Increasing economic drought impacts in Europe with anthropogenic warming

Naumann G.*, Cammalleri C., Mentaschi L., Feyen L.
European Commission, Joint Research Centre, 21027, Ispra, Italy
*Corresponding author address:
Dr. Gustavo Naumann
European Commission, Joint Research Centre, Via Enrico Fermi 2749, I-21027, Ispra, Italy. Email:
Gustavo.NAUMANN@ec.europa.eu; Tel: +39 033278-5535

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While climate change will alter the distribution in time and space of water, quantifications of drought risk in view of global warming remain little explored. Here, we show that in Europe drought damages could strongly increase with global warming and cause a strong regional imbalance in future drought impacts. In the absence of climate action (4°C in 2100 and no adaptation) annual drought losses in the EU + UK are projected to rise to more than 65 billion €/year compared to baseline 9 billion €/year, or two times larger when expressed relative to the size of the economy. Drought losses show the strongest rise in southern and western parts of Europe, where drought conditions at 4°C could reduce regional agriculture economic output by 10%. With high warming, drought impacts will become a fraction of present risk in northern and northeastern regions. Keeping global warming well below 2°C would avoid most impacts in the affected regions.

Prolonged heat and dryness exposed farmers, households and wildlife around Europe to severe droughts in the summers of 2018 and 2019[1,2]. Drastic 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.

Droughts originate from a temporary reduction in the normal precipitation regime, but other climatic factors such as high temperatures and low relative humidity can significantly aggravate the severity of the event. Intensive water use and poor water management can exacerbate drought conditions in watersheds, with a consequent increase in socioeconomic vulnerability[3–6]. Since the 1950s, northern Europe shows wetting patterns while southern and eastern Europe show a drying tendency[7] . Climate change is expected to further alter the water balance throughout Europe through modifications in the spatial and temporal distribution of precipitation, including more frequent and persistent dry spells, and increased potential evapotranspiration with higher temperatures[8,9]. Hence, with global warming droughts could become more frequent, severe, and longer-lasting in parts of Europe, especially in the south[10–12].

The diffuse, delayed and often intangible nature of drought impacts makes it difficult to retrieve correct or attributable loss records. As a result, little information is available on the economic cost of drought impacts[13] and estimates of present annual drought losses in Europe vary substantially. Reported losses in MunichRe's NatCatSERVICE[a] database indicate annual losses of around 1.3 billion € over the last 35 years, while the European Environment Agency reported that in the early 2000s the average annual economic consequences of droughts in Europe amounted to around 6 billion € per year[14]. 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 €[14] – exemplified what the potential impacts could be if climate change leads to an increase in the frequency and intensity of droughts across Europe[15].

Assessments of future drought losses in view of climate change are rare in literature[16–19]. Here, we present the first quantitative assessment of future drought economic impacts across Europe. A hydrological and water use model was used to simulate minimum river flows as indicator of drought hazard for the present and with 1.5, 2, 3 and 4°C global warming levels (GWLs) above preindustrial times. Economic losses were estimated based on a statistical relationship between drought intensity, expert-derived sector sensitivity to drought and their economic output, and reported losses of past

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

drought events. Long-term demographic, land use and sector productivity dynamics correspond to economic and budgetary projections for the EU[20] (more details in Methods).

