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Global warming and drought impacts in the EU

JRC PESETA IV project – Task 7

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Executive summary

Droughts induce a complex web of impacts that span many sectors of the economy, as exemplified by extensive crop failure, reduced power supply, and shipping interruptions in the EU during 2018 and 2019. With global warming droughts will happen more frequent, last longer and become more intense in southern and western parts of Europe, while drought conditions will become less extreme in northern and north-eastern Europe. With 3°C global warming in 2100 drought losses could be 5 times higher compared to today, with the strongest increase in drought losses projected in the Mediterranean and Atlantic regions of Europe. When expressed with respect to the total size of the economy the effects are dampened relatively, because drought-sensitive sectors like agriculture are projected to become relatively less economically prevalent in future EU economies than they are nowadays. The consequences on ecosystems are typically not monetized and hence are not reflected in the loss estimates.

Current economic losses from drought

PESETA IV estimates current annual losses from drought to be around 9 €billion for the EU and UK, with the highest losses in Spain (1.5 €billion/year), Italy (1.4 €billion/year) and France (1.2 €billion/year). Depending on the region, between 39-60% of the losses relate to agriculture and 22-48% to the energy sector. Public water supply accounts for between 9-20% of the total damage. Losses in the transport sector relate only to inland water transportation and on average represent 1.5% of total losses, while subsidence damage to infrastructures accounts for around 8% of total losses. Drought also affects the environment in many different ways, yet these impacts are difficult to valuate.

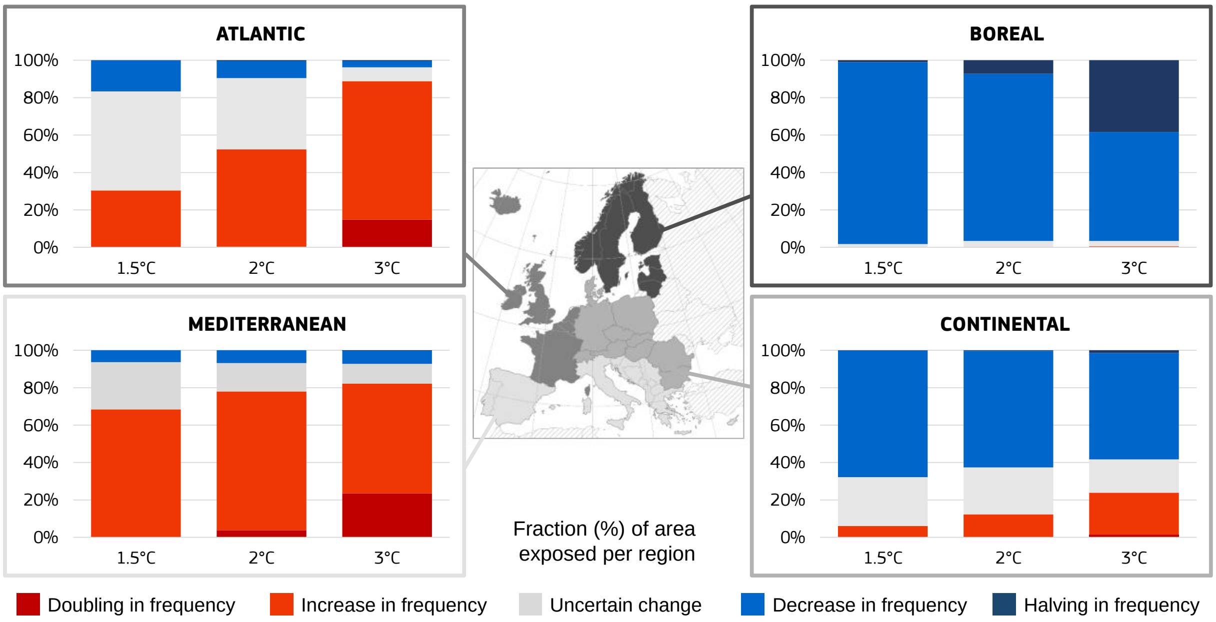


Figure 1. Fraction of area exposed to changes in drought occurrence for European sub-regions.

Drought hazard across Europe in a warmer climate

Hydrological droughts will progressively happen more frequently and intensify in Mediterranean and Atlantic European regions with global warming. Drought conditions will also worsen in southern parts of the Continental region. With 3°C warming drought frequency is projected to double over nearly 25% of the Mediterranean and 15% Atlantic region. Limiting global warming to 1.5°C would still result in an increase in drought frequency over two-thirds of the Mediterranean and one-third of the Atlantic region, but would avoid a doubling of drought frequency everywhere in Europe (Figure 1). In contrast, in Boreal Europe and the north-eastern parts of Continental Europe drought hazard will decline due to increasing precipitation with climate change. In central and eastern Europe the projected trends show more climate variability and are more uncertain.

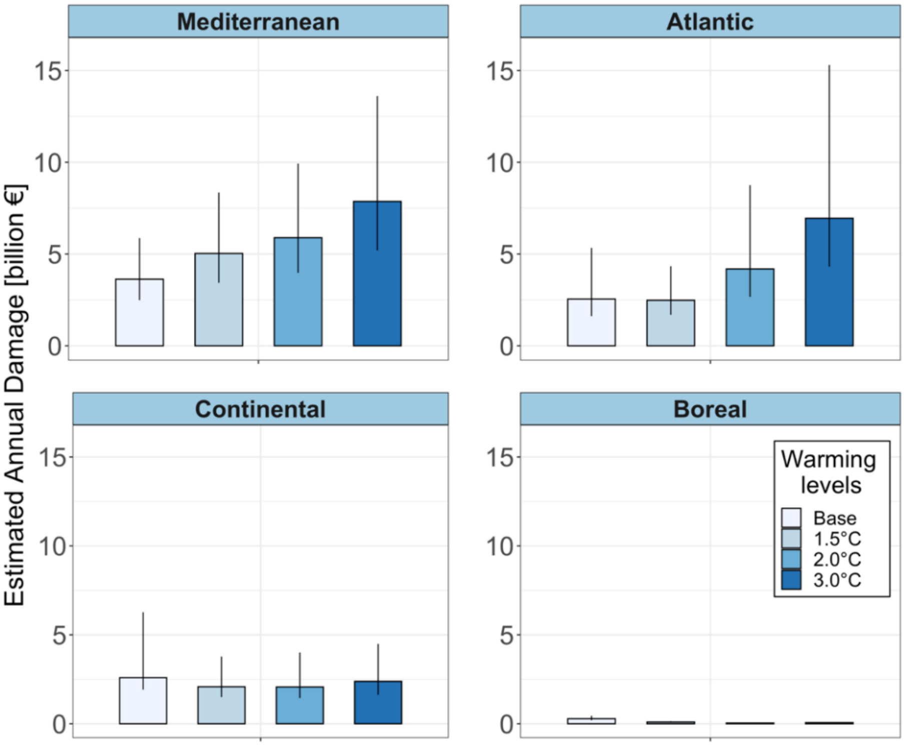
Economic losses from droughts assuming no socioeconomic change

If future climate would act on today's society, total EU and UK drought damage slightly increases with global warming of 1.5°C (9.7 €billion/year) but then increases stronger with further warming to reach 17.3 €billion/year at 3°C (Figure 2). The Mediterranean and Atlantic regions see the largest losses from global warming (Figure 3), with Belgium, Greece, Ireland, Portugal and the UK showing the strongest increase in losses relative to now. Countries in Atlantic and especially Mediterranean Europe already suffer the highest drought impacts. These regions contribute to 68% of the total European losses in the recent past and their share progressively increases with warming and could grow to 85% at 3°C warming. Drought losses will also increase in the most southern countries of Continental Europe (Bulgaria and Romania).

base	1.5˚C	2.0˚C	3.0˚C
Drought losses (€ billion)			
9.0	9.7	12.2	17.3
Drought losses (% of GDP)			
0.07	0.08	0.10	0.14

Figure 2. Average annual losses from drought for the EU and UK assuming that current socioeconomic conditions continue into the future.

