on days of high fire danger. Larger fires have slowed since 2017. Fires with a burnt area of more than 1,000 ha reduced from an average of 19 events to 8 in more recent years. Although forest losses are decreasing in the last period, Portugal has seen an increasing trend in forest loss due to fires between 2001 and 2019 (Tyukavina et al., 2022). Fires occurring from recent forest loss due to other drivers were excluded, e.g. burning of felled logs following mechanical canopy removal, which is common in slash-and-burn agriculture and large-scale deforestation. In this sense, the decrease in fire events may not have been so obvious without the unique events of 2017, indicating the difficulties of interpreting long term trends of damage.

5.6. Outlook

6.1 Future trends and biophysical feedbacks of forest cover changesfeedback and impacts on forests

Future global warming is expected to lead to more frequent and intense periods with heatof 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 next fewcoming decades compared tothan in recent years (Suarez-Gutierrez et al., 2023). For example, Hari et al.,. (2020) found a sevenfold increase in the occurrence of consecutive droughtsdrought events as of 2018-2019 in Europe under the highest Representative Concentration Pathway RCP 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 ~~increasingly strongly the closer one gets~~with increasing proximity to the Mediterranean, linked to roughly similar spatial changes in surface runoff (~~see~~ IPCC ~~*AR6*~~2021a, b). At the same time, evapotranspiration increases the further east in Europe one gets (~~see~~ IPCC ~~*AR6*~~2021a, b). Combined, those two meteorological aspects lead to a pronounced surface soil moisture deficit, which increases the (hydrological) drought risk substantially (~~see~~ IPCC ~~*AR6*~~2021a, b). Accordingly, forest disturbance regimes are expected to intensify with continuing ~~climate change~~global warming, leading to increasing forest biomass losses due to windthrow, fires and insect outbreaks (Forzieri et al., 2021, Patacca et al., 2023).

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

~~Increase in forest cover are seen as important measures to mitigate climate extremes. Changes in forest cover due to land use and climate change modulate local and regional climate conditions through changes of land surface properties, such as land surface reflectance, water holding capacity and aerodynamic roughness. This affects biophysical land surface processes such as the exchange of energy, momentum and water, and the partitioning of turbulent fluxes into sensible and latent heat flux. A quantitative understanding of regional and local biophysical effects of such land use changes is required to enable effective land-based mitigation and adaptation measures (e.g. Perugini et al., 2017). However, these effects are complex and strongly depend on local conditions, and therefore their quantification is still largely unclear.~~

Biophysical ~~feedbacks~~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 ~~from~~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). ~~The LUCAS RCM inter-comparison study by~~ Davin et al~~.,~~. (2020) ~~reveal~~found significant biophysical effects of re-/afforestation on ~~the~~ regional and local ~~climate at seasonal scale. It shows an overall agreement of~~ climates seasonally, with RCMs ~~in~~showing consistent winter warming ~~with consistently simulated~~due to albedo ~~change,~~changes but ~~no agreement on the sign of~~differing summer temperature ~~response in summer, with disagreement in~~responses due to varying evaporative ~~fraction. The study concludes that summer~~fractions. Summer temperature ~~response is dominantly~~changes are mainly driven by land processes, ~~whereas~~while atmospheric processes ~~are important for~~dominate winter ~~response~~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 ~~colder~~cooler daytime and warmer nighttime summer surface temperatures ~~during the day and warmer summer surface temperatures during the night, which is in line~~, aligning with ~~observation-based~~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 ~~cycle of~~ soil temperature ~~over the European continent with~~ cycle using the LUCAS RCM ensemble~~. The multi-model mean shows~~, finding a general reduction ~~of~~in the annual amplitude ~~of soil temperature over all European regions, although~~across Europe, though not all ~~the~~ models ~~show~~showed this trend. ~~In addition,~~Observations at paired FLUXNET sites ~~were investigated to compare the simulated results with observations. In line with models, observations indicate a~~confirmed summer ground cooling in forested areas ~~when~~ 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.

~~While most models align with the observed reduction in the annual amplitude of soil temperature, there is notable variability in the magnitude of these changes. Addressing the broader climatic implications, Daloz et al., (2022) specifically examined the snow-albedo effect of FPS LUCAS RCMs in sub-polar and alpine climates. Additionally, Mooney et al., (2022) explored FPS LUCAS simulations in the context of extreme forest cover changes. The findings from these studies collectively indicate that re-/afforestation plays a role in diminishing the snow-albedo sensitivity index, thereby contributing to enhanced snowmelt. While the direction of change is robustly modelled, there is still uncertainty in the magnitude of change. The results of the FPS LUCAS Phase 1 simulations show the importance of biophysical effects and feedbacks from forest cover changes in Europe. Climate change-driven changes in forest cover in Europe will intensify under further climate change and may become regionally and locally self-reinforcing through biophysical processes and feedbacks.~~

~~Trees and forests may adapt to a hotter and drier climate, inter alia, by mechanisms currently predominant in drylands (Grünzweig et al., 2022). By hydraulic redistribution, plants transport water from moist to dry soil layers through their root system along a water potential gradient, thus improving plant nutrition, extending root lifespan, and preserving hydraulic conductance in the xylem during dry periods (Prieto et al., 2012). Non-rainfall water, such as dew and fog are also a source of moisture, whereby trees absorb water through leaves and bark, thus alleviating drought-stress and enabling humidity-enhanced biotic activity (Earles et al., 2016, Wang et al., 2017). In addition, heat stress in forests can be mitigated by lowering the aerodynamic resistance of heat transfer from trees to the surrounding air, a mechanism termed the canopy convector effect (Banerjee et al., 2017; Rotenberg and Yakir, 2010). For instance, surface temperatures in forests rose less than those in non-forested ecosystems during the 2003 extreme heatwave in Central and Western Europe, thus enabling forests to save water and~~

prevent long-term amplification of the consequences of extreme heat (Teuling et al., 2010). These pathways of adaptation may diminish or even prevent damage caused by water scarcity and high temperatures.

6.2 Policies related to drought and heat waves

Based on the above assessment, it is very clear that recurrent heat wave and drought events lead to very complex and multi-faceted impacts to our society. The impacts of enduring heat wave and drought include not only reduced water resources, crop failure, limited renewable energy, and pressure on human health, but also others like land use planning and human activities. More dramatic consequences are likely given that multiple risk factors for political instability will increase as a consequence, e.g. wildfires, plant and human mortality, crop failure, or famine. The recent extreme events like the drought and heat wave in Central Europe in 2018 (e.g. Rousi et al., 2023) or the severe floods in the border region between Germany, Belgium, Netherlands, and Luxembourg in July 2021 (e.g. Mohr et al., 2023) has clearly demonstrated that the preparedness our society to face such extraordinary events is insufficient. This is the case for the forecasting capacities, including impact modelling chains, in which several agencies are typically involved and currently often lead to inefficient and late warning for civil protection and for the population at large. Moreover, it has become clear from recent events that the population also does not know how to act properly under extreme weather conditions. In fact, much more efforts need to be put into place regarding information accessibility for the public, e.g., on how to save water under long-term drought, or to protect “endangered groups” like old or sick citizens when affected by an enduring heat wave. This is particularly important, as extreme heat and drought are expected to not only to be more extreme but also to affect our region for a longer period of the year (e.g. Hundhausen et al., 2023) and to occur more frequently over successive years (Suarez-Gutierrez et al., 2023). In fact, some parts of Europe like the Iberian Peninsula may be by the late 21st century under the influence of constant drought (e.g. Moemken et al, 2022). In the face of these events, the need to act has been recognized by agencies and stakeholders at least in Germany. Joint task forces have been put into place to develop tailored forecasts products for the civil protection, public agencies, and the population, which will serve as a basis both to act under adverse conditions and to develop new policies and streamline procedures between public agencies. A key factor will be the adequate communication of information and political measures, as this was often an issue in the past. Existing language barriers and accessibility of information must be overcome, leading to a raised awareness in the population of the severe impacts of drought and heat on our livelihoods under current and future climate conditions.

6.3 Issues due to data availability and reporting

Different impact reporting strategies and timelines across sectors and across countries hinder the rapid assessments of multi-country drought impacts. In particular, we found a systematic lack of consistent reporting for specific regions and ecosystems, e.g., grasslands over the Iberian Peninsula. Furthermore, we also find substantial delays or discontinuities in official impact reporting efforts, which we found were often no longer available for recent years, e.g. Spain's National Forest Damage

Inventories were available at the time only until 2020 (AIEF, 2020). Initially, a description of the damage due to heat and drought to grassland was also planned. However, the data availability regarding grassland is very limited, although this is the second large-scale non-irrigated ecosystem providing many ecosystem services that are important for our well-being.
A uniform data collection that is accessible across languages would be valuable considering the existing lack of coverage. Our intent is to support or initiate a platform where all relevant data for drought damage is collected. This daunting task requires the collaboration of many researchers across different subjects.

6.4 Conclusions

In conclusion, heat and drought are significant drivers of forest damages, including increased 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, changes in increased risk of insect pests and wildfires, and diminished forest productivity and carbon sequestration, and increased wildfire risk. Mitigating these damages requires a holistic approach that includes forest management, climate change adaptation measures, and global efforts to reduce greenhouse gas emissions. Understanding the impacts of heat and drought on forests and implementing appropriate strategies to mitigate these impacts is crucial for the conservation and sustainability of . 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 in the face of climate changeare 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. However, there are opportunities to mitigate this damage. The extent to which we comprehend the damage already incurred can guide us in making informed decisions for the future, whether in selecting appropriate tree species or implementing effective management techniques. But mitigating this damage caused by heat and drought in forests requires a multi-faceted approach that includes forest management and monitoring strategies, climate change adaptation measures, and global efforts to reduce greenhouse gas emissions. Forest management practices, such as thinning, prescribed burning, and reforestation, can help increase forest resilience to heat and drought by reducing competition for water, improving tree vigour, and promoting more diverse species composition. Climate change adaptation measures, such as increasing water availability through irrigation, improving forest monitoring and early warning systems, and implementing strategies to reduce wildfire risk, can also help mitigate damage. Finally, global efforts to mitigate climate change by reducing greenhouse gas emissions are essential because this is the root cause of heat and drought impacts on forests.

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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References

Aalto, J. and Venäläinen, A. (eds.) 2021. Climate change and forest management affect forest fire risk in Fennoscandia. Finnish Meteorological Institute Reports 2021:3, Helsinki. 156 p. http://hdl.handle.net/10138/330898

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of sciences, 113(42), 11770-11775.

Abatzoglou, J. T., Williams, A. P., & Barbero, R. (2019). Global emergence of anthropogenic climate change in fire weather indices. Geophysical Research Letters, 46(1), 326-336.

Abrams, M. D., & Nowacki, G. J. (2016). An interdisciplinary approach to better assess global change impacts and drought vulnerability on forest dynamics. Tree Physiology, 36(4), 421-427.

AIEF (2019): https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/es-00-memoria-19-dist_tcm30-524045.pdf

AIEF (2020): https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/idf2020_tcm30-524136.pdf

Agrar-&Forstbericht Südtirol (2021): https://www.provinz.bz.it/land-forstwirtschaft/landwirtschaft/publikationen.asp?publ_action=300&publ_image_id=616940

Aeschbach-Hertig, W., and T. Gleeson (2012), Regional strategies for the accelerating global problem of groundwater depletion, Nature Geoscience, 5(12), 853-861.

Albrich, K., Rammer, W., & Seidl, R. (2020). Climate change causes critical transitions and irreversible alterations of mountain forests. *Global Change Biology*, *26*(7), 4013-4027.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., ... & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest ecology and management*, *259*(4), 660-684.

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere, 6(8), 1-55.

Anderegg, W. R., Kane, J. M., & Anderegg, L. D. (2013). Consequences of widespread tree mortality triggered by drought and temperature stress. Nature climate change, 3(1), 30-36.

AON (2018): https://www.aon.com/reinsurance/getmedia/1b516e4d-c5fa-4086-9393-5e6afb0eeded/20220125-2021-weather-climate-catastrophe-insight.pdf

APA (2023): https://rea.apambiente.pt/content/seca (last access 27.6.23)

Banerjee, T., De Roo, F., and Mauder, M.: Explaining the convector effect in canopy turbulence by means of large-eddy simulation. Hydrol. Earth Syst. Sci., 21, 2987-3000, 2017.

Martin K.-F. Bader, D. Scherrer, R. Zweifel, C. Körner, Less pronounced drought responses in ring-porous than in diffuse-porous temperate tree species, Agricultural and Forest Meteorology, Volume 327, 2022, 109184, doi:10.1016/j.agrformet.2022.109184

Bakke, S. J., Ionita, M., & Tallaksen, L. M. (2020). The 2018 northern European hydrological drought and its drivers in a historical perspective. Hydrology and Earth System Sciences, 24(11), 5621–5653. https://doi.org/10.5194/hess-24-5621-2020

Bakke, S.J., Ionita, M. & Tallaksen, L.M. Recent European drying and its link to prevailing large-scale atmospheric patterns. Sci Rep 13, 21921 (2023). https://doi.org/10.1038/s41598-023-48861-4

Bardalen, Arne; Pettersen, Ivar; Dombu, Siri Voll; Rosnes, Orvika; Mittenzwei, Klaus; Skulstad, Andreas. (2022). Klimaendring utfordrer det norske matsystemet. Kunnskapsgrunnlag for vurdering av klimarisiko i verdikjeder med matsystemet som case. NIBIO rapport 8 (110).