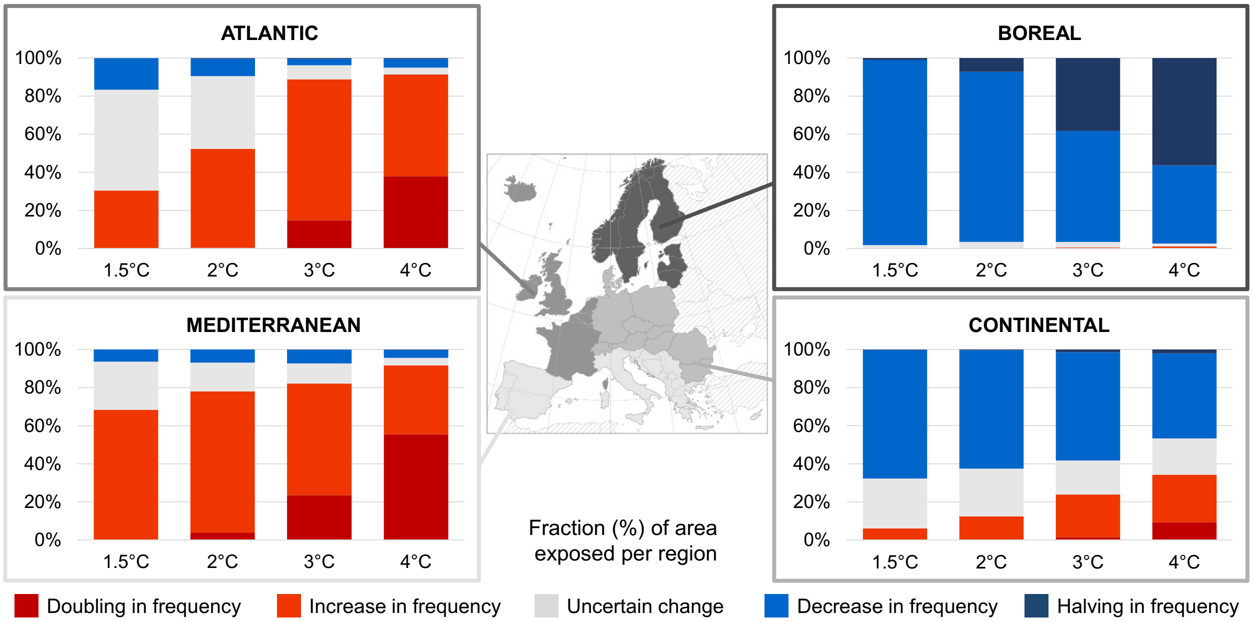

Figure 1. Fraction of area exposed to an increase (red shades) or decrease (blue shades) in drought occurrence for IPCC AR5 European sub-regions. Dark red (blue) indicates the area with a doubling (halving) of the frequency of drought. Grey indicates the fraction with no model agreement, meaning that less than 2/3 of the climate models agree on the sign of the projected change.

Drought hazard in Europe with global warming

Hydrological droughts will progressively happen more frequently and intensify in Mediterranean and Atlantic regions of Europe with global warming due to the combined effects of increasing evaporative demand[21] and decreasing precipitation especially in summer[22]. Drought conditions will also worsen in southern parts of the Continental region (Figure 1, Figure S3). With 4°C GWL drought frequency is projected to double over nearly 60% of Mediterranean, 40% of Atlantic, and 10% of Continental Europe. 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. In contrast, in Boreal Europe and north-eastern parts of Continental Europe drought hazard will decline due to increasing precipitation with climate change. In central and eastern Europe the projected mostly declining trends in drought intensity are less strong and show more climate variability.