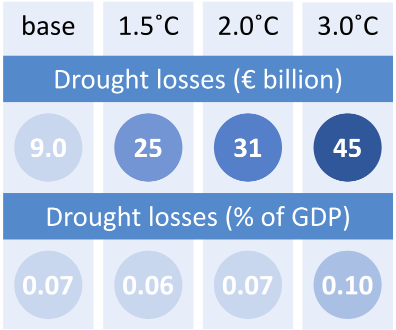
Figure 3. Annual losses (EAD, €billion, 2015 values) nowadays and with global warming for EU+UK countries by region, assuming that current socio-economic conditions continue into the future. The top of each bar shows the average estimate and the vertical lines indicate climate uncertainty.



Economic losses from droughts with socioeconomic change

The projected losses in absolute terms are larger when future socioeconomic change is accounted for compared to when it is assumed that current socioeconomic conditions continue into the future, because of the growth of the size of the economy. By the end of this century, 3°C global warming would result in drought losses of 45 €billion/year in the EU and UK, compared to 25 and 31 €billion/year for 1.5 and 2°C, respectively (Figure 4).

When drought losses are expressed relative to the size of the economy (share of GDP) the effects of climate change are dampened compared to the absolute estimates because drought-sensitive sectors, and especially agriculture, are projected to become less economically prevalent in future EU economies. Losses from drought account for 0.06% and 0.07% of the EU+UK GDP in 2050 and 2100 under both the 1.5 and 2°C warming scenarios respectively, and 0.1% in 2100 for 3°C warming, compared to 0.07% nowadays. Regional and national-level relative impacts can be greater than the EU average, with losses of 0.19% of GDP in the Mediterranean for 3°C warming with 2100 socioeconomics, and in some countries even above 0.3% (e.g., Greece Bulgaria and Romania). Sector-level impacts can also be much greater, with losses to agriculture amounting to 4.6% of sector economic output at 3°C of warming.



base	1.5˚C	2.0˚C	3.0˚C
Drought losses (€ billion)			
9.0	25	31	45
Drought losses (% of GDP)			
0.07	0.06	0.07	0.10

Figure 4. Average annual losses from drought for the EU and UK assuming socioeconomic conditions in 2100 according to the 2015 Ageing Report.

Adaptation and resilience to drought

The PESETA IV drought impact projections are based on present vulnerability estimates of sectors to drought and hence assume no adaptation. There exists a wide variety of drought risk mitigation measures. Rather than supply-side measures, which can lead to higher dependence on water resources and increase drought vulnerability, adaptation should be targeted at strengthening drought resilience of society and sectors. This includes specific measures in drought-sensitive sectors, such as improved cooling techniques, drought-resistant crops, or lighter river navigation vessels, but also institutional transformations, livelihood and economic diversification, insurance and other market tools, social safety nets, monitoring and data collection, and early warning and alert systems. Evaluating the costs and benefits of investments made and policy actions taken to mitigate drought impacts remains a huge challenge. Yet, it is generally accepted that the costs of action are usually lower than the costs of inaction, and the returns from investing in ex ante risk management actions are higher than those of investing in ex post crisis management. The actual costs and benefits of adaptation measures will vary substantially depending on the local geographical, climate, and socioeconomic conditions.

Approach

The LISFLOOD hydrological and water use model was forced by climate projections for a high emissions (RCP8.5) and moderate-mitigation (RCP4.5) scenario to simulate minimum river flow (an indicator of drought hazard) for present climate and climate at 1.5, 2 and 3°C global warming above preindustrial levels. Drought hazard was estimated at high spatial resolution. Economic losses were estimated at country scale for EU+UK countries, based on a statistical relationship between drought intensity and drought impact derived from reported losses of past drought events. Drought damages were disaggregated over economic sectors based on expert-derived sector sensitivity to drought and their economic output. Losses are reported in € 2015 values and are inherently uncertain due to limited availability of data on past droughts and damages upon which the statistical relationship was derived. Losses were estimated under two main assumptions of socioeconomic change: 1) a continuation of 2015 conditions into the future; and 2) socioeconomic development according to the 2015 Ageing Report. As it is very unlikely that 3°C warming will happen by mid-century, this warming level was only combined with 2100 socioeconomic conditions in the dynamic economic scenario. We present average estimates of drought losses over the ensemble of climate models and the spread due to climate uncertainty. Other sources of uncertainty due to model conceptualisation and parameterisation, and limited empirical drought loss data are not accounted for.

1 Introduction

Prolonged heat and dryness have made farmers, private households and wildlife around Europe facing unprecedented droughts in the summers of 2018 and to a lesser extent 2019. Raging wildfires in the south as well as the north, severe shipping interruptions in major rivers, irrigation restrictions and reduced power supply has heightened the concern in Europe about the possible rise in the severity and frequency of drought events as a manifestation of climate change. In order to plan suitable adaptation strategies it is important for decision makers to know how drought conditions will develop at regional scales, and what could be the impacts on societies in Europe.

Drought is a natural feature of climate variability and the water cycle and it can occur in all climatic zones. It originates from a temporary reduction in the normal precipitation regime over a large area, but other climatic factors, such as high temperatures and winds or low relative humidity, can significantly aggravate the severity of the event. Anthropogenic drivers, such as intensive water use and poor water management, can further exacerbate drought conditions in watersheds, with a subsequent increase in social vulnerability (e.g., Vörösmarty et al., 2000; Tallaksen and van Lanen 2004; Döll et al., 2009; Wada et al., 2013).

Since 1950s, Northern Europe shows wetting patterns (increasing precipitation, especially in winter and spring), while Southern and Eastern Europe show a drying tendency (Spinoni et al., 2017). Climate change is expected to further alter the water balance throughout Europe through changes in the spatial and temporal distribution of precipitation, including more frequent and persistent dry spells, and increased potential evapotranspiration with higher temperatures (e.g., Beniston et al., 2007, Christensen and Christensen, 2007; Nikulin et al., 2011). Hence, with global warming droughts could become more frequent, severe, and longer-lasting in parts of Europe.

Droughts can have wide-reaching economic, social and environmental impacts. Yet, the diffuse and often intangible nature of their impacts combined with a prolonged duration and delayed effects make it extremely difficult to retrieve correct or attributable loss estimates. As a result, little information is available on the economic cost of drought impacts (Stahl et al., 2016) and droughts are estimated unrealistically at less than 7% of total losses from natural hazards (Gall et al., 2009). Estimates of present annual drought losses in Europe vary substantially. Reported losses in MunichRe's NatCatSERVICE[1] database indicate annual losses of around 1.3 €billion over the last 35 years. According to the EEA, over the period 1991-2010, the average annual economic consequences of droughts in Europe have drastically increased, rising to 6.2 €billion per year (EEA, 2010). The severe drought that hit southern and central Europe in the summer of 2003 – with an estimated economic damage of more than 8.7 €billion (EEA, 2010) – exemplified what the potential impacts could be if climate change leads to an increase in the frequency and intensity of droughts across Europe (Schär et al., 2004). Many sectors suffered from the 2018 drought in Europe, especially in northern and central parts of the continent (EDO, 2018). Parts of the Rhine in Germany were at record-low levels for months in 2018, forcing ships to reduce their cargo or stop navigating altogether. France, Germany, Sweden and Finland had to cut back on the amount of power they produce because of the lack of water and raised water temperatures, and overheated water from cooling resulted in mass fish die-offs in Germany. The 2018 event has had a devastating impact on crops in many EU countries. Also in the summer of 2019 water levels were far below normal conditions in many regions of Europe. Apart from the understanding that a range of sectors were distressed, detailed and harmonised estimates of the economic losses for different sectors from such events are generally lacking.

Assessments of future drought losses in view of climate change are rare in literature, and to date no pan-European estimates are available. In this report, we present results of the PESETA IV task on drought, which provides the first quantitative assessment of how drought impacts across Europe are expected to evolve with global warming.