Bastos, A., Orth, R., Reichstein, M., Ciais, P., Viovy, N., Zaehle, S., Anthoni, P., Arneth, A., Gentine, P., Joetzjer, E., Lienert, S., Loughran, T., McGuire, P. C., O, S., Pongratz, J., and Sitch, S. (2021): Vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019, Earth Syst. Dynam., 12, 1015–1035, https://doi.org/10.5194/esd-12-1015-2021

BBC (2018): https://www.bbc.com/news/uk-england-lancashire-44853173 last visited on 14.3.2023

https://www.bbc.com/news/uk-scotland-north-east-orkney-shetland-48043860

BBC (2021a~~:~~): COP26: Wildfires and flooding prompt Welsh firefighter warning - BBC News

BBC (2021b~~:~~): Climate change: Droughts and fires 'may be features of Wales' - BBC News

BBC (2022): https://www.bbc.com/news/uk-england-64118239 last visited 20.3.2022

Beguería, S., Vicente-Serrano, S. M., Reig, F. and Latorre, B. (2013), Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatology.

Beloiu M, Stahlmann R, Beierkuhnlein C. High Recovery of Saplings after Severe Drought in Temperate Deciduous Forests. Forests. 2020; 11(5):546. https://doi.org/10.3390/f11050546

Beloiu, M., Stahlmann, R., & Beierkuhnlein, C. 2022. Drought impacts in forest canopy and deciduous tree saplings in Central European forests. Forest Ecology and Management 509: 120075. https://doi.org/10.1016/j.foreco.2022.120075

Bento, V. A., Ribeiro, A. F., Russo, A., Gouveia, C. M., Cardoso, R. M., & Soares, P. M. (2021). The impact of climate change in wheat and barley yields in the Iberian Peninsula. *Scientific reports*, *11*(1), 1-12.

Benton, T. G., Vickery, J. A., Wilson, J. D. (2003): Farmland biodiversity: is habitat heterogeneity the key? In: *Trends in Ecology & Evolution* 18 (4), S. 182–188. DOI:10.1016/S0169-5347(03)00011-9

Beobide-Arsuaga, G., Düsterhus, A., Müller, W. A., Barnes, E. A., & Baehr, J. (2023). Spring Regional Sea Surface Temperatures as a Precursor of European Summer Heatwaves. Geophysical Research Letters, 50(2), e2022GL100727. https://doi.org/10.1029/2022gl100727

Bezak, N., & Mikoš, M. (2020). Changes in the compound drought and extreme heat occurrence in the 1961–2018 period at the European scale. Water, 12(12), 3543.

BFW (2020): https://www.bfw.gv.at/wp-content/uploads/Abb_Borkenkaefer_SturmSchnee_bis2020_Oesterreich.pdf

BFW (2021): https://www.waldwissen.net/de/waldwirtschaft/schadensmanagement/waldbrand/weissbuch-waldbraende

BFW (2023): https://www.bfw.gv.at/pressemeldungen/borkenkaefer-fichtenwaelder-im-sueden-oesterreichs-stark-betroffen/

Blunden, J., & Arndt, D. S. (2019). State of the Climate in 2018. Bulletin of the American Meteorological Society, 100(9), Si-S306. https://doi.org/10.1175/2019BAMSStateoftheClimate.1

Bundesforste (2023): https://www.bundesforste.at/service-presse/presse/pressedetail/news/bundesforste-waldbilanz-2022-gepraegt-von-hitze-trockenheit-und-kaefer.html

BMEL (2020~~)~~): Referat 515—Nachhaltige Waldbewirtschaftung. Ergebnisse der Waldzustandserhebung 2019; BMEL: Bonn, Germany, 2020; p. 60.

~~BMEL (2022): https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/waldzustandserhebung-2022.pdf?__blob=publicationFile&v=6~~

BMEL (2020~~).~~): Waldschäden: Bundesministerium veröffentlicht aktuelle Zahlen, Pressemitteilung Nr 40/2020. (https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2020/040-waldschaeden.html).

BMEL (2021): Bundesministerium für Ernährung und Landwirtschaft (2021):; Zahlen & Fakten zum Waldgipfel am 2. Juni 2021 (https://www.bmel.de/SharedDocs/Downloads/DE/_Wald/waldgipfel-zahlen-fakten.pdf?__blob=publicationFile&v=3)

BMEL (2022): https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/waldzustandserhebung-2022.pdf?__blob=publicationFile&v=6

BMEL (2023 a): https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/waldzustandserhebung-2022.pdf?__blob=publicationFile&v=5

BMEL (2023b): https://www.bmel-statistik.de/forst-holz/waldbrandstatistik/

BMEL (2023c): https://www.bmel.de/DE/themen/wald/waelder-weltweit/tag-des-waldes.html

BMLRT (2020): https://www.alpine-region.eu/sites/default/files/uploads/result/2233/attachments/200206_forestfires_whitepaper_final_online.pdf

BMU (2020): Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU); Klimaschutz in Zahlen (2020) Broschüre Nr. 10034 (https://www.bmuv.de/publikation/klimaschutz-in-zahlen-2020)

Bork, K.; Triebenbacher, C.; Hahn, A. (2024): Schadholz muss schnell raus. BLW 5, S. 48-50

Boergens, E., Güntner, A., Dobslaw, H., & Dahle, C. (2020). Quantifying the Central European droughts in 2018 and 2019 with GRACE Follow-On. Geophysical Research Letters, 47(14), e2020GL087285.

~~BMEL (2021): Bundesministerium für Ernährung und Landwirtschaft (2021):; Zahlen & Fakten zum Waldgipfel am 2. Juni 2021 (https://www.bmel.de/SharedDocs/Downloads/DE/_Wald/waldgipfel-zahlen-fakten.pdf?__blob=publicationFile&v=3)~~

BOE (2022): Boletín Oficial del Estado (BOE) núm. 64, de 16 de marzo de 2022, páginas 31393 a 31426 (34 págs.), BOE-A-2022-4136 (https://www.boe.es/eli/es/rdl/2022/03/15/4)

Bonaldo, D., Bellafiore, D., Ferrarin, C., Ferretti, R., Ricchi, A., Sangelantoni, L. and Vitelletti, M. L.: The summer 2022 drought: a taste of future climate for the Po valley (Italy)?, Reg. Environ. Chang., 23(1), 1, doi:10.1007/s10113-022-02004-z, 2023.

Brás, T. A., Seixas, J., Carvalhais, N., & Jägermeyr, J. (2021). Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environmental Research Letters, 16(6), 065012.

Breil, M., Rechid, D., Davin, E. L., de Noblet-Ducoudré, N., Katragkou, E., Cardoso, R. M., ... & Warrach-Sagi, K. (2020). The opposing effects of reforestation and afforestation on the diurnal temperature cycle at the surface and in the lowest atmospheric model level in the European summer. Journal of Climate, 33(21), 9159-9179.

Brecka, A. F., Shahi, C., & Chen, H. Y. (2018). Climate change impacts on boreal forest timber supply. *Forest Policy and Economics*, *92*, 11-21.

Brodribb, T. J., Powers, J., Cochard, H., & Choat, B. (2020). Hanging by a thread? Forests and drought. Science, 368(6488), 261-266.

Brun, P., Psomas, A., Ginzler, C., Thuiller, W., Zappa, M., & Zimmermann, N. E. (2020). Large-scale early-wilting response of Central European forests to the 2018 extreme drought. Global change biology, 26(12), 7021-7035.

Büntgen, Ulf, Otmar Urban, Paul J. Krusic, Michal Rybníček, Tomáš Kolář, Tomáš Kyncl, Alexander Ač et al., "Recent European drought extremes beyond Common Era background variability." Nature Geoscience 14, no. 4 (2021): 190-196.

Bülow, K., Bauer, S., Steuri, B., Groth, M., Knutzen, F., & Rechid, D. (2024). Stadtwald Karlsruhe im Klimawandel - Der Wald heute und in Zukunft. Zenodo. https://doi.org/10.5281/zenodo.11473737

Buras, A., Rammig, A., & Zang, C. S. (2021). The European Forest Condition Monitor: using remotely sensed forest greenness to identify hot spots of forest decline. Frontiers in plant science, 12, 689220.

Buras, A., Meyer, B., & Rammig, A. (2023). *Record reduction in European forest canopy greenness during the 2022 drought* (No. EGU23-8927). Copernicus Meetings.

Bussotti, F., Papitto, G., Di Martino, D., Cocciufa, C., Cindolo, C., Cenni, E., Bettini, D., Iacopetti, G., Pollastrini, M.: Le condizioni delle foreste italiane stanno peggiorando a causa di eventi climatici estremi? Evidenze dalle reti di monitoraggio nazionali ICP Forests - CON.ECO.FOR., Forest@, 19, 74-81, doi: 10.3832/efor4134-019, 2022.

Bussotti, F., Bettini, D., Carrari, E., Selvi, F., Pollastrini, M.: Cambiamenti climatici in atto: osservazioni sugli impatti degli eventi siccitosi sulle foreste toscane, Forest@, 20, 1-9, doi: 10.3832/efor4224-019, 2023.

Byrne, Michael P., and Paul A. O'Gorman. "Link between land-ocean warming contrast and surface relative humidities in simulations with coupled climate models." Geophysical Research Letters 40, no. 19 (2013): 5223-5227.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature, 556, 191–196. https://doi.org/10.1038/s41586-018-0006-5

P. Choler, A. Bayle, B. Z. Carlson, C. Randin, G. Filippa, E. Cremonese, The tempo of greening in the European Alps: Spatial variations on a common theme. Global Change Biol. 27, 5614–5628 (2021).

Cheshire (2023): https://jcheshire.com/featured-maps/the-scarred-landscape-of-the-climate-crisis/

N. Christidis, P.A. Stott, The influence of anthropogenic climate change on wet and dry summers in Europe, Science Bulletin, vol 66, 8, 2021, p 813-823, https://doi.org/10.1016/j.scib.2021.01.020

CipraCIPRA (2022): https://www.cipra.org/de/news/bergwald-im-klimawandel

CIW (2019): https://www.integraalwaterbeleid.be/nl/nieuws/downloads-van-nieuwsberichten/evaluatierapport-waterschaarste-en-droogte-2018 Last visited 16.8.2024

CIW (2020): https://www.integraalwaterbeleid.be/nl/nieuws/downloads-van-nieuwsberichten/evaluatierapport-waterschaarste-en-droogte-2019 Last visited 16.8.2024

CIW (2021): https://www.integraalwaterbeleid.be/nl/overleg/droogtecommissie/evaluatierapport-waterschaarste-en-droogte-2020-1 Last visited 16.8.2024

Copernicus (2023:): https://emergency.copernicus.eu/mapping/list-of-components/EMSR281

Cook, E.R., R. Seager, Y. Kushnir, K.R. Briffa, U. Buntgen, D. Frank, P.J. Krusic, W. Tegel, G. van der Schrier, L. Andreu-Hayles, M. Baillie, C. Baittinger, N. Bleicher, N. Bonde, D. Brown, M. Carrer, R. Cooper, K. Cufar, C. Dittmar, J. Esper, C. Griggs, B. Gunnarson, B. Gunther, E. Gutierrez, K. Haneca, S. Helama, F. Herzig, K-U. Heussner, J. Hofmann, P. Janda, R. Kontic, N. Kose, T. Kyncl, T. Levanic, H. Linderholm, S. Manning, T. M. Melvin, D. Miles, B. Neuwirth, K. Nicolussi, P. Nola, M. Panayotov, I. Popa, A. Rothe, K. Seftigen, A. Seim, H. Svarva, M. Svoboda, T. Thun, M. Timonen, R. Touchan, V. Trotsiuk, V. Trouet, F. Walder, T. Wazny, R. Wilson, and C. Zang, 2015: Old World megadroughts and pluvials during the Common Era. Science Advances, 1, doi: 10.1126/sciadv.1500561

Cartwright, J. M., C. E. Littlefield, J. L. Michalak, J. J. Lawler, and S. Z. Dobrowski (2020), Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA, Sci Rep-Uk, 10(1).

Daloz, A. S., Schwingshackl, C., Mooney, P., Strada, S., Rechid, D., Davin, E. L., ... & Lund, M. T. (2022). Land–atmosphere interactions in sub-polar and alpine climates in the CORDEX flagship pilot study Land Use and Climate Across Scales (LUCAS) models–Part 1: Evaluation of the snow-albedo effect. The Cryosphere, 16(6), 2403-2419.

Davies, G.M., Gray, A., Rein, G., and Legg, C.J.: Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. Forest Ecol. Manag., 308, 169-177. 2013.

Davin, E., Rechid, D., Breil, M., Cardoso, R. M., Coppola, E., Hoffmann, P., ... & Wulfmeyer, V. (2020). Biogeophysical impacts of deforestation in Europe First results from the LUCAS Regional Climate Mode intercomparison.

Davies, S., Bathgate, S., Petr, M., Gale, A., Patenaude, G., & Perks, M. (2020). Drought risk to timber production–A risk versus return comparison of commercial conifer species in Scotland. *Forest Policy and Economics*, *117*, 102189.