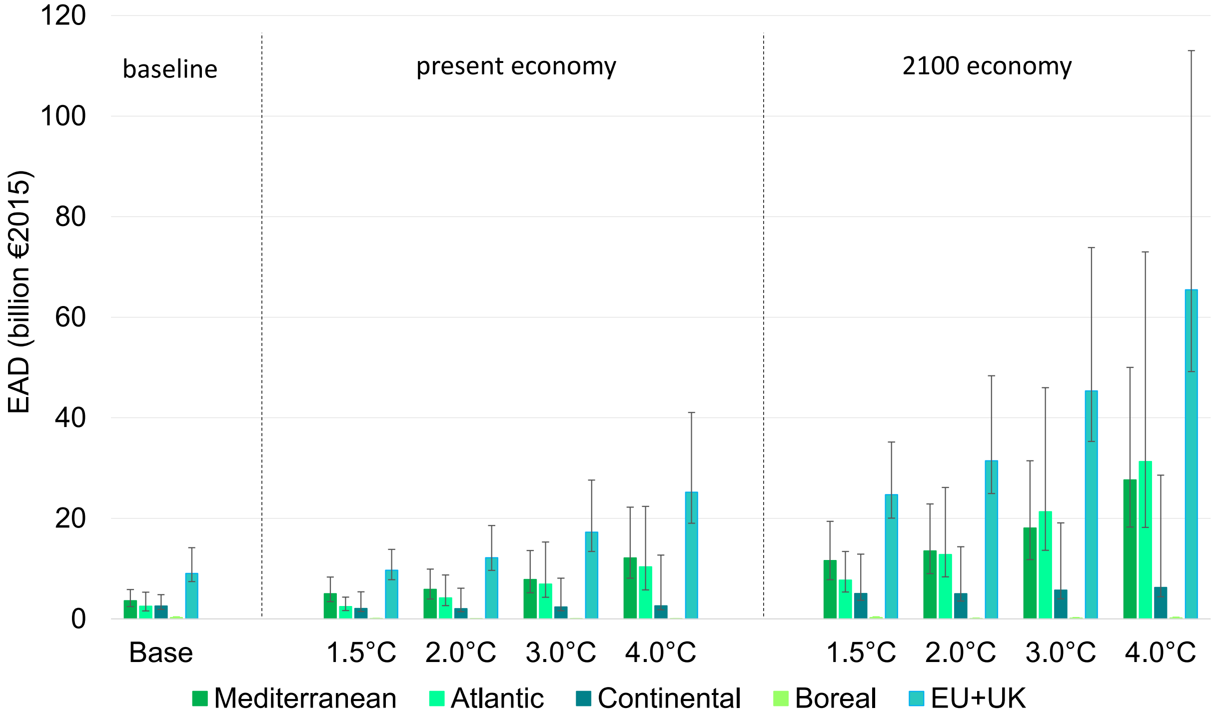

Figure 2. Expected Annual Damage (EAD, billion €2015) in the baseline and at global warming levels (average estimate and 95% confidence interval) for EU + UK and IPCC AR5 European sub-regions, assuming static and 2100 economic conditions.

Present impacts of droughts

We estimate baseline (1981-2010) annual economic drought losses in the EU and UK at 9 billion €/year (Figure 2 and Table 1). The 95% confidence interval (ranges further denoted between square brackets, Table S6) on this estimate lies 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 corresponds to 0.07% [0.06-0.11%] of 2015 EU+UK GDP (Table S7 and S8), compared to nearly 0.06% for river flooding[23] and 0.01% for coastal flooding[24]. Our estimate is considerably higher than drought damages reported in international disaster databases and 35% higher than the estimate (after inflation correction to 2015) of the EEA[14], which suggests that true drought losses are likely much higher than currently understood.

This is further supported by the fact that in the European Drought Impact report Inventory (EDII) the number and relative fractions of reported impacts for sectors differs regionally and from event to event[13] and that for many records in EDII no counterpart loss entries can be found in international disaster databases. This relates to difficulties in monetising drought losses and the lack of harmonised loss recording across the wide range of affected sectors. As a consequence there are also large uncertainty ranges around our central estimates.