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[1] https://natcatservice.munichre.com/

2 Methodology

The PESETA IV task on drought provides a first-ever pan-European quantitative assessment of drought risk and economic impacts in Europe. As an indicator of drought hazard we used minimum river streamflow. The advantage of using streamflow drought (rather than simpler meteorological indicators, such as standardised precipitation indexes) is that it reflects the spatially integrated shortage in water resources over river basins, and as such forms a major concern to water managers. It further allows accounting for water use from ground and surface water by different sectors, so also represents socioeconomic drivers of drought. Streamflow simulations were obtained through offline coupling of the hydrological and water use model LISFLOOD with an ensemble of high-resolution regional climate projections for RCP4.5 and RCP8.5. The LISFLOOD hydrological simulations used for the drought assessment are identical to those used in the water resources, energy and river flood tasks of PESETA IV, but here they were analysed in terms of minimum flow.

We appraised vulnerability to droughts on the basis of damage records collected from disaster databases during the period 1990-2016 and correlating these with the intensity of drought events derived from weather reanalysis by means of a power-law damage function (see Annex 1, Figure A1). The reported damages correspond to the overall economic losses recorded in a country for each drought event. Loss estimates are accompanied by a very brief description of the event in textual form, specifying the type of damages produced and the affected sectors, but no sectoral disaggregation of the economic losses is provided. Due to the lack of a sectoral breakdown of reported losses, we applied a top-down sectoral partitioning of the damages as in Forzieri et al. (2018). This was done by combining a qualitative appraisal of the vulnerability of sectors to drought based on the combination of an extensive literature review and a survey run amongst ~2000 experts (Forzieri et al., 2018), with the economic value (in terms of their Gross Value Added) of drought-sensitive sectors obtained from Eurostat. Because the reported damages are at country scale and droughts typically spread over large spatial extents, we aggregated the drought hazard indicator to this scale and the damage modelling was performed at country level.

We evaluated drought hazard and risk in Europe throughout the 21st century by comparing impacts under baseline (1981-2010) climate with those in climate corresponding to global warming levels (GWLs) of 1.5, 2 and 3°C above preindustrial levels. As is common to all PESETA IV impact categories, we evaluated drought impacts if GWLs would act on today's society (static economic analysis), therefore only considered the influence of the climate change signal. This allows understanding drought risk if climate conditions under different levels of warming would be imposed on today's society, without any assumptions on socioeconomic developments over long time spans. In addition, we also provide a dynamic socioeconomic assessment considering the 2015 Ageing Report projections[2] of population and economy, and look at how droughts at the different warming levels would impact EU society projected for 2050 and 2100. As a 3°C warming scenario is unlikely to occur by mid-century, only the Paris targets are considered in 2050. Comparison of the static and dynamic economic analyses allows disentangling the effects of climate and socioeconomic changes. The vulnerability derived from recent drought events is assumed constant in the projections, hence the results presented do not include any additional adaptation of sectors to changing drought conditions. Our hazard analysis includes all EU member states plus a number of neighbouring countries (Iceland, Norway, and Switzerland and Balkan countries). Economic impacts are presented for EU countries and UK only. More details on the methodology can be found in Annex 1. We report average drought losses over the ensemble of climate projections, as well as the 95% uncertainty bounds that represent uncertainty in the climate projections.

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[2] During the PESETA IV project, the 2018 Ageing projections became available but they could not be incorporated. Compared to the 2015 Ageing Report, GDP growth projections are slightly lower over the period 2025-2050 and marginally higher during 2055-2070. These updated projections do not affect the main conclusions of this report.

3 Results

In the first part of the results section we present projected changes in extreme low river streamflow to portray expected changes in drought hazard at high resolution. In the second part, we present results of the impact analysis, which was performed at national scale, including the partitioning of the impacts among drought-sensitive socioeconomic sectors.

3.1 Projections of drought hazard

The spatial distribution of the projected changes in drought frequency between the warming levels and climate in the baseline (1981-2010) are presented in Figure 5. The corresponding fractions of area exposed to changes in drought occurrence for the European sub-regions are summarised in Figure 1. Results of the hazard analysis show that with global warming extreme low river flows will become more severe and persistent in southern Europe. Also, most of western Europe will face increasingly frequent and intense drought conditions. An opposite trend can be observed in northern and north-eastern parts of Europe, where droughts hazard generally decreases with global warming.

The Mediterranean sub-region shows the highest fraction of area where drought hazard will increase. At 1.5°C drought frequency will increase in two-thirds of its territory (+68%), which further grows to 82% at 3°C warming. With high warming, drought frequency will double over 23% of the Mediterranean sub-region, while stringent mitigation would avoid this. Only in very few locations in the Mediterranean sub-region, such as some Alpine mountain drainage basins in northern Italy, drought conditions could become less severe and frequent with global warming.

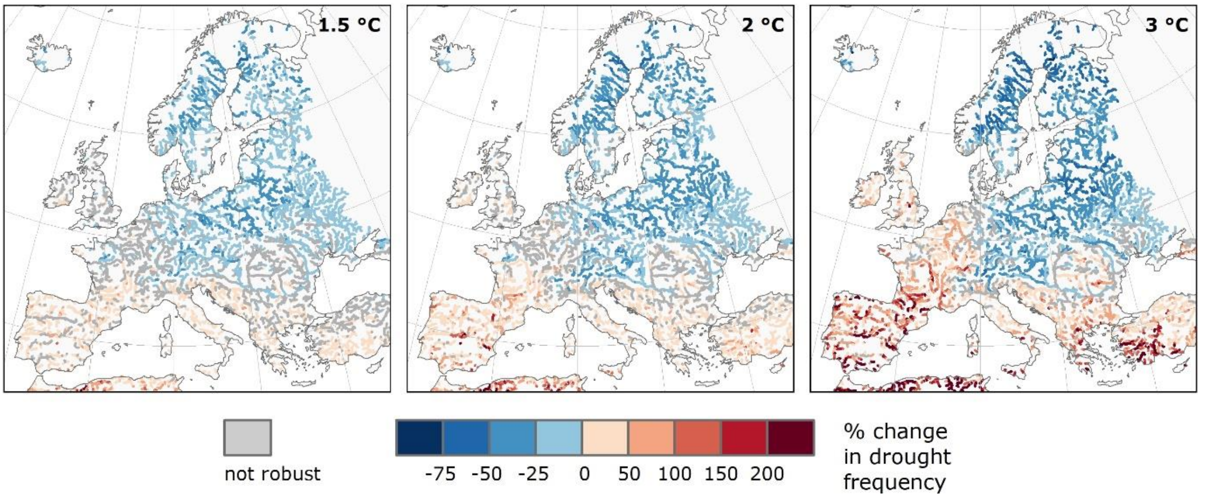

Figure 5. Projected change in drought frequency between warming levels and baseline (1981-2010) climate. Red represents an increase in frequency, whereas blue represents a reduction in frequency. Grey means that the projected changes are not robust (less than 2/3 of the climate projections agree on the sign of change in drought frequency).

In the Atlantic sub-region the increase is less marked at lower warming levels, with an increase in drought hazard over 30% of the area at 1.5°C warming and an unclear signal over 50% of the river basins. Yet, with higher warming drought frequency increases gradually over more of the Atlantic domain and at 3°C warming drought occurrence will increase over nearly 90% of the territory, with a doubling in frequency over 15% of the Atlantic sub-region. Only in Iceland droughts are consistently projected to occur less frequent in a warmer world.

For Continental Europe the projected changes in drought conditions vary across the region. In general drought conditions become less severe with warming in north-eastern parts (Poland), while an opposite trend is projected for the southern parts of the region (Romania and Bulgaria). In central parts of the region (Czechia, Austria, Slovakia, Hungary, eastern part of Germany) drought hazard conditions are projected to reduce slightly, yet uncertainty in the projections is highest here, while in the most western parts (western Germany and Denmark) the trend is uncertain at lower levels but then reverses to increasing drought conditions with higher levels of warming. At 3°C warming drought conditions will worsen in 24% and become less severe in 58% of the region.

Finally, the projections show that drought hazard will strongly reduce in the Boreal sub-region, with a halving of drought frequency in 38% of the territory at 3°C warming.