DAV (2022): https://magazin.alpenverein.de/artikel/waldbrand-klima-mensch_a8c8fe7a-67c8-417c-9e65-95835ba16f17

Decruyenaere, Virginie 2022 : La sécheresse frappe la Wallonie. Quelles conséquences? Online: : https://www.cra.wallonie.be/fr/la-secheresse-frappe-la-wallonie-quelles-consequences

DAERA, 2022: https://www.daera-ni.gov.uk/news/wildfire-damage-across-mournes-assessed-by-daera-and-partner-agencies
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094493/Agriculture-in-the-UK-27jul22.pdf

Danielewicz W. (red.). 2016. Dąbrowy Krotoszyńskie monografia przyrodniczo-gospodarcza. G&P Oficyna Wydawnicza, PTL, Poznań

Desiato, F.; Fioravanti, G.; Fraschetti, P.; Perconti, W.; Piervitali, E.; Pavan, V.: Gli indicatori del clima in Italia nel 2018 — ISPRA Report, [online] Available from: https://www.isprambiente.gov.it/it/pubblicazioni/stato-dellambiente/gli-indicatori-del-clima-in-italia-nel-2018 (Accessed 24 July 2022), 2018. https://www.isprambiente.gov.it/it/pubblicazioni/stato-dellambiente/gli-indicatori-del-clima-in-italia-nel-2018 (Accessed 24 July 2022), 2018.

DFWR (2021): https://dfwr.de/wp-content/uploads/2022/01/DFWR-Position-Schaeden-Fowi-Langfassung-Studie.pdf last visited 15.8.2024

Drouard, M., Kornhuber, K., & Woollings, T. (2019). Disentangling Dynamic Contributions to Summer 2018 Anomalous Weather Over Europe. Geophysical Research Letters, 46(21), 12537–12546. https://doi.org/10.1029/2019GL084601

D.W. Storms and Drought Destroy Thousands of Acres of German Forests. 2019. Available online:https://www.dw.com/en/storms-and-drought-destroy-thousands-of-acres-of-german-forests/a-48493443

DWD Dokumentation SPEI: https://www.dwd.de/DE/fachnutzer/landwirtschaft/dokumentationen/agrowetter/spei.pdf?__blob=publicationFile&v=2 - last visited 10-4-2024.

DSB (Direktoratet for samfunnssikkerhet og beredskap). (2021). Emergency Preparedness Analysis - Forest fires. Online: https://www.dsb.no/rapporter-og-evalueringer/emergency-preparedness-analysis-forest-fires/ (last access: 09.03.2023).

Dubach, V.; Beenken, L.; Bader, M.; Odermatt, O.; Stroheker, S.; Hölling, D.; treenet; Vögtli, I.; Augustinus, B.A.; Queloz, V. 2021: Protection des forêts –Vue d'ensemble 2020. WSL Ber. 110: 57 p.

Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., McCarthy, G. D., Sinha, B., Berry, D. I., & Hirschi, J. J.-M. (2016). Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 Earles,

~~J.M., Sperling, O., Silva, L.C., McElrone, A.J., Brodersen, C.R., North, M.P., and Zwieniecki, M.A.: Bark water uptake promotes localized hydraulic recovery in coastal redwood crown. Plant Cell Environ., 39, 320-8, 2016.~~ European heat wave. Environmental Research Letters, 11(7), 074004. https://doi.org/10.1088/1748-9326/11/7/074004

DESTATIS (2020): https://www.destatis.de/DE/Presse/Pressemitteilungen/2020/07/PD20_N041_412.html#:~:text=Im%20Jahr%202019%20wurden%2046,waren%20es%2054%20Millionen%20Kubikmeter.

DESTATIS (2023): https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Wald-Holz/aktuell-holzeinschlag.html

Dittus, A. J., Collins, M., Sutton, R., & Hawkins, E. (2024). Reversal of projected European summer precipitation decline in a stabilizing climate. Geophysical Research Letters, 51, e2023GL107448

Dolomitenstadt (2023): https://www.dolomitenstadt.at/2022/08/03/220-mio-borkenkaefer-gingen-in-osttirol-in-die-falle/

DSB (2019) Skogbrannsesongen 2018. DSB. ~~from: https://www.dsb.no/globalassets/dokumenter/rapporter/skogbrannsesongen_2018_nn.pd~~from: https://www.dsb.no/globalassets/dokumenter/rapporter/skogbrannsesongen_2018_nn.pd

Dobor, L., Hlásny, T., Rammer, W., Zimová, S., Barka, I., & Seidl, R. (2020a). Is salvage logging effectively dampening bark beetle outbreaks and preserving forest carbon stocks?. Journal of Applied Ecology, 57(1), 67-76.

Dobor, L., Hlásny, T., & Zimová, S. (2020b). Contrasting vulnerability of monospecific and species-diverse forests to wind and bark beetle disturbance: The role of management. Ecology and Evolution, 10(21), 12233-12245.

DWD (2022): https://www.dwd.de/DE/wetter/thema_des_tages/2022/4/20.html

Dyderski, M. K., Pawlik, Ł., Chwistek, K., & Czarnota, P. (2023). Tree aboveground biomass increment and mortality in temperate mountain forests: Tracing dynamic changes along 25-year monitoring period. *Forest Ecology and Management*, *540*, 121054.

EUFORGEN (2024): https://www.euforgen.org/species/pinus-cembra last visited 22.8.2024

EC-JRC Drought Reports (2024): https://joint-research-centre.ec.europa.eu/european-and-global-drought-observatories/drought-reports_en last visited 21.8.2024

European Commission, Libertà, G., Vivancos, T., Leray, T., Costa, H., San-Miguel-Ayanz, J., Branco, A., Durrant, T., Lana, F., Nuijten, D., Ahlgren, A., Löffler, P., Ferrari, D., De Rigo, D., Boca, R., & Maianti, P. (2018). Forest fires in Europe, Middle East and North Africa 2017. Publications Office. https://doi.org/doi/10.2760/663443

EFFIS 2023 - Annual Statistics for UK: https://effis.jrc.ec.europa.eu/apps/effis.statistics/estimates last visited 20.3.2023

EFFIS 2023 - Annual Statistics for Ireland: https://effis.jrc.ec.europa.eu/apps/effis.statistics/estimates last visited 20.3.2023

EUROSTAT (2016): https://ec.europa.eu/eurostat/documents/3217494/7777899/KS-FK-16-001-EN-N.pdf/cae3c56f-53e2-404a-9e9e-fb5f57ab49e3?t=1484314012000

EUROSTAT (2023~~:~~): https://ec.europa.eu/eurostat/web/products-eurostat-news/w/edn-20230321-1 last visited at 24-4-23.

Eriksen~~ and Hauri (2021): Eriksen~~, C., & Hauri, A. (2021). Climate Change in the Swiss Alps. *CSS Analyses in Security Policy*, *290*

Euwid (2022): https://www.euwid-wood-products.com/news/roundwood-sawnwood/sweden-assuming-51m-m3-of-beetle-damaged-wood-for-2022-211222/ last visited 22.3.2024

Fan, Y., G. Miguez-Macho, E. G. Jobbágy, R. B. Jackson, and C. Otero-Casal (2017), Hydrologic regulation of plant rooting depth, Proceedings of the National Academy of Sciences, 114(40), 10572-10577.

Feller, U., Kingston-Smith, A. H. & Centritto, M. Editorial: abiotic stresses in agroecology: a challenge for whole plant physiology. Front. Environ. Sci. 5, 13 (2017).

Feuerwehrverband (2022): https://www.feuerwehrverband.de/rekord-waldbrandsommer-2022-fast-4300-hektar-wald-verbrannt-waldeigentuemer-und-feuerwehren-fordern-finanzielle-unterstuetzung-fuer-praeventionsmassnahmen/

Fernandez-Carrillo, A., Patočka, Z., Dobrovolný, L., Franco-Nieto, A., & Revilla-Romero, B. (2020). Monitoring bark beetle forest damage in Central Europe. A remote sensing approach validated with field data. *Remote Sensing*, *12*(21), 3634.

Feurdean, A.; Vannière, B.; Finsinger, W.; Warren, D.; Connor, S.C.; Forrest, M.; Liakka, J.; Panait, A.; Werner, C.; Andriˇc, M.;et al., Fire hazard modulation by long-term dynamics in land cover and dominant forest type in eastern and central Europe. Biogeosciences 2020, 17, 1213–1230.

Finnish Food Authority (2019). Viime vuoden kuivuus voi aiheuttaa yhä ongelmia maatiloilla – ylivoimaiseen esteeseen vetoaminen mahdollista. (in Finnish), Url: https://www.ruokavirasto.fi/viljelijat/uutiset/viime-vuoden-kuivuus-voi-aiheuttaa-yha-ongelmia-maatiloilla/ press release, last access: 02.03.2023.

Fetting, C. (2020). “The European Green Deal”, ESDN Report, December 2020, ESDN Office, Vienna. URL: https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf , last access: 15.2.2024

Food and Agricultural Organization of the United Nations: Halting bark beetles that cause pine forests dieback in Belarus and Ukraine, Food and Agricultural Organization of the United Nations, Rome, Italy, 2018

Forest health 2021: https://assets.gov.ie/136864/6a39a3ce-3f1d-461b-bbd9-7dd9bf7da570.pdf

Forestry~~.com.~~ (2018~~.~~): Forest fires in Sweden - huge areas burned in 2018. Available at https://www.forestry.com/editorial/forest-fires-sweden/

~~Forest research 2023c: https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/phytophthora-pluvialis/~~

~~Forest Research 2008: https://cdn.forestresearch.gov.uk/2008/01/fcrn101.pdf~~

Forest Research (2008): https://cdn.forestresearch.gov.uk/2008/01/fcrn101.pdf last visited on 20.3.2023

Forest Research (2019~~:~~): Public Opinion of Forestry 2019 - Northern Ireland ~~https://cdn.forestresearch.gov.uk/2022/03/pof2020ni.pdf~~https://cdn.forestresearch.gov.uk/2022/03/pof2020ni.pdf last visited on 20.3.2023

Forest Research (2021): Public Opinion of Forestry 2021: UK and England: ~~https://cdn.forestresearch.gov.uk/2022/02/pof_uk_eng_2021.pdf~~ https://cdn.forestresearch.gov.uk/2022/02/pof_uk_eng_2021.pdf last visited on 20.3.2023

Forest Research (2022a~~:~~): Provisional Woodland Statistics 2022 ~~https://cdn.forestresearch.gov.uk/2022/06/PWS-statsnotice-16jun22.pdf~~ https://cdn.forestresearch.gov.uk/2022/06/PWS-statsnotice-16jun22.pdf last visited on 20.3.2023

Forest Research (2022b~~:~~): Forestry Statistics 2022 ~~https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/~~ https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/ last visited on 20.3.2023

Forest Research (2022c): https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/phytophthora-pluvialis/ last visited on 20.3.2023

Forest Statistics Ireland (2020): https://www.teagasc.ie/media/website/crops/forestry/advice/Forest-Statistics-Ireland-2020.pdf last visited on 20.3.2023

Forestry and Land Scotland 2023: https://forestryandland.gov.scot/what-we-do/health-safety-wellbeing/wildfire-prevention last visited 22.3.23

Forestry Commission (2023): Wildfire statistics for England: Report to 2020-21 ~~https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1136838/FC-Wildfire-statistics-for-England-Report-to-2020-21-.pdf~~https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1136838/FC-Wildfire-statistics-for-England-Report-to-2020-21-.pdf

forskning (2019): https://www.forskning.no/insekter-nibio-partner/uvanlig-barkbilleangrep-i-vestfold/1319291 last visited 21.8.2024

Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., ... & Cescatti, A. (2021). Emergent vulnerability to climate-driven disturbances in European forests. Nature communications, 12(1), 1081.

Freistaat Thüringen (2022): https://infrastruktur-landwirtschaft.thueringen.de/fileadmin/Forst_und_Jagd_Fischerei/Forstwirtschaft/2022_Waldzustandsbericht_barrierefrei.pdf

GAN-NIK(2019): https://www.navarra.es/NR/rdonlyres/4FC06980-DB33-40F3-8698-3BC9938F0142/480640/Resultados2021ReddeEvaluacionFitosanitariadelasMas.pdf last visited 20.8.2024

Garbarino, M., Morresi, D., Urbinati, C., Malandra, F., Motta, R., Sibona, E. M., ... & Weisberg, P. J. (2020). Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines. Landscape Ecology, 35(12), 2679-2694.

García-León, D. et al., Current and projected regional economic impacts of heatwaves in Europe. Nat. Commun. 12, 5807 (2021).

García-Herrera, R., Garrido-Perez, J. M., Barriopedro, D., Ordonez, C., Vicente-Serrano, S. M., Nieto, R., ... & Yiou, P., 2019. The European 2016/17 Drought. Journal of Climate, 32(11), 3169-3187. https://doi.org/10.1175/JCLI-D-18-0331.1

Gazol, A., & Camarero, J.J J. (2022). Compound climate events increase tree drought mortality across European forests. Science of the Total Environment, 816, 151604.

Gazol, A., Camarero, J. J., Jiménez, J. J., Moret-Fernández, D., López, M. V., Sangüesa-Barreda, G., and& Igual, J. M.:. (2018). Beneath the canopy: Linking drought-induced forest die off and changes in soil properties. Forest Ecol. Manag.,Ecology and Management, 422, 294-302, 2018.

GeoSphere Austria (2024): https://www.zamg.ac.at/cms/de/klima/klima-aktuell/klimamonitoring/?param=t&period=period-ymd-2024-08-20&ref=1 last visited at 22.8.2024

Geological Survey of Sweden (2017). Årsredovisning 2017. Available from: https://resource.sgu.se/produkter/broschyrer/arsredovisning-2017.pdf

George, J. P., Bürkner, P. C., Sanders, T. G., Neumann, M., Cammalleri, C., Vogt, J. V., & Lang, M. (2022). Long-term forest monitoring reveals constant mortality rise in European forests. *Plant Biology*.