	Base economy					Economy 2100 static vulnerability				Economy 2100 dynamic vulnerability			
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**4.0°C**	**1.5°C**	**2.0°C**	**3.0°C**	**4.0°C**	**1.5°C**	**2.0°C**	**3.0°C**	**4.0°C**
Austria	244	164	155	78	141	453	427	216	388	236	223	112	202
Belgium	210	250	408	641	1,200	862	1,408	2,213	4,144	462	754	1,185	2,220
Bulgaria	89	117	133	176	327	246	280	369	687	107	121	160	298
Croatia	72	81	74	66	131	176	161	143	282	80	73	65	128
Cyprus	38	57	79	166	218	156	217	457	600	71	100	210	275
Czechia	169	122	106	113	104	345	299	321	295	157	136	146	134
Denmark	121	133	106	154	80	404	322	470	244	194	155	225	117
Estonia	14	7	5	5	2	16	10	10	3	7	4	4	1
Finland	66	31	16	27	15	82	42	72	40	43	22	37	21
France	1,244	1,041	2,117	3,640	6,111	2,924	5,947	10,224	17,164	1,478	3,006	5,168	8,676
Germany	996	717	780	948	946	1,650	1,794	2,181	2,176	855	930	1,131	1,128
Greece	326	527	653	905	1,897	908	1,125	1,561	3,270	438	543	753	1,577
Hungary	162	141	128	124	165	354	323	313	414	167	152	147	195
Ireland	122	198	286	566	493	827	1,193	2,362	2,058	405	585	1,157	1,008
Italy	1,395	1,612	1,719	2,144	3,544	4,071	4,339	5,415	8,948	2,083	2,220	2,770	4,578
Latvia	18	9	4	4	1	23	10	10	4	10	4	4	1
Lithuania	29	12	4	1	1	24	8	2	2	10	3	1	1
Luxembourg	20	3	22	24	51	14	88	96	206	8	51	56	121
Malta	13	15	16	20	33	38	41	51	84	19	20	25	41
Netherlands	265	287	524	734	968	733	1,338	1,871	2,470	373	681	953	1,257
Poland	338	178	134	90	55	386	292	195	120	176	133	89	55
Portugal	252	418	511	565	905	805	983	1,087	1,742	399	488	539	864
Romania	388	424	449	632	748	1,017	1,078	1,516	1,793	446	473	665	787
Slovakia	84	83	75	67	57	221	198	178	151	94	84	76	64
Slovenia	45	91	55	59	141	227	136	147	350	110	66	71	169
Spain	1,487	2,228	2,782	3,940	5,291	5,222	6,520	9,236	12,402	2,531	3,160	4,476	6,010
Sweden	157	38	10	21	40	148	40	81	155	74	20	40	77
United Kingdom	686	700	831	1,342	1,549	2,391	2,838	4,585	5,289	1,217	1,445	2,334	2,692
Mediterranean	3,627	5,029	5,888	7,866	12,159	11,603	13,523	18,096	27,678	5,730	6,668	8,908	13,642
Atlantic	2,546	2,480	4,188	6,947	10,372	7,750	12,811	21,351	31,331	3,943	6,522	10,853	15,974
Continental	2,590	2,079	2,066	2,383	2,622	5,076	5,013	5,758	6,267	2,431	2,407	2,751	2,979
Boreal	285	97	38	57	58	294	110	174	203	144	54	87	102
EU+UK	9,048	9,685	12,181	17,254	25,211	24,723	31,457	45,380	65,479	12,247	15,650	22,600	32,697

Table 1. Expected Annual Damage (EAD) in million €/year (2015 values) for countries, regions and EU + UK for the baseline and different scenarios. Average estimates over climate ensemble and uncertainty of damage function, 95% uncertainty bounds are tabulated in Table S6.

The highest absolute expected drought losses currently 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) (Table 1 and S6). Relative to the size of the economy (share of GDP), drought losses are highest in Romania (0.30% [0.13-0.63%]) and Bulgaria (0.24% [0.10-0.52%]), and lowest in Finland (0.04% [0.02-0.07%]), Sweden (0.04% [0.02-0.08%]) and the UK (0.04% [0.02-0.08%]) (Table S7 and S8).