3.2 Projections of drought-related losses

3.2.1 Baseline drought losses

Estimated annual economic losses for the baseline (1981-2010) are 9.0 €billion/year for EU+UK (Figure 6 and Table A2). The 95% confidence interval on this estimate ranges between 7.4 and 14.2 €billion/year, which relates to uncertainty in the fitted damage function and variability in the climate simulations for the baseline. This exemplifies the large uncertainty in the estimation of drought losses. In the text below we report the ensemble average estimate followed by the 95% confidence interval in square brackets. The highest absolute expected losses occur in Spain (1.5 [0.7-3.0] €billion/year), Italy (1.4 [0.6-2.9] €billion/year) and France (1.2 [0.4-3.8] €billion/year). Aggregated losses for EU and UK represent approximately 0.07% [0.03-0.19%] of GDP (of the year 2015), compared to nearly 0.06% for river flooding and 0.01% for coastal flooding. Relative to the size of the economy, present drought losses are highest in the Mediterranean (0.12% [0.08-0.19%] of GDP), followed by the Continental (0.06% [0.05-0.16%]) region, while they are lowest in the Atlantic (0.05% [0.03-0.11%]) the Boreal (0.05% [0.03-0.07%]) regions. Countries with the highest relative impact today are Romania and Bulgaria, while in the UK, Germany, Finland and Sweden they are lowest.

3.2.2 Impacts at warming levels with static economy

When accounting only for the effects of climate change (i.e., combining static 2015 economy with drought conditions at global warming levels) aggregated European drought damage slightly increases to 9.7 [7.4-13.8] €billion/year at 1.5°C warming. With higher levels of warming damage further increases to 12.2 [9.7-18.6] €billion/year at 2°C warming and 17.2 [13.4-27.6] €billion/year at 3°C warming (Figure 6). This corresponds to 0.07% [0.06-0.10%], 0.08% [0.08-0.12%] and 0.14% [0.11-0.16] of EU+UK GDP of the year 2015 (Table A5), respectively. Hence, a 3°C warmer climate applied on today's (2015) economy would result in a 90% increase of absolute drought losses in Europe compared to present climate.

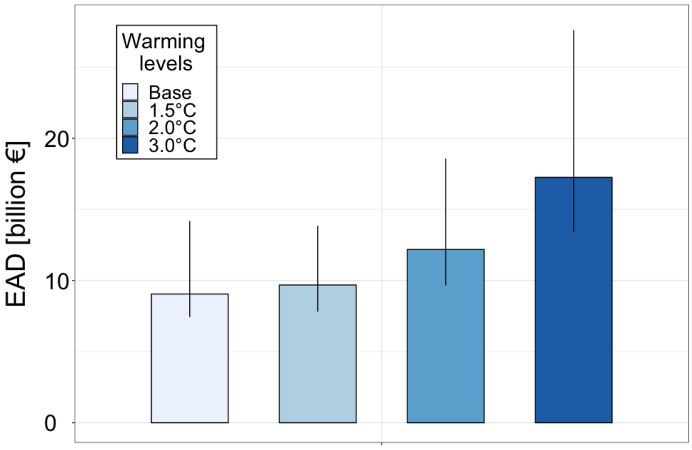

Figure 6. Expected annual drought damage (EAD, €billion) for the EU and UK in the baseline and at global warming levels of 1.5, 2 and 3°C when assuming static economic conditions. The bars represent the ensemble average estimate while the thin lines show the ensemble spread reflecting climate uncertainty.

There are, however, strong regional differences in Europe in the evolution of drought losses with warming. Our projections show that the Mediterranean and Atlantic sub-regions of Europe could see a more than two-fold rise in drought impacts without mitigation and if no additional adaptation measures are implemented (Figure 7). The strongest rise in drought losses at 3°C warming is projected for Ireland, Cyprus, Belgium, Greece, France, Greece, the Netherlands and Spain. Relative to the size of the economy, impacts under this scenario are highest (close to 0.5% of GDP) in Romania, Bulgaria and Greece. Higher shares of GDP at risk indicate larger impacts on the country overall economy and a higher potential of cross-sectorial shocks.

The Continental sub-region will see a reduction in drought losses of approximately 20% at 1.5 and 2°C warming, but with higher warming this trend is reversed and losses rise again to amount to 92% of baseline damages at 3°C warming (or a reduction of 8% compared to baseline damages). This hides a strong regional variability within the Continental region, with drought losses that will decrease in north-eastern parts (Poland), increase in southern parts (Romania and Bulgaria) and more uncertain changes in between. The Boreal sub-region will experience a very strong decrease in drought losses due to a general increase in precipitation and water availability with warming. As a consequence of the regional tendencies, the share of the total losses attributed to the Mediterranean and Atlantic sub-regions will increase from about 68% under baseline climate to about 85% at 3°C warming.

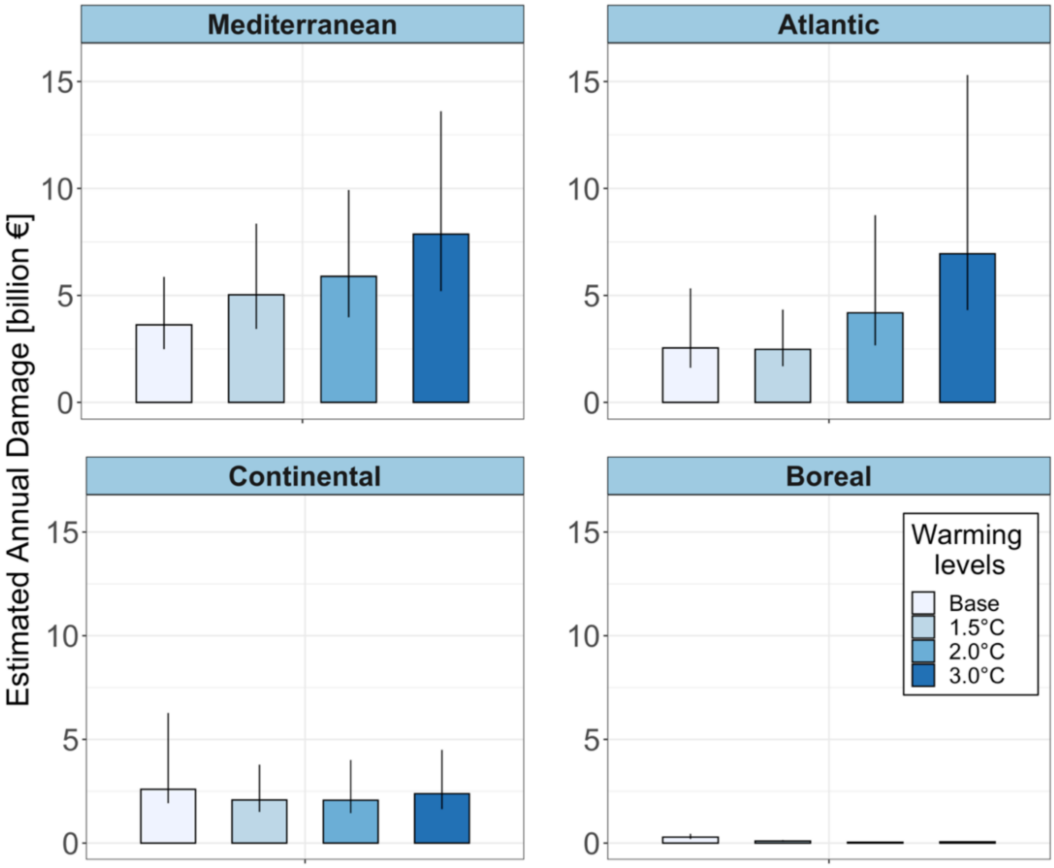

Figure 7. Expected annual damage (EAD, €billion) for the four IPCC AR5 European sub-regions in the baseline and at global warming levels of 1.5, 2 and 3°C when assuming static economic conditions of 2015. Total damage presented here for a sub-region includes damages for EU countries only (and UK for Atlantic region), and not the damages for non-EU countries in that region (e.g. Albania or Norway).