Geosphere Austria: https://www.zamg.ac.at/cms/de/klima/klima-aktuell/klimamonitoring

Gliksman, D., Averbeck, P., Becker, N., Gardiner, B., Goldberg, V., Grieger, J., ... & Franzke, C. L. (2023). A European perspective on wind and storm damage–from the meteorological background to index-based approaches to assess impacts. Natural Hazards and Earth System Sciences, 23(6), 2171-2201.

Global Fire Monitoring Center (2018): https://gfmc.online/media/2018/02-2018/news_20180223_pt.html

Greenpeace (2022, accessed in April 2023):): : https://es.greenpeace.org/es/sala-de-prensa/comunicados/2022-un-ano-horribilis-para-espana-incendios-sequia-olas-de-calor-e-inundaciones/ accessed in April 2023

Gimbel, K.F., Puhlmann, H., and Weiler, M.: Does drought alter hydrological functions in forest soils? Hydrol. Earth Syst. Sci., 20, 1301-1317, 2016.

Głowacka B. (Ed.), Hilszczański J., Jabłoński T., Łukaszewicz J., Skrzecz I., Tarwacki G. (2013) Metodyka integrowanej ochrony drzewostanów iglastych. Instytut Badawczy Leśnictwa, Sękocin Stary, ISBN 978-83-62830-28-2. (in Polish)

Grodzki, W. (2010) The decline of Norway spruce Picea abies (L.) Karst. stands in Beskid Slaski and Zywiecki: Theoretical concept and reality. Beskydy, 3, 19–26.

Grünig, M., Seidl, R., & Senf, C. (2023). Increasing aridity causes larger and more severe forest fires across Europe. Global Change Biology, 29(6), 1648-1659.

Grünzweig, J.M., de Boeck, H.J., Rey, A., Santos, M.J., Adam, O., Bahn, M., Belnap, J., Deckmyn, G., Dekker, S.C., Flores, O., Gliksman, D., Helman, D., Hultine, K.R., Liu, L., Meron, E., Michael, Y., Sheffer, E., Throop, H.L., Tzuk, O., and Yakir, D.: Dryland mechanisms could widely control ecosystem functioning in a drier and warmer world. Nature Ecol. Evol., 6, 1064-1076, 2022.

Gouvernement Français (2020:): France Relance –Toutes les mesures du plan de relance national online : https://agriculture.gouv.fr/telecharger/118602

Haarsma, R. J., Selten, F. M., & Drijfhout, S. S. (2015). Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes. Environmental Research Letters, 10(9), 94007. https://doi.org/10.1088/1748-9326/10/9/094007

Hanewinkel, M., Cullmann, D. A., Schelhaas, M. J., Nabuurs, G. J., & Zimmermann, N. E. (2013). Climate change may cause severe loss in the economic value of European forest land. *Nature climate change*, *3*(3), 203-207.

Hanssen-Bauer, I., Hisdal, H., Hygen, H. O., & Mayer, S. (2017). Climate in Norway 2100: a national climate assessment. *Norwegian Center for Climate Services* report 1/2017.

Hari, V., Rakovec, O., Markonis, Y., Hanel, M., & Kumar, R. (2020). Increased future occurrences of the exceptional 2018–2019 Central European drought under global warming. Scientific reports, 10(1), 1-10.

Hartick, C., Furusho-Percot, C., Goergen, K., & Kollet, S. (2021). An interannual probabilistic assessment of subsurface water storage over Europe using a fully coupled terrestrial model. Water Resources Research, 57(1), e2020WR027828.

Heinze, B. (2017): Bei uns und über dem Gartenzaun: die Entwicklung des Eschentriebsterbens in Österreich im europäischen Kontext. BFW-Praxisinformation Nr. 43: 7-12. Translation: Reneema Hazarika/BFW

Hellwig, J., de Graaf, I. E. M., Weiler, M., & Stahl, K. (2020). Large-Scale Assessment of Delayed Groundwater Responses to Drought. Water Resources Research, 56(2). https://doi.org/10.1029/2019WR025441

The Herald (2021): https://www.heraldscotland.com/news/19482198.scotland-escaped-global-2021-wildfire-crisis-far/ last visited on 14.3.2023

Hermann, M., Röthlisberger, M., Gessler, A., Rigling, A., Senf, C., Wohlgemuth, T., & Wernli, H. (2023). Meteorological history of low-forest-greenness events in Europe in 2002–2022. *Biogeosciences*, *20*(6), 1155-1180.

Hemery, G., Petrokofsky, G., Ambrose-Oji, B., Forster, J., Hemery, T., and O'Brien, L., (2020). Awareness, action, and aspirations in the forestry sector in responding to environmental change: Report of the British Woodlands Survey 2020. 33pp.

Hewelke, E., Oktaba, L., Gozdowski, D., Kondras, M., Olejniczak, I., and Górska, E.B.: Intensity and persistence of soil water repellency in pine forest soil in a temperate continental climate under drought conditions. Water, 10, 1121, 2018.

~~Highland Council 2023: https://www.highland.gov.uk/news/article/15161/scotland_s_firefighters_responded_to_more_than_one_wildfire_a_day_during_spring_last_year last visited at 22.3.23~~

Highland Council 2023: https://www.highland.gov.uk/news/article/15161/scotland_s_firefighters_responded_to_more_than_one_wildfire_a_day_during_spring_last_year last visited at 22.3.23

Hicks, L. C., Rahman, M. M., Carnol, M., Verheyen, K., & Rousk, J. (2018). The legacy of mixed planting and precipitation reduction treatments on soil microbial activity, biomass and community composition in a young tree plantation. Soil Biology and Biochemistry, 124, 227-235.

Hlásny, T., Krokene, P., Liebhold, A., Montagné-Huck, C., Müller, J., Qin, H., ... & Viiri, H. (2019). Living with bark beetles: impacts, outlook and management options (No. 8). European Forest Institute.

Hlásny, T., S. Zimová, K. Merganičová, P. Štěpánek, R. Modlinger, M. Turčáni, (2021): Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications, Forest Ecology and Management, Volume 490, 2021, 119075, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2021.119075.

Holman, I. P., Hess, T. M., Rey, D., & Knox, J. W. (2021). A multi-level framework for adaptation to drought within temperate agriculture. Frontiers in Environmental Science, 8, 589871.

Hoy, A., Haensel, S., Skalak, P., Ustrnul, Z., & Bochníček, O. (2017). The extreme European summer of 2015 in a long-term perspective. International Journal of Climatology, 37(2), 943-962.

Hundhausen, M., Feldmann, H., Laube, N., & Pinto, J. G. (2023). Future heat extremes and impacts in a convection-permitting climate ensemble over Germany. Natural Hazards and Earth System Sciences, 23(8), 2873-2893.

Huuskonen S., Domisch T., Finér L., Hantula J., Hynynen J., Matala J., Miina J., Neuvonen S., Nevalainen S., Niemistö P., Nikula, A., Piria, T., Siitonen, J., Smolander, A., Tonteri, T., Uotila, K. and Viiri, H. (2021): What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? For Ecol Manag. 479:118558. doi:10.1016/j.foreco.2020.118558.

Hroššo, Branislav, Pavel Mezei, Mária Potterf, Andrej Majdák, Miroslav Blaženec, Nataliya Korolyova, and Rastislav Jakuš. 2020. "Drivers of Spruce Bark Beetle (Ips typographus) Infestations on Downed Trees after Severe Windthrow" Forests 11, no. 12: 1290. https://doi.org/10.3390/f11121290

ICP forests (2007): https://www.icp-forests.org/pdf/TR2007.pdf (last access 27.06.2023)

ICCP (2021a): Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210, doi:10.1017/9781009157896.010

ICCP (2021b): IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001

Ilmastokatsaus (2019). Elokuu 2019 (mainly Finnish with English summary), DOI: 10.35614/ISSN-2341-6408-IK-2019-08-00

Ilmastokatsaus (2020). Ilmastovuosikatsaus 2020 (mainly Finnish with English summary), DOI: 10.35614/ISSN-2341-6408-IVK-2020-00

Ilmastokatsaus (2021). Ilmastovuosikatsaus 2021 (mainly Finnish with English summary), DOI: 10.35614/ISSN-2341-6408-IVK-2021-00

Ilmastokatsaus (2022). Ilmastovuosikatsaus 2022 (mainly Finnish with English summary), DOI: 10.35614/ISSN-2341-6408-IVK-2022-00

IMKTRO (2023a):
Wetter und Klima - Fakten zum Klimawandel - Klimawandel in Mitteleuropa - Niederschlag (kit.edu)
last visited 21.8.2024

IMKTRO (2023b):
Wetter und Klima - Fakten zum Klimawandel - Klimawandel in Mitteleuropa - Temperatur (kit.edu)
last visited 21.8.2024

Inward, D. J. G., Caiti, E., Barnard, K., Hasbroucq, S., Reed, K., & Grégoire, J. C. (2024). Evidence of cross-channel dispersal into England of the forest pest Ips typographus. Journal of Pest Science, 1894(Dourojeanni 1971). https://doi.org/10.1007/s10340-024-01763-4

Ionita, M. and Nagavciuc, V. (2021a): Changes in drought features at the European level over the last 120 years, Nat. Hazards Earth Syst. Sci., 21, 1685–1701, https://doi.org/10.5194/nhess-21-1685-2021

Ionita, M., Dima, M., Nagavciuc, V. et al., (2021b): Past megadroughts in central Europe were longer, more severe and less warm than modern droughts. Commun Earth Environ 2, 61 . https://doi.org/10.1038/s43247-021-00130-w

Ionita, M., Nagavciuc, V., Scholz, P., & Dima, M. (2022). Long-term drought intensification over Europe driven by the weakening trend of the Atlantic Meridional Overturning Circulation. Journal of Hydrology: Regional Studies, 42, 101176. https://doi.org/10.1016/J.EJRH.2022.101176

Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T. M., Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J. N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P., … Eisenhauer, N. (2015): Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature, 526, 574–577. https://doi.org/10.1038/nature15374

Jabłoński, T., Małecka, M., Sierota, Z., Tarwacki, G., Sukovata, L., Sowińska, A., Ślusarski, S., Wolski, R., Plewa, R., Grodzki, W., Szmidla, H., Sikora, K., Pudełko, M., Tkaczyk, M. (2019a) Krótkoterminowa prognoza występowania ważniejszych szkodników i chorób infekcyjnych drzew leśnych w Polsce w 2019 r. Instytut Badawczy Leśnictwa, Analizy i Raporty, 26, 160 s. (in Polish)

Jabłoński, T., Tarwacki, G., Sukovata, L. (2019b) Pine forest conditions in Poland in 201–2018. Conference Papers: PINE FORESTS: CURRENT STATUS, EXISTING CHALLENGES AND WAYS FORWARD. Kyiv

Jactel, Hervé, Julia Koricheva, Bastien Castagneyrol, Responses of forest insect pests to climate change: not so simple, Current Opinion in Insect Science, Volume 35, 2019, Pages 103-108, ISSN 2214-5745, https://doi.org/10.1016/j.cois.2019.07.010.

Jakoniuk, H. (2022) Zamieranie dębów i deprecjacja surowca przez szkodniki techniczne – wyrynnika dębowego Platypus cylindrus (Fabr.) oraz rozwiertka większego Xyleborus monographus (Fabr.) na terenie RDLP w Poznaniu. Materiały konferencyjne: Aktualne Problemy Ochrony Lasu 2022. Instytut Badawczy Lesnictwa (in Polish)

Jiang, Y., Marchand, W., Rydval, M., Matula, R., Janda, P., Begović, K., ... & Svoboda, M. (2024). Drought resistance of major tree species in the Czech Republic. Agricultural and Forest Meteorology, 348, 109933.

Jenkins, M., & Schaap, B. (2018). Forest ecosystem services. Background analytical study, 1.

Karavani, A., Boer, M. M., Baudena, M., Colinas, C., Díaz-Sierra, R., Pemán, J., ... & Resco de Dios, V. (2018). Fire-induced deforestation in drought-prone Mediterranean forests: drivers and unknowns from leaves to communities. *Ecological Monographs*, *88*(2), 141-169.

Kautz, M., Peter, F. J., Harms, L., Kammen, S., & Delb, H. (2023). Patterns, drivers and detectability of infestation symptoms following attacks by the European spruce bark beetle. *Journal of Pest Science*, *96*(1), 403-414.

Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J., & Anslow, F. S. (2019). Attribution of the influence of human-induced climate change on an extreme fire season. Earth's Future, 7(1), 2-10.

Kirkpatrick Baird, F., Stubbs Partridge, J. & Spray, D. 2021. Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland, 2021-2040. NatureScot Research Report No. 1228.

Knoke, Thomas, Elizabeth Gosling, Dominik Thom, Claudia Chreptun, Anja Rammig, Rupert Seidl, Economic losses from natural disturbances in Norway spruce forests – A quantification using Monte-Carlo simulations, Ecological Economics, Volume 185, 2021, 107046, ISSN 0921-8009, https://doi.org/10.1016/j.ecolecon.2021.107046.

Koehler, J., Dietz, A. J., Zellner, P., Baumhoer, C. A., Dirscherl, M., Cattani, L., Vlahović, Ž., Alasawedah, M. H., Mayer, K., Haslinger, K., Bertoldi, G., Jacob, A. and Kuenzer, C.: Drought in Northern Italy: Long Earth Observation Time Series Reveal Snow Line Elevation to Be Several Hundred Meters Above Long-Term Average in 2022, Remote Sens., 14(23), 6091, doi:10.3390/RS14236091/S1, 2022.