Impacts at warming levels under present socioeconomic conditions

Future drought impacts will be the result of the combined effects of climate change and socioeconomic dynamics. Because assumptions of demographic and economic developments over long-time spans are highly uncertain[25,26] it is important to single out the effect of climate change. When accounting only for the effects of climate change by combining today's (2015) population and economy with drought conditions at the GWLs, aggregated European drought losses slightly increase at 1.5°C GWL to 9.7 [7.8-13.9] but rise faster with further warming to reach 12.2 [9.7-18.6] billion €/year at 2°C GWL, 17.3 [13.4-27.6] billion €/year at 3°C GWL and 25 [19-41] at 4°C GWL (Figure 2, Table 1 and S6). This corresponds to 0.08% [0.06-0.11%] (1.5°C), 0.10% [0.08-0.15%] (2°C), 0.14% [0.11-0.22] (3°C) and 0.20% [0.15-0.33%] (4°C) of 2015 EU+UK GDP (Table S7 and S8). Hence, a 4°C warmer climate applied on today's (2015) economy would result in drought losses that are nearly 3 times larger as under today's climate (1981-2010, on average 0.7°C warmer compared to preindustrial times), while stringent mitigation that limits warming to well below 2°C would mostly stabilise overall EU drought losses.

There are, however, strong regional differences across Europe in the evolution of drought losses with global warming (Figure 2). The strongest rise is projected for the Atlantic region, especially at higher warming levels, with an increase in damage of more than 300% at 4°C GWL. Drought damages will also grow strongly in the Mediterranean (+235% at 4°C GWL), while aggregated over the Continental region damages reduce with lower GWLs but then increase again with higher GWLs. The Boreal region will experience a strong decrease in drought losses, which drop to 20% of baseline values at high GWLs.

At country level, the spread in the projected changes in drought damage is even more pronounced. In the Atlantic and Mediterranean region a strong relative increase in drought damages is projected for Greece, Belgium and Cyprus (> +450% at 4°C), France (+391%), Ireland (+304% at 4°C), and the Netherlands, Portugal, and Spain (> +250% at 4°C). In the Continental region drought losses strongly reduce in the northeast (Poland -84% at 4°C), reduce to a lesser extent (-30 to -40% at 4°C) in central parts (Czechia, Slovakia, Austria), remain stable in western parts (Denmark and Germany), and increase in the south (Bulgaria +269% and Romania +93% at 4°C). In Scandinavian countries drought damages would drop by 75% at 4°C and in the Baltics by 90% or more.

Sectorial impacts

Drought affects ecosystems and societies in many different ways because water is essential to life and important for many of our activities. Drought reports[1,2,13], expert judgement[27] and a wide body of literature indicate that drought losses largely relate to impacts to agriculture (crop and livestock), energy production, water supply, river navigation, and damage to buildings due to soil subsidence (see Methods and Table S3). As the consequences on ecosystems are typically not monetized and included in damage reports, they are also not reflected in our estimates.

A sectorial disaggregation of estimated economic losses (Figure 3) based on present (2015) socioeconomic conditions shows that agriculture losses account for more than 50% of total drought losses in Europe, with the highest sector share in the Mediterranean (60%) and the lowest in the Boreal (39%). Impacts to the energy sector represent 23% of the total damage, but with a considerable higher share in the Boreal (48%) where hydropower is an important energy source. The share of public water supply ranges between 8 and 20%, while infrastructure subsidence damages account for around 8% of total losses with higher shares in regions with elastic soils. Losses in the transport sector are marginal (2% overall) in relative terms and relate only to inland water transportation that is limited to the Atlantic and Continental region.