3.2.3 Impacts at warming levels under future economic conditions

By mid-century, it is likely that global warming has reached 1.5 or 2°C warming, yet unlikely to have reached 3°C warming. Hence, this warming level is not considered when evaluating drought damages if different warming levels would happen in 2050. EU+UK aggregated absolute damage for 1.5 and 2°C warming combined with the economy in 2050 (under the EU Reference Scenario) totals 12.4 [10-19] and 15.5 [12.4-19.8] €billion/year, respectively, or an increase of nearly +37 and +70% compared to baseline damages (see Tables A2-A4). If climate stabilises at these warming levels, the absolute losses of drought to the economy in 2100 grow to 24.7 [20-35] €billion/year for 1.5°C warming and 31.5 [25-48] €billion/year for 2°C warming, or an increase of respectively 170 and 248%. With global warming of 3°C by the end of this century, absolute losses to the economy of 2100 would grow by 400% to 45.4 [35-74] €billion/year.

Similar as for impacts with a static (2015) economy, the strongest increase in absolute drought losses to economies in 2050 and 2100 are projected for southern and western parts of Europe. With 3°C global warming by the end of this century, the Atlantic and Mediterranean sub-regions will see an 8- and 5-fold increase in absolute drought losses, while for the Boreal sub-region absolute losses would be just a fraction of baseline losses. In the Continental sub-region as a whole drought damages would approximately double, with a halving of drought damages in north-eastern parts while in southern parts drought damages would be 4 times larger compared to today.

Table 1. Main sectors affected by droughts in Europe and covered in this assessment.

Sector	Description
Agriculture	Farmers might be adversely affected if a drought damages their crops. They may spend more money due to increasing irrigation costs, drilling new wells, or feeding and providing water to their animals. Industries linked with farming activities, such as companies that make tractors and food, may lose business when drought damages crops or livestock.
Public water supply	Drought conditions impact water supplies by decreasing supply and increasing demand for various usages (industrial, tourism or municipal use).
Power generation: hydropower, thermal, and nuclear	Hydroelectricity production is related to the amount of water stored in the upper reservoirs, the production level can be lower during a drought. Peak demands for electricity then need to be satisfied by other means available in the short term (e.g. gas turbines). The amount of losses depends on hydroelectricity infrastructures and drought severity. Reduced availability of cooling water can force the reduction of power generation and even shutdown of thermal or nuclear power plants during droughts.
Commercial shipping	During low-flow conditions, barges and ships may have difficulty in navigating streams, rivers, and canals because of low water levels, affecting businesses that depend on water transportation for receiving or delivering goods and materials. People might have to pay more for food or fuel as a result.
Buildings and infrastructure	Depending on their composition soils swell and shrink with moisture changes. If the soil shrinkage is very pronounced under drought conditions, this can cause serious damage to buildings and infrastructure. For instance, in France soil subsidence has caused as much damage as floods in recent years. The effects of drought could be aggravated due to aquifer over-exploitation.

3.3 Sectorial impacts

Drought conditions often remain unnoticed until water shortages become severe and adverse impacts on environment and society become evident. The consequences on ecosystems are typically not monetized and included in damage reports, hence they are also not reflected in our estimates. Table 1 presents the main sectors that are adversely affected by droughts and that have been considered in our sectorial breakdown of the estimated losses. They include limited public water supplies, agriculture losses, damage to buildings and infrastructure due to soil subsidence, reduction of inland water transportation and reduced energy production.

With some regional variation, economic losses are highest for the agriculture, public water supply and energy sectors. Between 39 and 60% of baseline drought impacts relate to agriculture, and 22 to 48% to the energy sector (Figure 8). The share of damages of public water supply ranges between 8 and 20%, while infrastructure subsidence damages account for around 8% of total losses. Losses in the transport sector relate only to inland water transportation and on average represent only 1.5% of the total losses.

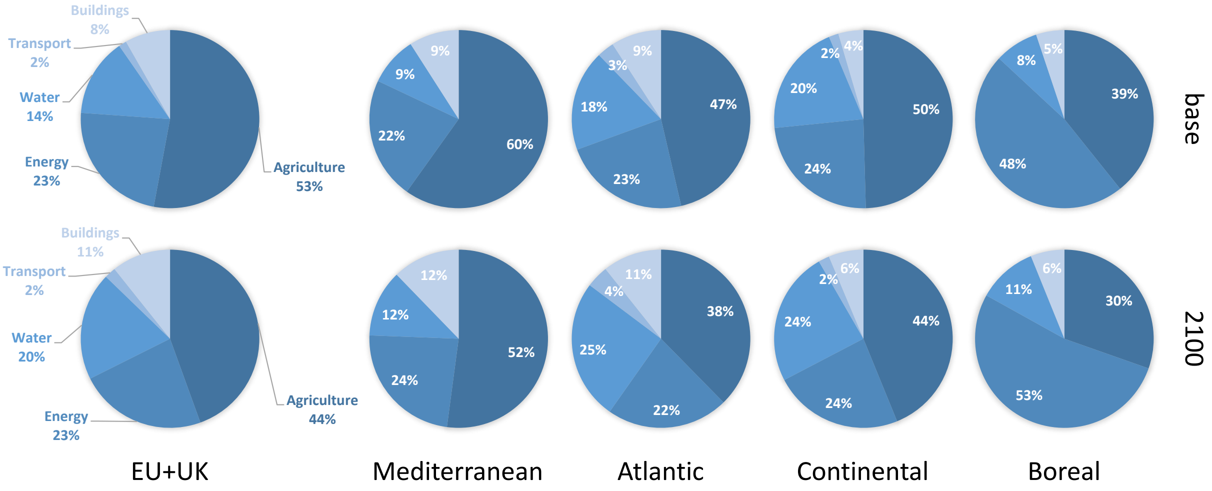

Figure 8. Share of drought losses by economic sector (agriculture, energy, water supply, subsidence and transport) for EU+UK and the four IPCC AR5 European sub-regions in the baseline (1981-2010) and in 2100.

Due to the effects of climate change only, in the Mediterranean and Atlantic sub-regions, annual drought-related damages in the agriculture sector will double from 3.3 €billion/year in the baseline (2.5% of the regional baseline agriculture GVA) to 8 €billion/year at 3°C of warming (6% of the baseline agriculture GVA). Energy sector drought damages in these regions will increase from 1.4 to 3.3 €billion/year (0.2% and 0.5% of baseline energy GVA, respectively). The Boreal region and northern parts of the Continental Europe will benefit from the increased water availability (due to increasing precipitation), which translates in a reduction of drought losses for all sectors analysed. Aggregated over the two sub-regions, annual damages in the agriculture sector are projected to reduce from 1.34 €billion/year in the baseline to 1.2 €billion/year at 3°C of warming (or 1.5% and 1.1% of regional baseline agriculture GVA, respectively) (Figure 9). Nevertheless, in the most southern countries of the Continental region, namely Romania and especially in Bulgaria, drought losses are projected to increase in all sectors.

In a dynamic economic setting according to the EU Reference Scenario the share in the total damages of the agriculture sector will gradually reduce because the economic importance (expressed by Gross Value Added) of the agriculture sector is projected to decline everywhere in Europe. The share of drought-induced agricultural losses to the overall drought losses reduces on average by 8%. On the other hand, losses in the water supply sector (+5%) and infrastructure losses due to swelling and shrinking of soils (+2%) will increase in all sub-regions (Figure 8).