Kotlarski, S., Gobiet, A., Morin, S., Olefs, M., Rajczak, J., & Samacoïts, R. (2023). 21st Century alpine climate change. Climate Dynamics, 60(1), 65-86.

Krikken, F., Lehner, F., Haustein, K., Drobyshev, I., & van Oldenborgh, G. J. (2021). Attribution of the role of climate change in the forest fires in Sweden 2018. Natural Hazards and Earth System Sciences, 21(7), 2169-2179.

Krumm, F., Rigling, A., Bollmann, K., Brang, P., Dürr, C., Gessler, A., ... & Winkel, G. (2020). Synthesis: Improving biodiversity conservation in European managed forests needs pragmatic, courageous, and regionally-rooted management approaches. *How to balance forestry and biodiversity conservation–A view across Europe. European Forest Institute (EFI), Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmersdorf, Switzerland*, 608-633.

Kunert, N. (2019). Das Ende der Kiefer als Hauptbaumart in Mittelfranken [The end of pine as main tree species in Central Frankonia]. AFZ-Der Wald, 3, 24-5.

Kunert, N. (2020). Preliminary indications for diverging heat and drought sensitivities in Norway spruce and Scots pine in Central Europe. iForest-Biogeosciences and Forestry, 13(2), 89.

Kollet, S. J., and R. M. Maxwell (2008), Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model, Water Resources Research, 44(2).

Kosenius, A-K., Tulla, T., Horne, P., Vanha-Majamaa ja I., Kerkelä, L. 2014. ECONOMICS OF FOREST FIRE MANAGEMENT AND ECOSYSTEM SERVICES – Cost analysis from North Karelia (in Finnish). PTT Working Papers 165, 54 p. ISBN 978-952-224-157-3 (pdf), ISSN 1796-4784.

Kozhoridze, G., Korolyova, N., & Jakuš, R. (2023). Norway spruce susceptibility to bark beetles is associated with increased canopy surface temperature in a year prior disturbance. Forest Ecology and Management, 547, 121400.

Kurz-Besson C, Otieno D, Lobo do Vale R, Siegwolf R, Schmidt M, Herd A, Nogueira C, David TS, David JS, Tenhunen J, Pereira JS, Chaves M. 2006. Hydraulic lift in cork oak trees in a savannah-type Mediterranean ecosystem and its contribution to the local water balance. Plant and Soil 282: 361-378.

Kurz-Besson C., Lousada J. L., Gaspar M. J., Correia I., Soares P. M. M., Cardoso R. M., Russo A., Varino F., Mériaux C., Trigo R.M. and Gouveia C. M. (2016) Effects of Recent Minimum Temperature and Water Deficit Increases on Pinus pinaster

Radial Growth and Wood Density in Southern Portugal (special issue "Tree responses to extreme events"). Front Plant Sci. 2016; 7: 1170. doi: 10.3389/fpls.2016.01170.

Kwiatkowski, M., Rutkiewicz, A., Sawicki, A., Wójcicki, A. (Ed.) (2020) Klęski żywiolowe w lasach. Instytut Badawczy Leśnictwa. ISBN: 978-83-62830-85-5 (in Polish)

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J. P., Stahl, K., Prudhomme, C., ... & Wong, W. K. (2017). The European 2015 drought from a hydrological perspective. Hydrology and Earth System Sciences, 21(6), 3001-3024.

Lambert, R. ; Van der Veeren, B. ; Decamps, C. ; Cremer, S. ; De Toffoli, M. & Javaux M. 2020: Production fourragère et sécheresse, quelles solutions en Wallonie ?, Fourrages 244, 31-37

LASY (2023): https://www.lasy.gov.pl/pl/informacje/aktualnosci/trudny-upalny-czas-dla-lesnikow (last access: 27.6.2023)

Lech P., Żółciak A., Hildebrand R. (2019) Występowanie jemioły (Viscum album L.) w lasach Polski w latach 2008-2018. Materiały konferencyjne: Aktualne Problemy Ochrony Lasu 2019. Instytut Badawczy Lesnictwa. (in Polish).

Lech, P., Zajączkowski, G. (Ed.), Boczoń, A., Hildebrand, R., Kluziński, L., Kowalska, Lech, P., Małachowska, J., Wawrzoniak, J., Zajączkowski, G. (2021) Stan zdrowotny lasów Polski w 2020 roku. Instytut Badawczy Lesnictwa, Sękocin Stary (in Polish).

Lehtonen, I. and Venäläinen, A. (2020). Metsäpalokesä 2018 muuttuvassa ilmastossa – poikkeuksellinen vuosi vai uusi normaali? (in Finnish), Finnish Meteorological Institute Reports 2020:2, ~~https://doi.org/10.35614/isbn.9789523361089~~https://doi.org/10.35614/isbn.9789523361089

Lejeune, Q., Davin, E. L., Gudmundsson, L., Winckler, J., & Seneviratne, S. I. (2018). Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. Nature Climate Change, 8(5), 386-390.

Leuschner C, Drought response of European beech (Fagus ~~MetEireann 2018SFRSsylvatica~~Sylvatica L.) – a review, Perspectives in Plant Ecology, Evolution and Systematics (2020), doi: https://doi.org/10.1016/j.ppees.2020.125576

Li, M., Yao, Y., Simmonds, I., Luo, D., Zhong, L., & Chen, X. (2020). Collaborative impact of the nao and atmospheric blocking on european heatwaves, with a focus on the hot summer of 2018. Environmental Research Letters, 15(11), 114003. https://doi.org/10.1088/1748-9326/aba6ad

Liebhold, A. M., Brockerhoff, E. G., Kalisz, S., Nuñez, M. A., Wardle, D. A., & Wingfield, M. J. (2017). Biological invasions in forest ecosystems. *Biological Invasions*, *19*, 3437-3458.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., ... & Marchetti, M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest ecology and management*, *259*(4), 698-709.

Locatelli, T., Beauchamp, K., Perks, M., Xenakis, G., Nicoll, B., & Morison, J. (2021). Drought risk in Scottish forests. Forest Research.

López, R., Cano, F. J., Choat, B., Cochard, H., & Gil, L. (2016). Plasticity in vulnerability to cavitation of Pinus canariensis occurs only at the driest end of an aridity gradient. Frontiers in Plant Science, 7, 769.

MAA (Ministère de l’Agriculture et de l’Alimentation) 2019a: Récolte de bois et production de sciages en 2018. Agreste Chiffres et Données, n°2019-17

MAA (Ministère de l’Agriculture et de l’Alimentation) 2021a: Récolte de bois et production de sciages en 2019. Baisse de la récolte de bois malgré une forte hausse des coupes sanitaires, Agreste Primeur, n°2021-2.

MAA (Ministère de l'Agriculture et de l'Alimentation) 2022a: Récolte de bois en 2020. Repli de 2,5 % dans le contexte de l’épidémie de Covid-19, n°2022-2

MAA (Ministère de l'Agriculture et de l'Alimentation) 2023 : Récolte de bois et production de sciages en 2021, Agreste Chiffres et Données, n° 2023-3

Mackie, K.A., Zeiter, M., Bloor, J.M.G., Stampfli, A. (2019): Plant functional groups mediate drought resistance and recovery in a multisite grassland experiment. J. Ecol. 107, 937-949.

Matías Resina, L., Bose, A. K., Gessler, A., Bolte, A., Bottero, A., Buras, A., & Cailleret, M. (2020). Growth and resilience responses of Scots pine to extreme droughts across Europe depend on predrought growth conditions. Global Change Biology, 26 (8), 4521-4537.

Merkur (2022): https://www.merkur.de/bayern/schloss-neuschwanstein-waldbrand-tirol-feuer-gefahr-bayern-feuer-trockenheit-grenze-news-91407046.html last time visited: 19-2-2024

Mao J, Nierop KGJ, Dekker SC, Dekker LW, Chen B. 2019. Understanding the mechanisms of soil water repellency from nanoscale to ecosystem scale: a review. Journal of Soils and Sediments 19: 171-185.

Martinez del Castillo, E., Zang, C.S., Buras, A. et al., Climate-change-driven growth decline of European beech forests. Commun Biol 5, 163 (2022). https://doi.org/10.1038/s42003-022-03107-3

Mette, T., & Kölling, C. (2020). Die Zukunft der Kiefer in Franken. *LWF aktuell*, *2*(2020), 14-17.

MET Norway (2019): Tørkesommeren 2018. MetINFO 14/2019. Available from: https://www.met.no/publikasjoner/met-info

Metsäkeskus 2022. Online news of the Finnish Forest Centre (in Finnish), available at https://www.metsakeskus.fi/fi/ajankohtaista/kirjanpainajatuhojen-kasvuun-kannattaa-varautua (last access: 01.03.2023).

Mezei, Pavel, Peter Fleischer, Jozef Rozkošný, Daniel Kurjak, Marek Dzurenko, Slavomír Rell, Michal Lalík, Juraj Galko, Weather conditions and host characteristics drive infestations of sessile oak (Quercus petraea) trap trees by oak bark beetles (Scolytus intricatus), Forest Ecology and Management, Volume 503, 2022,119775, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2021.119775.

Michel A, Kirchner T, Prescher A-K, Schwärzel K, editors (2022b) Forest Condition in Europe: The 2022 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). Online supplementary material, 48 p. Eberswalde: Thünen Institute.

Michel A, Kirchner T, Prescher A-K, Schwärzel K, editors (2022) Forest Condition in Europe: The 2022 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). Eberswalde: Thünen Institute. https://doi.org/10.3220/ICPTR1656330928000

Michel A, Kirchner T, Prescher A-K, Schwärzel K, editors (2021) Forest Condition in Europe: The 2021 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). Eberswalde: Thünen Institute. https://doi.org/10.3220/ICPTR1624952851000

Michel, A. K., Prescher, A. K., Schwärzel, K. (2020). Forest Condition in Europe: The 2020 Assessment; ICP Forests Technical Report Under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). Thünen-Institut, Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei.

Michel A, Prescher A-K, Schwärzel K, editors (2019) Forest Condition in Europe: 2019 Technical Report of ICP Forests. Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). BFW-Dokumentation 27/2019. Vienna: BFW Austrian Research Centre for Forests.

Milanovic, S.; Markovic, N.; Pamucar, D.; Gigovic, L.; Kostic, P.; Milanovic, S.D. Forest Fire Probability Mapping in Eastern Serbia: Logistic Regression versus Random Forest Method. Forests 2021, 12, 5. https://dx.doi.org/10.3390/ f12010005

Miljødirektoratet (2023). Tiltaksanalyse for skog- og arealbrukssektoren (LULUCF): Hvordan Norge kan redusere utslipp av klimagasser fra arealbruksendringer innen 2030. Rapport M-2493.

Moemken J, Koerner B, Ehmele F, Feldmann H, Pinto JG (2022) Recurrence of drought events over Iberia. Part II: Future changes using regional climate projections. Tellus A 74:262-279. doi:10.16993/tellusa.52

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., ... & Wisotzky, C. (2022). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe. Part 1: Event description and analysis. Natural Hazards and Earth System Sciences Discussions, 2022, 1-44.

Möhring B, Bitter A, Bub G, Dieter M, Dög M, Hanewinkel M, Hatzfeld N, Köhler J, Ontrup G, Rosenberger R, Seintsch B, Thoma F (2021) Schadenssumme insgesamt 12,7 Mrd. Euro - Abschätzung der ökonomischen Schäden der Extremwetterereignisse der Jahre 2018 bis 2020 in der Forstwirtschaft. Holz-Zentralblatt (9): 155 – 158

Montanari, A., Nguyen, H., Rubinetti, S., Ceola, S., Galelli, S., Rubino, A., & Zanchettin, D. (2023). Why the 2022 Po River drought is the worst in the past two centuries. Science Advances, 9(32), eadg8304.

Mooney, P. A., Rechid, D., Davin, E. L., Katragkou, E., de Noblet-Ducoudré, N., Breil, M., ... & Lund, M. T. (2022). Land–atmosphere interactions in sub-polar and alpine climates in the CORDEX Flagship Pilot Study Land Use and Climate Across Scales (LUCAS) models–Part 2: The role of changing vegetation. The Cryosphere, 16(4), 1383-1397.

Moravec, V., Markonis, Y., Rakovec, O., Svoboda, M., Trnka, M., Kumar, R., & Hanel, M. (2021). Europe under multi-year droughts: how severe was the 2014–2018 drought period?. Environmental Research Letters, 16(3), 034062.

Moemken J, Koerner B, Ehmele F, Feldmann H, Pinto JG (2022) Recurrence of drought events over Iberia. Part II: Future changes using regional climate projections. Tellus A 74:262-279. doi:10.16993/tellusa.52

Morin, X., Fahse, L., Jactel, H., Scherer-Lorenzen, M., García-Valdés, R., & Bugmann, H. (2018). Long-term response of forest productivity to climate change is mostly driven by change in tree species composition. *Scientific Reports*, *8*(1), 5627.

Morcillo, L., Gallego, D., González, E., & Vilagrosa, A. (2019). Forest decline triggered by phloem parasitism-related biotic factors in Aleppo pine (Pinus halepensis). Forests, 10(8), 608.

Motta, R., Ascoli, D., Corona, P., Marchetti, M. and Vacchiano, G.: Selvicoltura e schianti da vento. Il caso della "tempesta Vaia," For. - J. Silvic. For. Ecol., 15(1), 94, doi:10.3832/EFOR2990-015, 2018.

Müller, M. M., Vilà-Vilardell, L., Vacik, H., Mayer, C., Mayr, S., Carrega, P., ... & Maier, H. (2020). Forest fires in the alps: State of knowledge, future challenges and options for an integrated fire management. EUSALP Action Group, 8.