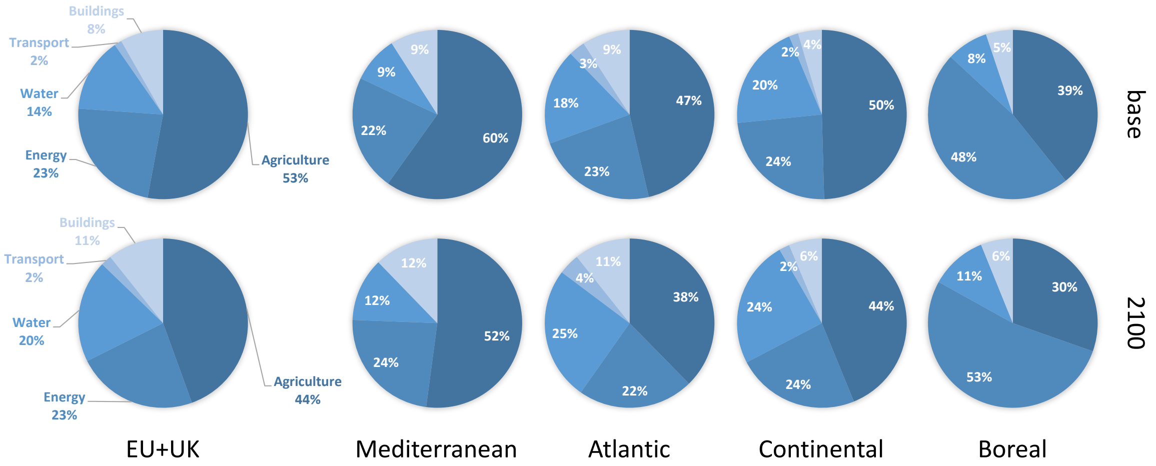

Figure 3. Sector shares in total drought damages under base (2015) and 2100 socioeconomic conditions for EU + UK and IPCC AR5 European sub-regions. Shares represent averages over different warming levels.

Economic losses of drought are fairly small compared to the total size of European economies and remain mostly well below 1% of total GDP even with very high warming (Table S7). For the agriculture sector, however, relative impacts can be much higher. While in the baseline drought losses destroy on average 2.3% of the annual sector Gross Value Added (GVA) in the EU + UK, this could grow to almost 7% at 4°C GWL (Table S9). In the Mediterranean, drought conditions at high levels of global warming could reduce agriculture economic output by more than 10%. For the energy and water supply sector the loss in GVA would be around 1% in these regions. Shipping interruptions can regionally affect supply chains[28] but relative impacts for the transport sector as a whole are small. While structural damage to buildings is an undervalued aspect of drought[29], its impact is negligible compared to the total stock value of buildings.

Impacts at warming levels under future socioeconomic conditions

When considering the EU economic, budgetary, and demographic projections[20] overall absolute drought losses for EU+UK in 2100 grow to 25 [20-35] billion €/year at 1.5°C GWL and 31 [25-48] billion €/year at 2°C GWL, or an increase of respectively 170% and 250% compared to baseline damages. With global warming of 3°C by the end of this century, absolute losses would grow to 45 [35-74] billion €/year (+400%) and to 65 [49-113] (+624%) with 4°C warming (Figure 2, Table 1 and S6). Similar as for impacts with a static economy, the strongest increase in absolute drought losses in 2100 are projected for western and southern parts of Europe. With 4°C global warming by the end of this century, absolute drought losses in the Atlantic and Mediterranean region are projected to be 12.3 and 7.6 times higher compared to the baseline, respectively.

When expressed with respect to the total size of the economy, in 2100 the effects of global warming are however dampened compared to those with baseline socioeconomic conditions (Table S7). This is because agriculture is projected to become relatively less economically prevalent in future EU economies. The share in the total damages of the agriculture sector will therefore gradually reduce everywhere (Figure 3), with reductions ranging between -9% in Atlantic to -6% in Continental Europe. On the other hand, the share in the total losses of impacts in the water supply sector (+6%) and infrastructure damage due to swelling and shrinking of soils (+3%) will increase in all regions.

The above estimates all assume static vulnerability. Empirical evidence shows that relative impacts (damage expressed as a share of the economic value exposed) of droughts have reduced considerably over the last four decades[30]. Continuous advances in drought-sensitive sectors, such as the development of stress-resistant crops to improve yield stability under water shortage conditions[31] or improved water use efficiency in power production[32], will likely further reduce vulnerability to drought. The large uncertainties over these developments across a wide range of potentially impacted sectors imply that the assessment of future vulnerability is complex[33]. There is a clear negative relation between wealth (GDP per capita) and drought vulnerability[30] and we estimate changes in vulnerability by applying this relation with the projected GDP per capita for each country[20]. According to this scenario, drought impacts in 2100 would be roughly halved compared to when assuming static vulnerability, with reductions ranging between 40% for the richest to 60% for the poorest countries in Europe. As a result, in most countries damages relative to the size of the economy would remain below present levels even with high warming. In Bulgaria (+17%), Spain (+22%), Portugal (+45%), Cyprus (+53%), France, (+70%), Ireland (+73%), Greece (+115%) and Belgium (+148%) effects of drought on the total economy would still be higher compared to present conditions. This suggests that additional adaptation efforts will be necessary in these countries to keep relative drought risk levels comparable to those of today. Adaptation could be targeted to reduce the reliance on large water infrastructures and on water conservation measures. Increasing supply through reservoir storage or desalinated water can trigger an accelerating spiral towards unsustainable exploitation of water resources and environmental degradation. This in turn may increase social vulnerability to and economic damage from droughts[34].