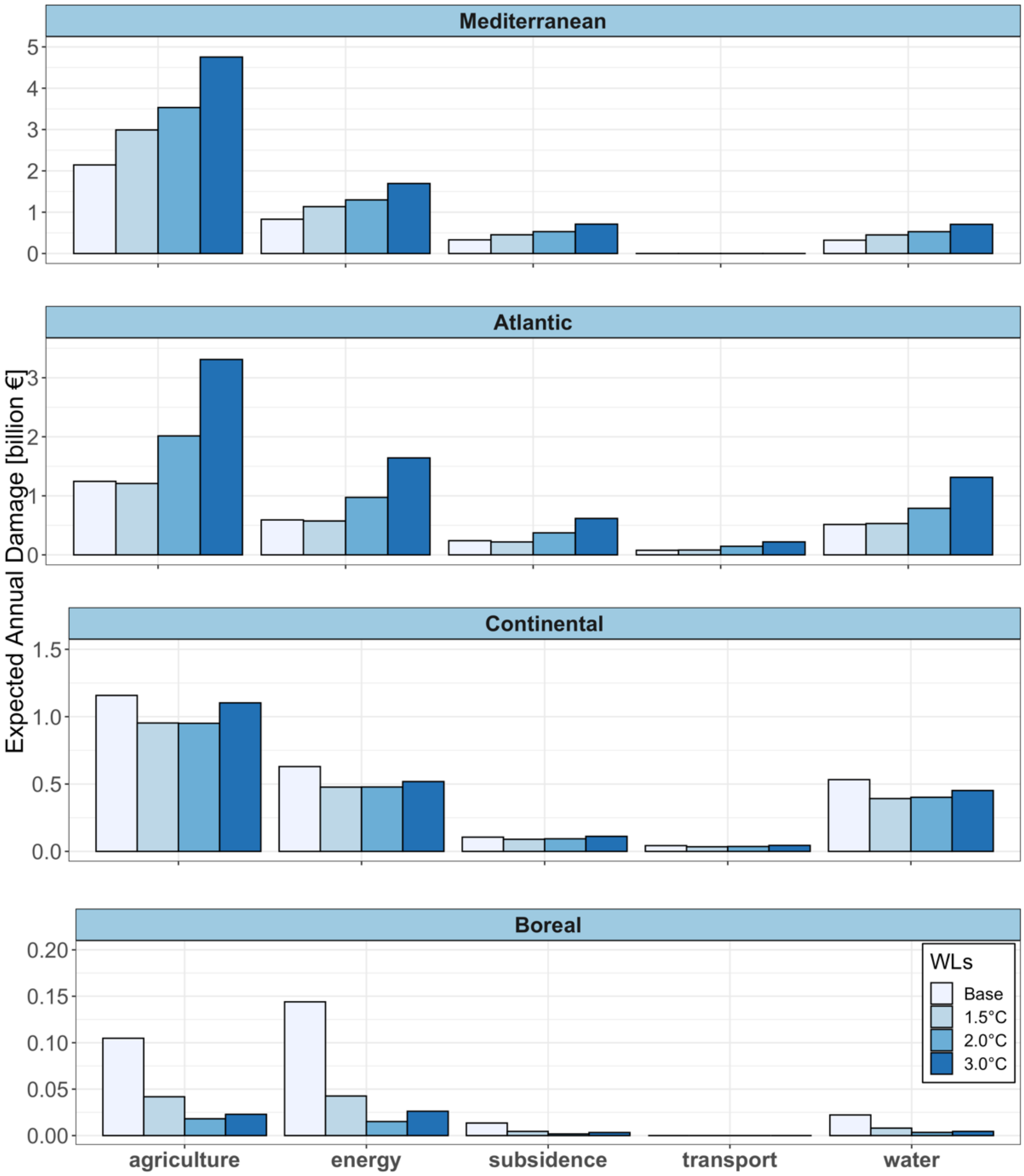

Figure 9. Projected expected annual damage (EAD, €million) by sector under baseline climate and at global warming levels for the four IPCC AR5 European sub-regions, assuming static economic conditions.

4 Conclusions

This study shows that hydrological drought intensity and frequency is expected to increase with global warming in south-western parts of Europe, whereas an opposite signal is projected for north-eastern Europe. Hence, climate change could further polarize current water availability and drought conditions in Europe.

An analysis of drought records of Munich Re's NatCatSERVICE disaster database over the period 1990-2016, together with reports of the European Drought Impact report Inventory and grey literature estimates, suggest a likely strong underestimation of impacts in drought loss records. We estimated annual economic losses for the recent past (1981-2010) of 9.0 €billion/year for EU and UK (confidence range 7.4-14.2 €billon/year), compared to 1.3 €billion/year of reported losses in NatCatSERVICE. Our estimate also does not include damages to ecosystems and their services, which are even more difficult to quantify in economic terms. This exemplifies the difficulties in the accurate estimation of drought damages.

With climate at 3°C global warming applied to Europe's economy in 2015, aggregated annual drought losses in Europe would increase with 90% compared to losses in present climate. Yet, this masks the strong regional contrast in climate-change induced changes in drought impacts, with a strong increase in southern and western parts of Europe, whereas drought losses will strongly decline in northern and north-eastern regions. Events like the 2018 drought in central and northern Europe, which caused yield reductions up to 50% for the main crops will become less likely but are still plausible. Wet conditions in southern Europe at the same time saw yield gains up to 34% (Toreti et al., 2019) and the overall losses were somehow balanced at continental level. In that sense, market cooperation across the EU could act as a form of adaptation to climatic extremes, preventing higher price volatility, yet it can never fully compensate for the damages that occur locally. With increasing levels of warming, however, it will become less likely that a drought such as the 2018 one will be balanced with favourable water availability conditions in southern Europe.

Drought losses are highest for the agriculture, public water supply and energy sector. These sectors will remain to be the most affected, notwithstanding that the share of agricultural losses in the total drought damages will reduce. The impacts in the transport sector, which include only the disruption of river navigation and reduced cargo carrying capacity of vessels, are limited compared to the other sectors but could be still relevant at regional scale, as exemplified by navigation restrictions in the river Rhine in 2018 and 2019. Finally, infrastructures could increasingly suffer damages from drought-induced soil subsidence, and become one of the costliest but least known risks for property owners and insurers.

The drought estimates presented herein account for uncertainty in climate. The problem of drought impact assessment is further compounded by the lack of data on drought vulnerability and impacts in different sectors, including the costs of indirect and longer-term drought impacts. Other sources of uncertainty include the disaggregation of reported losses over sensitive drought sectors. Furthermore, investments and actions for drought impact mitigation and the management of natural resources (notably water and land) can have a significant effect on the magnitude of the impacts of droughts, while this study assumed that drought vulnerability of sectors remains unchanged in the projections (hence assuming no further adaptation). These additional sources of uncertainty are not accounted for and the estimated impacts presented herein should be interpreted in view of this.

There is a wide range of measures to increase resilience to droughts, which differ among the sectors potentially affected. These include insurance and other market tools, improved water use efficiency in various sectors, reduction of water leakages from the distribution networks, use of regenerated water, sea water desalinized with renewable energies, improved water harvesting techniques, conjunctive use of surface and groundwater, replacement of cooling system types and fuel switches, design of lighter river navigation vessels, drought-resistant crops, changed cropping patterns and timing, capacity building of relevant stakeholders, early warning and alert systems, among others (Vogt et al., 2018). However, some measures could have potentially deleterious environmental impacts, such as brine waste from desalination plants. Recent research (Di Baldassarre et al., 2018) also shows that water shortages are often worsened by increasing supply through reservoir storage or desalinated water, as the supply-demand cycle can trigger an accelerating spiral towards unsustainable exploitation of water resources and environmental degradation. This in turn increases social vulnerability to and economic damage from droughts. Hence, adaptation should be targeted to reduce our reliance on large water infrastructures and more on water conservation measures.

Very few studies have assessed the benefits of the implementation of drought impact mitigation measures. However, the costs of proactive drought risk management are usually lower than the costs of inaction, hence it can generate significant economic benefits. For example, in the US it has been estimated that every dollar spent by the Federal Emergency Management Agency (FEMA) on drought risk mitigation, would save the country at least $2 on future drought disaster costs. However, benefit to ratios of adaptation measures can vary substantially depending on the local geographical, climate, and socioeconomic conditions. Identifying not only the costs of inaction, but also the immediate and long-term benefits of being better prepared for drought will be crucial in making a convincing case for mitigating drought risks.