Müller, M. M. (2022). Rekordbrand TÜPl Allentsteig. Available online: https://fireblog.boku.ac.at/2022/04/12/rekordbrand-tuepl-allentsteig

Müller, L. M., & Bahn, M. (2022). Drought legacies and ecosystem responses to subsequent drought. *Global Change Biology*, *28*(17), 5086-5103.

Nardi, D., Jactel, H., Pagot, E., Samalens, J. C., & Marini, L. (2023). Drought and stand susceptibility to attacks by the European spruce bark beetle: A remote sensing approach. *Agricultural and Forest Entomology*, *25*(1), 119-129.

NBI-6: Schelhaas, M., Clerkx, A. P. P. M., Daamen, W. P., Oldenburger, J. F., Velema, G., Schnitger, P., ... & Kramer, H. (2014). Zesde Nederlandse bosinventarisatie: methoden en basisresultaten (No. 2545). Alterra.

NBI-7: Lerink, B., Schelhaas, M. J., Clerkx, S., Teeuwen, S., Oldenburger, J., & Beerkens, G. (2022). 7e Nederlandse Bosinventarisatie: een gemengde boodschap. Vakblad Natuur Bos Landschap, 19(190), 8-11.

Neuvonen, S. (2020) Ilmastonmuutos ja metsien hyönteistuhot (in Finnish), Metsätieteen aikakauskirja vuosikerta 2020:10498. https://doi.org/10.14214/ma.10498

Nevalainen, S. and Pouttu, A. (Ed.) (2017). Metsätuhot vuonna 2016 (in Finnish), Luonnonvara- ja biotalouden tutkimus 50/2017. Natural Resources Institute Finland, Helsinki. ~~URN: http://urn.fi/URN:ISBN:978-952-326-447-2~~URN: http://urn.fi/URN:ISBN:978-952-326-447-2

NIBIO (Norsk institutt for bioøkonomi - Norwegian Institute of Bioeconomy Research). Online: https://www.skogbruk.nibio.no/skogbrann (in Norwegian; last access: 09.03.2023).

NIBIO (2023) *Kilden Forest data portal*. from: https://kilden.nibio.no/?lang=nb&topic=skogportal&bgLayer=graatone_cache&X=6773739.61&Y=-94941.10&zoom=1.979699915287064&layers_opacity=0.75,0.75,0.75,0.75&layers=barkbille_registrering_17,barkbille_historiske,barkbille_granressurser,barkbille_utsatte_omrader&catalogNodes=1237,1238

de Noblet-Ducoudré, N., Boisier, J. P., Pitman, A., Bonan, G. B., Brovkin, V., Cruz, F., ... & Voldoire, A. (2012). Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. Journal of Climate, 25(9), 3261-3281.

Norwegian Center for Climate services. (2023) Observations and weather statistics. Available from https://seklima.met.no/observations/

Nuorteva, H. (Ed,). (2019). Metsätuhot vuonna 2018 (in Finnish), Luonnonvara- ja biotalouden tutkimus 85/2019. Natural Resources Institute Finland, Helsinki.

Nuorteva, H. (Ed.), Kytö, M. (Ed.), Aarnio, L., Ahola, A., Balázs, A., Elfving, R., Haapanen, M., Hantula, J., Henttonen, H., Huitu, O., Ihalainen, A., Kaitera, J., Kuitunen, P., Kashif, M., Korhonen, K. T., Lindberg, H., Linnakoski, R., Matala, J., Melin, M., Neuvonen, S., Niemimaa, J., Pietilä, V., Piri, T., Poteri, M., Pusenius, J., Silver, T., Strandström, M., Tikkanen, O-P., Uimari, A, Vanha-Majamaa, I., Viiri, H., Vuorinen M. and Ylioja, T. (2022a2022) Metsätuhot vuonna 2019 (in Finnish). Luonnonvara- ja biotalouden tutkimus 1/2022, Natural Resources Institute Finland, Helsinki.

NWFVANVE (2023). Groundwater observations Norway, July 2018. Available from: https://www.senorge.no/

NW-FVA (2022): https://www.ml.niedersachsen.de/download/190134/Waldzustandsbericht_Niedersachsen_2022.pdf

Melin, M. (Ed.), Terhonen, E. (Ed.), Aarnio, L., Hantula, J., Helenius, P., Henttonen, H., Huitu, O., Härkönen, M., Isberg, T., Kaitera, J., Kasanen, R., Koivula, M., Kuitunen, P., Korhonen, K. T., Laurila, I., Lindberg, H., Linnakoski, R., Luoranen, J., Matala, J., Niemimaa, J., Nuorteva, H., Piri, T., Poimala, A., Poteri, M., Pouttu, A., Siitonen, J., Silver, T., Strandström, M., Uimari, A., Vainio, E., Vanha-Majamaa, I., Vuorinen M. and Ylioja, T. (2022) Metsätuhot vuonna 2021 (in Finnish). Luonnonvara- ja biotalouden tutkimus 38/2022, Natural Resources Institute Finland, Helsinki.

Mitchell, D., Heaviside, C., Schaller, N., Allen, M., Ebi, K. L., Fischer, E. M., ... & Vardoulakis, S. (2018). Extreme heat-related mortality avoided under Paris Agreement goals. Nature climate change, 8(7), 551-553.

Luonnonvara- ja biotalouden tutkimus 38/2022, Natural Resources Institute Finland, Helsinki.

O'Hanlon, R., Ryan, C., Choiseul, J., Murchie, A. K., & Williams, C. D. (2021). Catalogue of pests and pathogens of trees on the island of Ireland. Biology and Environment: Proceedings of the Royal Irish Academy, 121B(1), 21–45. https://doi.org/10.3318/bioe.2021.02

Öhrn, P., Berlin, M., Elfstrand, M., Krokene, P., & Jönsson, A. M. (2021). Seasonal variation in Norway spruce response to inoculation with bark beetle-associated bluestain fungi one year after a severe drought. Forest Ecology and Management, 496, 119443.

Olefs, M., Formayer, H., Gobiet, A., Marke, T., Schöner, W., & Revesz, M. (2021). Past and future changes of the Austrian climate–Importance for tourism. Journal of Outdoor Recreation and Tourism, 34, 100395.

ONF (Office National des Forêts) 2020 : Forêts publiques françaises : quel nouveau visage ? Online : https://www.onf.fr/onf/lonf-agit/+/8cf::forets-publiques-francaises-quel-nouveau-visage.html

ONF (Office National des Forêts) 2021 : En forêt, la crise des scolytes s'accélère partout en France. Online: https://www.onf.fr/onf/+/2e0::epidemie-de-scolytes-les-forestiers-de-lonf-sur-le-front.html

Orwig, D. A., & Abrams, M. D. (1997). Variation in radial growth responses to drought among species, site, and canopy strata. Trees, 11, 474-484.

Peñuelas J, Filella I. 2003. Deuterium labelling of roots provides evidence of deep water access and hydraulic lift by Pinus nigra in a Mediterranean forest of NE Spain. Environmental and Experimental Botany 49: 201-208.

Perlińska, A. (2019) Zamieranie drzewostanów w Polsce – sytuacja aktualna, zagrożenia i prognoza. Materiały konferencyjne: Aktualne Problemy Ochrony Lasu 2019. Instytut Badawczy Lesnictwa. (in Polish)

Peters, W., Bastos, A., Ciais, P. and Vermeulen, A.: A historical, geographical and ecological perspective on the 2018 European summer drought. Philos. Trans. R. Soc. Lond. B Biol. Sci., 375, 20190505, 2020.

Pilli, R., Vizzarri, M. and Chirici, G.: Combined effects of natural disturbances and management on forest carbon sequestration: the case of Vaia storm in Italy, Ann. For. Sci., 78(2), 1–18, doi:10.1007/S13595-021-01043-6, 2021.

Piton, Benjamin; Benest, Fabienne ; Caroulle, Fabien ; Cuny, Henri ; Gosselin, Marion ; Montagné-Huck, Claire ; Nicolas, Manuel ; Rocquencourt, Agnès 2021 : État et évolution des forêts françaises métropolitaines. Synthèse des indicateurs de gestion durable 2020.

Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., ... & Schelhaas, M. J. (2023). Significant increase in natural disturbance impacts on European forests since 1950. *Global change biology*, *29*(5), 1359-1376.

Pirtskhalava-Karpova, N., Trubin, A., Karpov, A., & Jakuš, R. (2024). Drought initialised bark beetle outbreak in Central Europe: Meteorological factors and infestation dynamic. Forest Ecology and Management, 554, 121666.

Pereira, M. G., Trigo, R. M., DaCamara, C. C., Pereira, J. M. C.,and Leite, S. M.: Synoptic patterns associated with large summer forest fires in Portugal, Agr. Forest Meteorol. 129, 11–25, doi:10.1016/j.agrformet.2004.12.007, 2005.

Perugini, L., Caporaso, L., Marconi, S., Cescatti, A., Quesada, B., de Noblet-Ducoudré, N., ... & Arneth, A. (2017). Biophysical effects on temperature and precipitation due to land cover change. Environmental Research Letters, 12(5), 053002.

Pettit, J. M., Voelker, S. L., DeRose, R. J., & Burton, J. I. (2020). Spruce beetle outbreak was not driven by drought stress: Evidence from a tree-ring iso-demographic approach indicates temperatures were more important. Global Change Biology, 26(10), 5829-5843.

Plewa, Radoslaw; Mokrzycki, Tomasz (2022) Występowanie, biologia i znaczenie gospodarcze kornika ostrozębnego Ips acuminatus (Gyllenhal, 1827) (Coleoptera, Curculionidae, Scolytinae) w Polsce. Sylwan (in Polish)

Polish Supreme Chamber of Control (2021): https://www.nik.gov.pl/aktualnosci/zapobieganie-suszy-rolniczej.html last visited at 27.6.23

Popkin G. Forest fight. Science. 2021 Dec 3;374 (6572):1184-1189. doi: 10.1126/science.acx9733. Epub 2021 Dec 2. PMID: 34855497.

Prieto, I., Armas, C., and Pugnaire, F.I.: Water release through plant roots: new insights into its consequences at the plant and ecosystem level. New Phytol., 193, 830-841, 2012.

Przybyl, K. (1989) Wpływ warunków klimatycznych na zamieranie dębów w Polsce oraz symptomy choroby. Arboretum Kornickie 34. (in Polish)

Rabbel, I., H. Bogena, B. Neuwirth, and B. Diekkrüger (2018), Using Sap Flow Data to Parameterize the Feddes Water Stress Model for Norway Spruce, Water-Sui, 10(3).

RAF Italia 2017-2018. (2019). Rapporto sullo stato delle foreste e del settore forestale in Italia. In Rapporto sullo stato delle foreste e del settore forestale in Veneto 2020. https://www.reterurale.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/19231

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., et al., (2022). The 2018–2020 multi-year drought sets a new benchmark in Europe. Earth's Future, 10, e2021EF002394. ~~https://doi.org/10.1029/2021EF002394~~https://doi.org/10.1029/2021EF002394

Ribeiro, A. F., Russo, A., Gouveia, C. M., & Pires, C. A. (2020). Drought-related hot summers: A joint probability analysis in the Iberian Peninsula. Weather and Climate Extremes, 30, 100279.

REA (2024): https://rea.ec.europa.eu/news/fighting-flames-eu-funded-projects-protecting-forests-fire-destruction-2024-07-23_en last visited 21.8.2024

Rechid, D., Davin, E., de Noblet-Ducoudré, N., & Katragkou, E. (2017, April). CORDEX Flagship Pilot Study" LUCAS-Land Use & Climate Across Scales"-a new initiative on coordinated regional land use change and climate experiments for Europe. In EGU General Assembly Conference Abstracts (p. 13172).

Rico, L., Ogaya, R., Barbeta, A., & Peñuelas, J. (2014). Changes in DNA methylation fingerprint of Quercus ilex trees in response to experimental field drought simulating projected climate change. Plant Biology, 16(2), 419–427. https://doi.org/10.1111/PLB.12049

Rita, A., Camarero, J. J., Nolè, A., Borghetti, M., Brunetti, M., Pergola, N., ... & Ripullone, F. (2020). The impact of drought spells on forests depends on site conditions: The case of 2017 summer heat wave in southern Europe. *Global change biology*, *26*(2), 851-863.

Rohner, B., Kumar, S., Liechti, K., Gessler, A., and Ferretti, M.: Tree vitality indicators revealed a rapid response of beech forests to the 2018 drought. Ecol. Indic., 120, 106903, 2021.

Rotenberg, E., and Yakir, D.: Contribution of semi-arid forests to the climate system. Science, 327, 451-454, 2010.

Rousi, E., Selten, F., Rahmstorf, S., and Coumou, D.: Changes in North Atlantic Atmospheric Circulation in a Warmer Climate Favor Winter Flooding and Summer Drought over Europe, J. Climate, 34, 2277–2295, https://doi.org/10.1175/JCLI-D-20-0311.1, 2021.

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., and Coumou, D.: Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia, Nat. Commun., 13, 1–11, https://doi.org/10.1038/s41467-022-31432-y, 2022.

Rousi, E., Fink, A. H., Andersen, L. S., Becker, F. N., Beobide-Arsuaga, G., Breil, M., Cozzi, G., Heinke, J., Jach, L., Niermann, D., Petrovic, D., Richling, A., Riebold, J., Steidl, S., Suarez-Gutierrez, L., Tradowsky, J. S., Coumou, D., Düsterhus, A., Ellsäßer, F., Fragkoulidis, G., Gliksman, D., Handorf, D., Haustein, K., Kornhuber, K., Kunstmann, H., Pinto, J. G., Warrach-Sagi, K., and Xoplaki, E.: The extremely hot and dry 2018 summer in central and northern Europe from a multi-faceted weather and climate perspective, Nat. Hazards Earth Syst. Sci., 23, 1699–1718, https://doi.org/10.5194/nhess-23-1699-2023, 2023.