Discussion

Although that there is large uncertainty in the damage estimates presented herein, they show a clear regional contrast in the evolution of future drought risk in Europe with global warming, with a strong increase in drought impacts in southern and western parts of Europe versus a strong decline in northern and northeastern regions. Events like the 2018 drought in central and northern Europe, which caused yield reductions up to 50% for the main crops[1], will become less likely but are still plausible. Wet conditions in southern Europe at the same time saw yield gains up to 34%[35] 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 that in 2018 will be balanced with favourable water availability conditions in southern Europe.

Our damage estimates are conditional on loss records of disaster risk databases, with the known difficulties in reporting them[36], but they are not comprehensive. Severe droughts impact vegetation productivity[37] and trigger tree mortality[38]. The loss of ecological, economic and social benefits of ecosystems, including carbon sequestration that is crucial for climate change mitigation[39], are even more difficult to quantify in economic terms. Droughts often do not happen in isolation, but simultaneously (compound events) or sequentially (cascading events) with other dry hazards such as heatwaves and wildfires[40]. Increasing frequencies and intensities of uncorrelated climate hazards like floods in view of climate change[23,24] could further increase the likelihood of consecutive climate extremes with overlapping and potentially amplified impacts while recovery is still under way[41].

To progress the quantification of drought risk and develop more drought resilient societies, we believe that more research efforts should aim to understand and quantify environmental, social, and economic vulnerability to drought[42]. Identifying the drivers of drought risk and the ways in which drought impacts materialise is crucial to develop plausible risk mitigation scenarios based on multi-criteria and cost-benefit analyses of potential measures in different geographical and socioeconomic contexts.

Author contributions

The authors co-designed the experiment. L.M. and C.C. conducted the drought hazard analysis, G.N. and L.F the exposure analysis, G.N., C.C. and L.F the vulnerability analysis, and G.N. and C.C. the impact analysis. G.N. and L.F. interpreted the results and wrote the manuscript with contributions from all authors.

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Methods

We assessed drought risk as a combination of drought hazard, exposed sectors and their vulnerability to drought. A schematic overview of the data and modelling framework is shown in Figure S1, with hazard, exposure and vulnerability components of the analysis shaded in blue, green and brown, respectively, while impacts are shaded in red. The different steps of the methodology are explained in more detail below.

Data and modelling framework

The data-modelling framework consists of two main parts. In the first 'historical' part, observed data and reported information on weather (1990-2016), socioeconomic statistics (2010 and later), sensitivity (2010 and later), and disaster impacts (1990-2016) were combined in order to establish at country scale a relationship between the intensity of droughts, the economic value exposed to the drought hazard, and the impact. This damage function expresses the economic loss that can be expected in a country in function of the recurrence frequency of a drought and the sensitive value exposed in that country.