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Annexes

Annex 1. Detailed Methodology

A1.1 Climate projections

Projections of drought hazard with warming are based on two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a high-end emissions scenario. Statistical and quantitative hazard analyses in this report are performed over 30-year time periods. The reference scenario spans the period 1981-2010, hereinafter referred to as “base”. We compare impacts for the baseline with those over 30-year time slices centred on the year that global average temperature is 1.5, 2 and 3°C above preindustrial temperature (Table A1). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

Table A1. Regional climate projections used in the drought hazard and impact analysis and corresponding years of exceeding 1.5, 2 and 3 °C global warming.

RCM (R)	Driving GCM (G)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
		1.5 °C		2 °C		3 °C	
CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043		2065
WRF331F	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042		2065
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
	MOHC-HadGEM2-ES	2021	2018	2037	2030	2069	2051
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067

For each RCP an ensemble of 11 EURO-CORDEX combinations of Global Climate Models (GCM) and Regional Climate Models (RCM) were used (Jacob et al., 2014). Drought hazard conditions at 1.5 and 2°C warming were derived from an ensemble of 22 climate projections (11 RCP4.5 and 11 RCP8.5 members), whereas the ensemble projections for 3°C warming are based on RCP8.5 only, as 10 out of 11 RCP4.5 climate simulations do not reach 3°C warming.

It should be noted that we derived climate at global warming levels from transient climate projections, which may differ from stabilized climate at those warming levels. Studies (e.g., Maule et al., 2017) suggest that the effect of pathway to global warming levels is small compared to the models’ variability, expect for strongly not time-invariant variables such as sea level rise.

A1.2 Socioeconomic projections

We performed the drought risk assessment with static socioeconomic conditions as well as with projections of socioeconomic development in Europe. The static approach provides information on how climate and consequent drought conditions at different global warming levels would affect today's societies in Europe. For the dynamic economic assessment we focus on 2050 and 2100. At mid-century we evaluate losses of 1.5 and 2°C warming on 2050's economy (as 3°C is unrealistic by mid-century) and at the end of the century we consider the effect of the three warming levels on 2100's economy.

The projections of socioeconomic development in Europe are based on the ECFIN 2015 Ageing Report, further also referred to as EU Reference Scenario. This scenario acts as a benchmark of current policy and market trends in the EU. High-resolution land use and population projections based on the EU Reference Scenario were derived with the LUISA modelling platform (Jacobs-Crisioni et al., 2017). The sector composition of the economy and gross value added was modelled by GEM-E3 at country level.

As the Ageing report deals with projections only to the year 2060, the projections have been extended to the year 2100. Regarding the GDP projections, the Ageing Report assumes that two out of the three determinants of economic growth, technical progress and capital accumulation, would reach a steady state (with constant growth rates) by the year 2060. That has been assumed as well for the following decades. The third contributor to growth (the labour input) has been assumed to evolve in a proportional way with respect to population (i.e. same growth rate). That means ignoring possible changes in the labour markets conditions, such as changes in the participation rates or the employment rate. The population projections for 2061-2100 are taken from the latest United Nations demographic report (medium variant), and they are explicitly considered in the computation of the economic growth figures (more details can be found in Ciscar et al., 2017).

A1.3 Hydrological simulations and drought indicator

Simulations of daily river discharge have been produced with the LISFLOOD hydrological model. This is a GIS-based spatially-distributed hydrological rainfall-runoff-routing model (van der Knijff et al., 2010), designed to simulate the water balance at cell scale, as well as the rooting of surface runoff in the river network. For the historical analysis an "observed" simulation was performed for the period 1981-2010 by forcing LISFLOOD with observation-based meteorological data in order to have a series of past discharge data and drought events to be used in the calibration of the damage function. For the analysis of changes in drought conditions in view of warming, LISFLOOD was forced with the ensemble of 22 (11 RCP4.5 + 11 RCP8.5) CORDEX climate simulations from 1981 up to 2100. For the dynamic economic scenario, this also includes water extractions simulated by a water use model. LISFLOOD simulations were performed at 5 × 5 km^2 resolution grid over the extended European domain, which includes all the EU countries, as well as some neighbouring ones such as Albania, Bosnia – Herzegovina, Iceland, Moldova, Montenegro, the Republic of Macedonia (FYROM), Norway, Serbia, and Switzerland. The LISFLOOD simulations used in the drought analysis are identical to those used in the Water Resources and River Floods tasks of PESETA IV. A more detailed description of the hydrological and water use model can be found in the report of the Water Resources task of PESETA IV.

In this study, the annual minimum river flow (q_{min}) was used as drought indicator. We analyzed q_{min} for all river cells with at least 1,000 km^2 of upstream drainage area in order to avoid the inclusion of small rivers with minimum flows near zero that may distort the extreme value analysis. Drought conditions typically extend over larger areas, so it is assumed that drought conditions in the excluded smaller catchments are similar to the larger adjacent ones. We fitted a non-stationary Generalized Extreme Value (GEV) distribution through the annual minimum flows. The fitted distribution provides a link between intensity of the drought event and its expected probability of occurrence (expressed in return period).

A1.4 Vulnerability assessment

Studies on the impact of drought to date have been mostly qualitative, while quantitative assessments are rare and typically focus on a specific sector. The key unknown is vulnerability of socioeconomic and eco-systems to drought. This is mainly due to the lack of drought impact data, in part because drought is a slow onset hazard with diffuse spatial and often delayed environmental, economic and social impacts that are difficult to quantify. Vulnerability defines the propensity to be harmed by a certain intensity of a hazard. In order to build a drought vulnerability model, it is therefore needed to quantify the intensity/frequency of past drought events and what assets were exposed to the hazard. Combining this information with observed drought losses for past event allows to quantify vulnerability.

The intensity and recurrence frequency of drought events in the recent past were estimated based on the statistical analysis of the LISFLOOD run for the historical period 1980-2016. Drought impact data in NatCatSERVICE are only available at national level and therefore a country-scale drought hazard indicator was computed as the median value of the drought frequencies within a country linked to the time of the reported event. Drought losses in NatCatSERVICE further do not provide a sectorial breakdown of the losses. In each country we disaggregated reported losses over different sectors based on expert-derived sensitivity of sectors and subsectors, harmonized intensity values of different sub-sectors, and the share of gross value added of the sensitive sectors to the total sensitive value (Forzieri et al., 2018). Subsidence-induced drought damages to buildings and infrastructure due to shrinking and swelling of soils was estimated based on soil clay content from the European Soil Database (EC, 2004), land use information (urban vs rural), degree of built-up area from the Global Human Settlements Layer (Pesaresi et al., 2013) and Total Construction values from Eurostat.

A power-law function was fitted between the country median inverse of its return period (RP) and the ratio of the damage reported in the NatCatSERVICE and the country total exposed sensitive value (Figure A1). The resulting damage function (depicted in Figure A1) thus relates the frequency of an event with the reported loss expressed as a share of the total estimated value exposed (over all sensitive sectors).