Ruffault, J. et al., Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci. Rep. 10, 13790 (2020).

Rukh, S., Sanders, T. G., Krüger, I., Schad, T., & Bolte, A. (2023). Distinct responses of European beech (Fagus sylvatica L.) to drought intensity and length—A review of the impacts of the 2003 and 2018–2019 drought events in Central Europe. Forests, 14(2), 248.

Russo, A., Gouveia, C. M., Páscoa, P., DaCamara, C. C., Sousa, P. M., & Trigo, R. M. (2017). Assessing the role of drought events on wildfires in the Iberian Peninsula. Agricultural and Forest Meteorology, 237, 50-59.

Ruosteenoja, K., Markkanen, T., & Räisänen, J. (2020). Thermal seasons in northern Europe in projected future climate. International Journal of Climatology, 40(10), 4444-4462.

Saintonge, François-Xavier; Gillette, Max; Blaser, Simon; Queloz, Valentin; Leroy, Quentin (2021): Situation et gestion de la crise liée aux scolytes de l'Épicéa commun fin 2021 dans l'est de la France, en Suisse et en Wallonie. Revue Forestiere Francaise 73(6), 619-641

Salomón, R. L., Peters, R. L., Zweifel, R., Sass-Klaassen, U. G., Stegehuis, A. I., Smiljanic, M., ... & Steppe, K. (2022). The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. Nature Communications, 13(1), 1-11.

San-Miguel-Ayanz, J., Oom, D., Artes, T., Viegas, D. X., Fernandes, P., Faivre, N., …, Castellnou, M., 2020. Forest fires in Portugal in 2017. in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, JRC114026. https://doi.org/doi:10.2760/571085

Scharnweber, T., Smiljanic, M., Cruz-García, R., Manthey, M., & Wilmking, M. (2020). Tree growth at the end of the 21st century-the extreme years 2018/19 as template for future growth conditions. Environmental Research Letters, 15(7), 074022.

Schreiner Zeitung (2022): https://www.schreinerzeitung.ch/de/artikel/zweithochster-je-registrierter-borkenkaferbefall-der-schweiz

Scherrer, D., Ascoli, D., Conedera, M., Fischer, C., Maringer, J., Moser, B., ... & Wohlgemuth, T. (2022). Canopy disturbances catalyse tree species shifts in Swiss forests. *Ecosystems*, *25*(1), 199-214.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., and Whitford, W.G.: Biological feedbacks in global desertification. Science, 247, 1043-1048, 1990.

Schnabel, F., Purrucker, S., Schmitt, L., Engelmann, R.A., Kahl, A., Richter, R., Seele-Dilbat, C., Skiadaresis, G., and Wirth, C.: Cumulative growth and stress responses to the 2018-2019 drought in a European floodplain forest. Glob. Change Biol., 28, 1870-1883, 2022.

Scottish Forestry 2023a: https://forestry.gov.scot/sustainable-forestry/tree-health/tree-pests-and-diseases/great-spruce-bark-beetle-in-scotland last visited at 22.3.23.

Scottish Forestry 2023b: https://forestry.gov.scot/publications/1385-updated-d-micans-distribution-map-in-scotland-january-2022/download last visited at 22.3.23.

Schuldt, B., Knutzen, F., Delzon, S., Jansen, S., Müller-Haubold, H., Burlett, R., ... & Leuschner, C. (2016). How adaptable is the hydraulic system of European beech in the face of climate change-related precipitation reduction?. New Phytologist, 210(2), 443-458.

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., ... & Kahmen, A. (2020). A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic and Applied Ecology, 45, 86-103.

Schumacher, D. L., Zachariah, M., Otto, F., Barnes, C., Philip, S., Kew, S., Vahlberg, M., Singh, R., Heinrich, D., Arrighi, J., Van Aalst, M., Hauser, M., Hirschi, M., Gudmundsson, L., Beaudoing, H. K., Rodell, M., Li, S., Yang, W., Vecchi, G. A., … Seneviratne, S. I. (2022). High temperatures exacerbated by climate change made 2022 Northern Hemisphere soil moisture droughts more likely. World Weather Attribution.

Seaton, F.M., Jones, D.L., Creer, S., George, P.B.L., Smart, S.M., Lebron, I., Barrett, G., Emmett, B.A., and Robinson, D.A.: Plant and soil communities are associated with the response of soil water repellency to environmental stress. Sci. Total Environ., 687, 929-938, 2019.

Senf, C. and Seidl, R.~~.:~~. (2021a): Persistent impacts of the 2018 drought on forest disturbance regimes in Europe, Biogeosciences, 18, 5223–5230, https://doi.org/10.5194/bg-18-5223-2021, 2021a.

Senf, C., & Seidl, R. (~~2021b~~2021). Storm and fire disturbances in Europe: ~~distribution~~Distribution and trends. Global ~~change biology~~Change Biology, 27(15), 3605-3619.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., ... & Zhou, B. Chapter 11: weather and climate extreme events in a changing climate. 2021.

Sierota, Z., Grodzki, W., Szczepkowski, A., (2019). Abiotic and Biotic Disturbances Affecting Forest Health in Poland over the Past 30 Years: Impacts of Climate and Forest Management. Forests. 10. 75. 10.3390/f10010075

Sierota, Z., Grodzki, W. (2020) Picea abies-Armillaria-Ips: A strategy or coincidence? Forests. DOI 10.3390/F11091023

Sire, L., Yáñez, P.S., Wang, C. et al., Climate-induced forest dieback drives compositional changes in insect communities that are more pronounced for rare species. Commun Biol 5, 57 (2022). https://doi.org/10.1038/s42003-021-02968-4

Sioen, G., Verschelde, P., & Roskams, P. (2019). Bosvitaliteitsinventaris 2018. Resultaten uit het bosvitaliteitsmeetnet (Level 1). (Rapporten van het Instituut voor Natuur- en Bosonderzoek; Nr. 20). Instituut voor Natuur- en Bosonderzoek. https://doi.org/10.21436/inbor.16207115

Sioen, G., Verschelde, P., & Roskams, P. (2020). Bosvitaliteitsinventaris 2019: Resultaten uit het bosvitaliteitsmeetnet (Level 1). (Rapporten van het Instituut voor Natuur- en Bosonderzoek 2020; Nr. 20). Instituut voor Natuur- en Bosonderzoek. https://doi.org/10.21436/inbor.18050253

Sioen, G., Verschelde, P., & Roskams, P. (2021). Bosvitaliteitsinventaris 2020: Resultaten uit het bosvitaliteitsmeetnet (Level 1). (Rapporten van het Instituut voor Natuur- en Bosonderzoek; Nr. 20). Instituut voor Natuur- en Bosonderzoek. https://doi.org/10.21436/inbor.34283136

Sioen, G., Verschelde, P., & Roskams, P. (2022). Bosvitaliteitsinventaris 2021. Resultaten uit het bosvitaliteitsmeetnet (Level 1). (Rapporten van het Instituut voor Natuur- en Bosonderzoek; Nr. 7). Instituut voor Natuur- en Bosonderzoek. https://doi.org/10.21436/inbor.71783042

Sioen et al., (2023): Sioen, G., Verschelde, P., & Roskams, P. (2023). Bosvitaliteitsinventaris 2022. Resultaten uit het bosvitaliteitsmeetnet (Level 1). (Rapporten van het Instituut voor Natuur- en Bosonderzoek; Nr. 4). https://doi.org/10.21436/inbor.90109478

Skaland, R.G., Colleuille, H., Andersen, A.S.H., Mamen, J., Grinde L., Tajet, T.T., Lundstad, E., Sidselrud, L.F, Tunheim, K., Hanssen-Bauer, I. Benestad, R. Heiberg, H & Hygen. (2019). Tørkesommeren 2018. Meteorological institute, Norway

SMHI (2023). Året 2022. Mycket tört i sydöstra Sverige. Available from: https://www.smhi.se/klimat/klimatet-da-och-nu/arets-vader/aret-2022-mycket-torrt-i-sydostra-sverige-1.190565

Sofiadis, G., Katragkou, E., Davin, E. L., Rechid, D., de Noblet-Ducoudre, N., Breil, M., ... & Warrach Sagi, K. (2022). Afforestation impact on soil temperature in regional climate model simulations over Europe. Geoscientific Model Development, 15(2), 595-616.

SSB (2022) Landskogtakseringen (forest volume statistics Norway), from https://www.ssb.no/statbank/table/06289/tableViewLayout1/

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. (2018). Will drought events become more frequent and severe in Europe?. *International Journal of Climatology*, *38*(4), 1718-1736.

Stagge, J. H., Kingston, D. G., Tallaksen, L. M. & Hannah, D. M. Observed drought indices show increasing divergence across Europe. Sci. Rep. 7, 1–10 (2017).

~~Standard (2021): https://www.derstandard.de/story/2000130717176/rax-gebiet-groesster-waldbrand-den-es-je-in-oesterreich-gab~~

Standard (2021): https://www.derstandard.de/story/2000130717176/rax-gebiet-groesster-waldbrand-den-es-je-in-oesterreich-gab

Statsforvalteren (2020) *Årsmelding 2019*. Skogbruket i Vestfold og Telemark.

Statsforvalteren (2021) *Årsmelding 2020*. Skogbruket i Vestfold og Telemark.

Stephan, R., Erfurt, M., Terzi, S., Žun, M., Kristan, B., Haslinger, K., and Stahl, K. (2021): An inventory of Alpine drought impact reports to explore past droughts in a mountain region, Nat. Hazards Earth Syst. Sci., 21, 2485–2501, https://doi.org/10.5194/nhess-21-2485-2021

Středová, H., Fukalová, P., Chuchma, F., & Středa, T. (2020). A complex method for estimation of multiple abiotic hazards in forest ecosystems. Water, 12(10), 2872.

Sturm, J., Santos, M.J., Schmid, B., and Damm, A.: Satellite data reveal differential responses of Swiss forests to unprecedented 2018 drought. Glob Chang Biol, 28, 2956-2978, 2022.

Suarez-Gutierrez, L., Li, C., Müller, W.A. & Marotzke, J. (2018). Internal variability in European summer temperatures at 1.5 °C and 2 °C of global warming. Environ. Res. Lett. 13, 064026. doi:10.1088/1748-9326/aaba58

Suarez-Gutierrez, L., Müller, W.A. & Marotzke, J. Extreme heat and drought typical of an end-of-century climate could occur over Europe soon and repeatedly. Commun Earth Environ 4, 415 (2023). https://doi.org/10.1038/s43247-023-01075-y

Süßel, F., & Brüggemann, W. (2021). Tree water relations of mature oaks in southwest Germany under extreme drought stress in summer 2018. Plant stress, 1, 100010.

Sommerfeld, A., Rammer, W., Heurich, M., Hilmers, T., Müller, J., & Seidl, R. (2021). Do bark beetle outbreaks amplify or dampen future bark beetle disturbances in Central Europe?. Journal of Ecology, 109(2), 737-749.

SRF (2020): https://www.srf.ch/news/schweiz/der-schweizer-wald-leidet-extremer-befall-von-borkenkaefern

~~Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., ... & Zhou, B. (2021). 11 Chapter 11: Weather and climate extreme events in a changing climate.~~

~~SZ (2022): https://www.sueddeutsche.de/bayern/schloss-neuschwanstein-allgaeu-waldbrand-1.5547353~~

~~Tagessschau (2022): https://www.rainews.it/tgr/tagesschau/articoli/2022/10/tag-Borkenkaefer-5000-Hektar-in-Suedtirol-befallen-e7437c6e-2139-4b00-87d4-bf6d265595e9.html~~

~~Statsforvalteren (2020) *Årsmelding 2019*. Skogbruket i Vestfold og Telemark.~~

~~Statsforvalteren (2021) *Årsmelding 2020*. Skogbruket i Vestfold og Telemark.~~

~~Stephan, R., Erfurt, M., Terzi, S., Žun, M., Kristan, B., Haslinger, K., and Stahl, K. (2021): An inventory of Alpine drought impact reports to explore past droughts in a mountain region, Nat. Hazards Earth Syst. Sci., 21, 2485–2501, https://doi.org/10.5194/nhess-21-2485-2021~~

~~Sturm, J., Santos, M. J., Schmid, B., & Damm, A. (2022). Satellite data reveal differential responses of Swiss forests to unprecedented 2018 drought. *Global Change Biology*, *28*(9), 2956-2978.~~

Sutanto, S.J., Vitolo, C., Di Napoli, C., D'Andrea, M., and Van Lanen, H.A.J.: Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. Environ. Int., 134, 105276, 2020.

SUSZA (2023): https://www.gov.pl/web/susza/susza (last visited: 27.06.2023)

Swedish Board of Agriculture (2019). Långsiktiga effekter av torkan 2018, och hur jordbruket kan bli mer motståndskraftigt mot extremväder. Jorbruksverkets rapport RA 19/13.

SZ (2022): https://www.sueddeutsche.de/bayern/schloss-neuschwanstein-allgaeu-waldbrand-1.5547353 4b00-87d4-bf6d265595e9.html

Tagessschau (2022): https://www.rainews.it/tgr/tagesschau/articoli/2022/10/tag-Borkenkaefer-5000-Hektar-in-Suedtirol-befallen-e7437c6e-2139-

Telegraph (2018): https://www.telegraph.co.uk/news/fire-storm-the-wildfires-sweeping-europe-and-britain/ last visited on 14.3.2023

Terhonen, E., Melin, M., Aarnio, L., Granberg, F., Hantula, J., Henttonen, H., Huitu, O., Huuskonen, S., Härkönen, M., Kaitera, J., Koivula, M., Kokko, A., Kokkonen, J., Korhonen, K. T., Laurila, I., Lehto, T., Luoranen, J., Niemimaa, J., Nuorteva, H., Pennanen, T., Piri, T., Poimala, A., Pouttu, A., Pätäri, V., Siitonen, J., Silver, T., Strandström, M., Sutela, S., Tikkanen, O.-P., Vainio, E., Vanha-Majamaa, I., Velmala, S. and Ylioja, T. (2023) Metsätuhot vuonna 2022 (in Finnish). Luonnonvara- ja biotalouden tutkimus 48/2023, Natural Resources Institute Finland, Helsinki.

Teuling, A.J., Seneviratne, S.I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luyssaert, S., van den Hurk, B., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grünwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M., and Wohlfahrt, G.: Contrasting response of European forest and grassland energy exchange to heatwaves. Nature Geosci., 3, 722-727, 2010.

Teutschbein, C., Jonsson, E., Todorović, A., Tootoonchi, F., Stenfors, E., & Grabs, T. (2022a). Drought Propagation through the Water-Energy-Food-Ecosystem Nexus: a Nordic Perspective.

Teutschbein, C., Montano, B. Q., Todorović, A., & Grabs, T. (2022b). Streamflow droughts in Sweden: Spatiotemporal patterns emerging from six decades of observations. Journal of Hydrology: Regional Studies, 42, 101171.

Thrippleton, T., Lüscher, F., & Bugmann, H. (2020). Climate change impacts across a large forest enterprise in the Northern Pre-Alps: dynamic forest modelling as a tool for decision support. *European Journal of Forest Research*, *139*(3), 483-498.

Thom, D., Seidl, R. Accelerating Mountain Forest Dynamics in the Alps. *Ecosystems* **25**, 603–617 (2022). https://doi.org/10.1007/s10021-021-00674-0

Thom, D., Rammer, W., Laux, P., Smiatek, G., Kunstmann, H., Seibold, S., & Seidl, R. (2022). Will forest dynamics continue to accelerate throughout the 21st century in the Northern Alps?.

TMIL (2022): https://infrastruktur-landwirtschaft.thueringen.de/fileadmin/Forst_und_Jagd_Fischerei/Forstwirtschaft/2022_Waldzustandsbericht_barrierefrei.pdf

Thonfeld, F., Gessner, U., Holzwarth, S., Kriese, J., da Ponte, E., Huth, J., Kuenzer, C. A First Assessment of Canopy Cover Loss in Germany's Forests after the 2018–2020 Drought Years. *Remote Sens.* **14**, 562 (2022). https://doi.org/10.3390/rs14030562

Toreti, A., Bavera, D., Acosta Navarro, J., Cammalleri, C., de Jager, A., Di Ciollo, C., Hrast Essenfelder, A., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., Niemeyer, S., Spinoni, J.,: Drought in Europe August 2022, Publications Office of the European Union, Luxembourg, JRC13049, doi:10.2760/264241, 2022a.~~.~~

Toreti, A., Bavera, D., Avanzi, F., Cammalleri, C., De Felice, M., de Jager, A., Di Ciollo, C., Gabellani, S., Maetens, W., Magni, D., Manfron G., Masante, D., Mazzeschi, M., McCormick, N., Naumann, G., Niemeyer, S., Rossi, L., Seguini, L., Spinoni, J., van den Berg, M.: Drought in northern Italy March 2022, EUR 31037 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-50158-9 (online), JRC128974, doi:10.2760/781876, 2022b.

Toreti, A., Bavera, D., Acosta Navarro, J., Arias-Muñoz, C., Avanzi, F., Marinho Ferreira Barbosa, P., De Jager, A., Di Ciollo, C., Ferraris, L., Fioravanti, G., Gabellani, S., Grimaldi, S., Hrast Essenfelder, A., Isabellon, M., Jonas, T., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., Mccormick, N., Meroni, M., Rossi, L., Salamon, P. and Spinoni, J.,: Drought in Europe March 2023, EUR 31448 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-68-01068-6, doi:10.2760/998985, JRC133025, 2023.

Toth, D., Maitah, M., Maitah, K., & Jarolínová, V. (2020). The impacts of calamity logging on the development of spruce wood prices in Czech forestry. Forests, 11(3), 283.

Turner, S., Barker, L. J., Hannaford, J., Muchan, K., Parry, S., & Sefton, C. (2021). The 2018/2019 drought in the UK: a hydrological appraisal. Weather, 76(8), 248-253.

Turco, M., Jerez, S., Augusto, S. et al. Climate drivers of the 2017 devastating fires in Portugal. Sci Rep 9, 13886 (2019). https://doi.org/10.1038/s41598-019-50281-2

Turco, M., Abatzoglou, J. T., Herrera, S., Zhuang, Y., Jerez, S., Lucas, D. D., ... & Cvijanovic, I. (2023). Anthropogenic climate change impacts exacerbate summer forest fires in California. Proceedings of the National Academy of Sciences, 120(25), e2213815120.

Tyukavina A, Potapov P, Hansen MC, Pickens AH, Stehman SV, Turubanova S, Parker D, Zalles V, Lima A, Kommareddy I, Song X-P, Wang L and Harris N (2022) Global Trends of Forest Loss Due to Fire From 2001 to 2019. Front. Remote Sens. 3:825190. doi: 10.3389/frsen.2022.825190

~~UBA 2021: Umweltbundesamt (UBA); https://www.umweltbundesamt.de/daten/land-forstwirtschaft/waldbraende#waldbrande-in-deutschland (visited at 14-1-2022)~~

UBA (2023a): https://www.umweltbundesamt.de/daten/land-forstwirtschaft/waldbraende#waldbrande-in-deutschland

UBA (2023b): https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/das-monitoringbericht_2023_bf_korr.pdf last visited 19.8.2023

UN (2024): https://www.un.org/en/about-us/member-states (visited at 9-2-2024)

UNECE Committee on Forest and the Forest Industry and the European Forestry Commission (Foresta2022). Sweden: country market statement 2022. Available at https://unece.org/forestry-timber/documents/2022/10/informal-documents/sweden-country-market-statement-2022 (last access 01.03.2023).

Van Der Wiel, K., Batelaan, T. J., & Wanders, N. (2022). Large increases of multi-year droughts in north-western Europe in a warmer climate. Climate Dynamics 2022, 1, 1–20. https://doi.org/10.1007/S00382-022-06373-3

Van Loon, A. F. (2015), Hydrological drought explained, Wires Water, 2(4), 359-392.

Veijalainen, N., Ahopelto, L., Marttunen, M., Jääskeläinen, J., Britschgi, R., Orvomaa, M., Belinskij, A. and Keskinen. M. (2019): Severe Drought in Finland: Modeling Effects on Water Resources and Assessing Climate Change Impacts. Sustainability 11, no. 8: 2450. https://doi.org/10.3390/su11082450

Venäläinen, A., Lehtonen, I., & Mäkelä, A. (2016). Laaja-alaisia metsäpaloja mahdollistavat säätilanteet Suomen ilmastossa [The risk of large forest fires in Finland]. Finnish Meteorological Institute, Reports 2016:3 (in Finnish, English Abstract). Retrieved from https://helda.helsinki.fi/handle/10138/161478

Verkerk, H., Delacote, P., Hurmekoski, E., Kunttu, J., Matthews, R., Mäkipää, R., ... & Trømborg, E. (2022). Forest-based climate change mitigation and adaptation in Europe.

Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., ... & Gasparrini, A. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. Nature climate change, 11(6), 492-500.

Vicente-Serrano, Sergio M., and Coauthors, (2012): Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. Earth Interact., 16, 1–27.

Vicente-Serrano, S.M., and Coauthors (2013). The response of vegetation to drought time-scales across global land biomes. Proceedings of the National Academy of Sciences of the United States of America 110: 52-57.

~~Vicente-Serrano, Sergio M., and Coauthors, 2012: Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. Earth Interact., 16, 1–27.~~

Vicente-Serrano, S. M., Quiring, S. M., Pena-Gallardo, M., Yuan, S., & Dominguez-Castro, F. (2020). A review of environmental droughts: Increased risk under global warming?. Earth-Science Reviews, 201, 102953.

Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D., & Seneviratne, S. I. (2019). Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change. Earth's future, 7(7), 692-703.

Vogel, J., Paton, E., Aich, V., & Bronstert, A. (2021). Increasing compound warm spells and droughts in the Mediterranean Basin. Weather and Climate Extremes, 32, 100312.

Wallonie agriculture, n.d. : Appréhender la croissance de l'herbe. Online : https://agriwalinfo.wixsite.com/website-1/about-2

~~WSL (2022): https://www.wsl.ch/de/newsseiten/2022/09/trockenheit-2018-buchen-mit-fruehzeitig-verfaerbtem-laub-neigen-zum-absterben-in-den-folgejahren.html~~

Waldschutz (2023): https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%3A32875/datastream/PDF/Stroheker-2023-Leichte_Zunahme_von_Buchdrucker-Befallsherden-%28published_version%29.pdf

Wataha (2021): https://wataha.no/en/2021/11/15/an-increase-in-the-bark-beetle-population-in-Norwegian-forests/ last visited 21.8.2024

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., ... & Costello, A. (2021). The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. The lancet, 397(10269), 129-170.

Wawrzoniak, J. (Ed.), Boczoń, A., Hildebrand, R., Kowalska, A., Lech, P., Małachowska, J., Wawrzoniak, J., Zajączkowski, G. (2019) Stan zdrowotny lasów Polski w 2018 roku. Instytut Badawczy Lesnictwa, Sękocin Stary (in Polish)

Weigel et al. (2023): Weigel, R., Bat-Enerel, B., Dulamsuren, C., Muffler, L., Weithmann, G., & Leuschner, C. (2023). Summer drought exposure, stand structure, and soil properties jointly control the growth of European beech along a steep precipitation gradient in northern Germany. Global change biology, 29(3), 763-779.

WSL (2022): https://www.wsl.ch/de/newsseiten/2022/09/trockenheit-2018-buchen-mit-fruehzeitig-verfaerbtem-laub-neigen-zum-absterben-in-den-folgejahren.html

WSL (2023a): https://www.wsl.ch/de/newsseiten/2023/03/leichte-zunahme-des-borkenkaefer-befalls-im-jahr-2022.html

WSL (2023b): https://www.waldwissen.net/assets/technik/inventur/wsl_zwischenergebnisse-lfi5/Zwischenergebnisse_LFI_print.pdf#page=2

~~Wang L, Kaseke KF, Seely MK. 2017. Effects of non-rainfall water inputs on ecosystem functions. Wiley Interdisciplinary Reviews: Water 4: e1179.~~

Winkel, G., Lovrić, M., Muys, B., Katila, P., Lundhede, T., Pecurul, M., ... & Wunder, S. (2022). Governing Europe's forests for multiple ecosystem services: Opportunities, challenges, and policy options. *Forest Policy and Economics*, *145*, 102849.

Zahradník, P., & Zahradníková, M. (2019). Salvage felling in the Czech Republic‘s forests during the last twenty years. *Central European Forestry Journal*, *65*(1), 12-20.

Winland-project Policy Brief VII (2019). Kuivuus koettelee myös Suomea - Olemmeko tarpeeksi varautuneita? (in Finnish), ISBN 978-952-60-3774-5 (PDF) https://winlandtutkimus.fi/wp-content/uploads/2019/04/Winland-kuivuus.pdf, last access: 2.06.2022.

~~Words~~Worlds Aid (2022): https://www.worldsaid.com/node/1378

Wulff and Roberge (2020): https://pub.epsilon.slu.se/21827/1/wulff_s_et_al_210201.pdf

Yu, G. R., J. Zhuang, K. Nakayama, and Y. Jin (2007), Root water uptake and profile soil water as affected by vertical root distribution, Plant Ecol, 189(1), 15-30.

Yu, Z., J. X. Wang, S. R. Liu, J. S. Rentch, P. S. Sun, and C. Q. Lu (2017), Global gross primary productivity and water use efficiency changes under drought stress, Environ Res Lett, 12(1).

Xoplaki, E., Ellsäßer, F., Grieger, J., Nissen, K. M., Pinto, J., Augenstein, M., Chen, T.-C., Feldmann, H., Friederichs, P., Gliksman, D., Goulier, L., Haustein, K., Heinke, J., Jach, L., Knutzen, F., Kollet, S., Luterbacher, J., Luther, N., Mohr, S., Mudersbach, C., Müller, C., Rousi, E., Simon, F., Suarez-Gutierrez, L., Szemkus, S., Vallejo-Bernal, S. M., Vlachopoulos, O., and Wolf, F.: Compound events in Germany in 2018: drivers and case studies, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1460, 2023.

Zas, Rafael, Roberto Touza, Luis Sampedro, Francisco José Lario, Gloria Bustingorri, Margarita Lema, Variation in resin flow among Maritime pine populations: Relationship with growth potential and climatic responses, Forest Ecology and Management, Volume 474, 2020, 118351, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2020.118351.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., ... & Vignotto, E. (2020). A typology of compound weather and climate events. Nature reviews earth & environment, 1(7), 333-347.