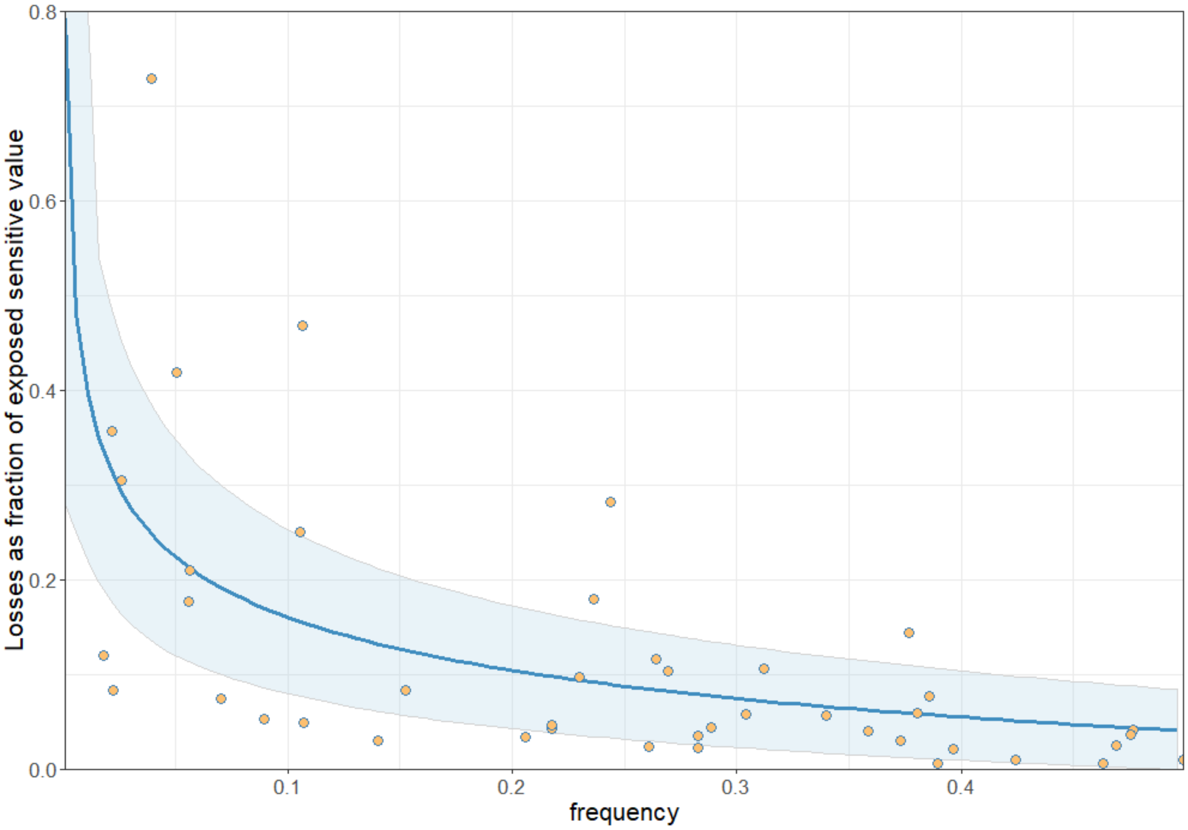

Figure A1. Damage function depicting the relationship between country-derived drought frequency and losses as a fraction of the exposed value of sensitive sectors. Shaded areas represent the uncertainty in the fitted model.

A1.5 Impact modelling

The drought risk assessment is based on the combination of the hazard, exposure and vulnerability (IPCC, 2012). For each year in the baseline (1981-2010) and 30-year time windows around the warming levels, the country-median drought return period was derived. Using the damage function as described in A1.4, the corresponding loss expressed as a fraction of the sensitive value exposed was obtained. For example, a drought with return period of 5 years (or probability of 0.2) in country A in year X would cause 10% of the exposed sensitive value of country A to be lost (see Figure A1). Multiplication with the present (static economic scenario) or future (dynamic economic assessment) exposed sensitive value for country A then provides a quantitative estimate of the drought losses for country A in year X. The country expected annual damage for the baseline and at the global warming levels was obtained by taking the average loss over the 30 year of annual losses in the respective time periods. The uncertainty in the fitted damage function (blue-shaded area in Figure A1) was translated into impact estimates through loss estimations for the 5 and 95% uncertainty bounds of the fitted vulnerability function. The total uncertainty in our damage estimates thus reflects uncertainty in future climate at the warming levels, as defined by the ensemble of climate projections, and uncertainty in the relation between damages and drought hazard.

Annex 2. Extended Results

A2.1 Projected expected annual damages

The data in Table A2 summarise the ensemble-average estimate of the expected annual damage (in million €) in the baseline (1981-2010) and at three warming levels (1.5, 2 and 3°C) for the EU countries and UK aggregated to the four IPCC AR5 European regions and for the EU+UK. The data in Table A3 and Table A4 present the lower and upper 95% confidence limits of these estimates (representing climate uncertainty in the estimates). In Table A5 the expected annual damages are expressed as a share of GDP of the corresponding time period, with the corresponding upper and lower uncertainty bounds in Table A6 and Table A7.

Note that drought impacts at 3°C on 2050s society are not evaluated as this warming level is not realistic by mid-century.

Table A2. Ensemble-average projected expected annual damage (in million €) in the baseline and at global warming levels for the EU countries and UK aggregated to four IPCC AR5 European regions and for EU+UK. Projections at warming levels are based on static economic conditions (those of the baseline) and socioeconomic conditions in 2050 and 2100 according to the 2015 Ageing Report.

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	3,627	5,029	5,888	7,866	6,072	7,087	11,603	13,523	18,096
Atlantic	2,546	2,480	4,188	6,947	3,348	5,561	7,750	12,811	21,351
Continental	2,590	2,079	2,066	2,383	2,803	2,776	5,076	5,013	5,758
Boreal	285	97	38	57	131	51	294	110	174
EU+UK	9,048	9,685	12,181	17,254	12,354	15,475	24,723	31,457	45,380

Table A3. Same as Table A2 but lower range of 95% confidence interval (representing climate uncertainty).

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	2,484	3,434	3,976	5,200	4,113	4,754	7,818	9,019	11,826
Atlantic	1,616	1,689	2,664	4,314	2,316	3,634	5,359	8,376	13,661
Continental	1,920	1,501	1,444	1,634	2,040	1,957	3,708	3,550	3,996
Boreal	195	70	28	39	93	37	205	79	119
EU+UK	7,427	7,813	9,658	13,432	10,009	12,335	20,040	24,969	35,302

Table A4. Same as Table A2 but upper range of 95% confidence interval (representing climate uncertainty).

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	5,865	8,353	9,927	13,611	8,030	10,486	19,411	22,879	31,464
Atlantic	5,331	4,338	8,753	15,300	7,045	6,944	13,445	26,148	46,021
Continental	6,272	3,779	4,007	4,492	7,985	4,947	9,130	9,573	10,801
Boreal	445	146	58	88	549	164	451	166	270
EU+UK	14,181	13,856	18,577	27,608	19,014	19,736	35,204	48,375	73,888

Table A5. Ensemble-average projected expected annual damage as a share of GDP (%) in the baseline and at global warming levels for EU-countries aggregated to the four IPCC AR5 European regions and for EU+UK. Projections at warming levels are based on static economic conditions (those of the baseline) and socioeconomic conditions in 2050 and 2100 according to the 2015 Ageing Report.

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	0.12	0.16	0.19	0.26	0.12	0.14	0.12	0.14	0.19
Atlantic	0.05	0.05	0.08	0.14	0.04	0.06	0.04	0.06	0.10
Continental	0.06	0.05	0.05	0.06	0.04	0.04	0.04	0.04	0.05
Boreal	0.05	0.02	0.01	0.01	0.01	0.00	0.01	0.00	0.01
EU+UK	0.07	0.08	0.10	0.14	0.06	0.07	0.06	0.07	0.10

Table A6. Same as Table A5 but lower range of 95% confidence interval (representing climate uncertainty).

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	0.08	0.11	0.13	0.17	0.08	0.10	0.08	0.09	0.12
Atlantic	0.03	0.03	0.05	0.09	0.03	0.04	0.03	0.04	0.07
Continental	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Boreal	0.03	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00
EU+UK	0.06	0.06	0.08	0.11	0.05	0.06	0.04	0.06	0.08

Table A7. Same as Table A5 but upper range of 95% confidence interval (representing climate uncertainty).

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	0.19	0.27	0.33	0.45	0.16	0.21	0.20	0.24	0.33
Atlantic	0.11	0.09	0.18	0.31	0.08	0.08	0.06	0.13	0.22
Continental	0.16	0.09	0.10	0.11	0.12	0.08	0.08	0.08	0.09
Boreal	0.07	0.02	0.01	0.01	0.04	0.01	0.02	0.01	0.01
EU+UK	0.11	0.11	0.15	0.22	0.09	0.09	0.08	0.11	0.16

List of abbreviations and definitions

EAD	Expected Annual Damage
IPCC AR5	Intergovernmental Panel on Climate Change Assessment Report 5
RCP	Representative Concentration Pathways
GWL	Global Warming Level
WL	Warming Level

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