In the 'projection' part, climate and socioeconomic projections were used to estimate future drought hazard, exposure and impact. The hazard analysis was performed over 30-year time periods. The baseline spans the period 1981-2010 and we compared drought hazard over this period with that over 30-year time slices centred on the year that global average temperature is 1.5, 2, 3 and 4°C above preindustrial temperature (Table S1). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while higher warming levels correspond to scenarios that could be expected by the end of the 21st century if adequate mitigation strategies are not taken. There are some climate projections that reach 4°C a few years after 2085 (Table S1). For these models the projections of the period 2071-2100 were considered as representative of 4°C GWL, although projected global warming over this period is slightly lower than 4°C for these models. The simulated drought hazard for the baseline was combined with exposure based on socioeconomic conditions representative of 2010-2015 and the damage function obtained in the 'historical' part of the analysis. Impacts of droughts for the global warming levels (GWLs) were evaluated for a static and dynamic socioeconomic setting, namely by imposing drought hazard at the GWLs on today's society and on that projected by the end of this century. In the latter, the vulnerability (damage function) was assumed constant in time, hence not accounting for technological development or adaptation of sectors to changing drought conditions. In addition, we considered a scenario with dynamic vulnerability based on an empirical relation between drought loss as a share of exposed economic value and wealth[30].

The projections of socioeconomic development in Europe are based on the ECFIN 2015 Ageing Report[20]. This scenario acts as a benchmark of current policy and market trends in the EU. High-resolution land use and population projections were derived with the LUISA modelling platform[43]. The sector composition of the economy and Gross Value Added (GVA) was modelled by GEM-E3 at country level[44], while energy demand was estimated with the POLES model[45].

The Ageing Report projections are limited until the year 2060. After that, land use was assumed static, while the relative distribution of people and importance of economic sectors in a country in 2060 was scaled according to country projections of GDP and population up to 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 was assumed as well for the following decades. The third contributor to growth (the labour input) was 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 the employment rate. Country population projections for 2061-2100 were taken from the medium variant of the United Nations demographic projections[46], and they were explicitly considered in the computation of the economic growth figures (more details can be found in [47]).

The Ageing Report socioeconomic projections (hence changes in exposure) are limited to the EU (including UK at that time) and impacts were only estimated for EU member states and the UK. As catchments do not follow country borders the hydrological model was run over a wider domain to minimise cross-border in- or outflow errors, with water use that was kept constant in non-EU countries apart from climate-induced changes in irrigation requirements for irrigated crops.

Drought hazard modelling

We used annual minimum river streamflow as an indicator of drought hazard. 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 includes socioeconomic drivers of drought.

Simulations of daily river discharge were produced with the LISFLOOD hydrological model[48]. This is a spatially distributed hydrological rainfall-runoff-routing model, designed to simulate the water balance at cell scale (5x5 km), as well as the rooting of surface runoff in the river network. Several studies[10,49] have used the model to assess changes in streamflow droughts across Europe. The model presently covers an extended European domain, which includes all EU countries, as well as neighbouring countries such as Albania, Bosnia-Herzegovina, Iceland, Moldova, Montenegro, the Republic of Macedonia (FYROM), Norway, Serbia, Switzerland and the UK.

LISFLOOD includes water use for industry, energy, domestic, livestock and irrigation water demand. The latter is estimated for irrigated agricultural land with an embedded dynamic irrigation water demand module that estimates the amount of water for crop transpiration that cannot be supplied by soil moisture above the wilting point. The module takes into account irrigation and conveyance efficiency and uses information from AQUASTAT[50] on the share of irrigation demand that is met by groundwater, surface water, or non-conventional sources (e.g., desalination). Water withdrawals by livestock are estimated by combining density maps for cattle, pigs, poultry, sheep and goats with livestock water requirements from literature[51]. Water demand for the household sector is simulated based on water use per capita and high-resolution population density[52]. Per capita use of water is based on a regression model between public water use and socioeconomic, demographic and climate variables that was derived from data collected at NUTS3 level (over 1200 regions in the EU) from 2000-2013[53]. Industrial water demand uses country-level data from national statistics offices on water use by manufacturing, mining and construction. National totals are disaggregated to the industrial land use class of the refined European land cover map[54]. Water demand for energy production is estimated based on country statistics from Eurostat and AQUASTAT that are downscaled to the locations of large power thermal power stations registered in the European Pollutant Release and Transfer Register database (E-PRTR). Different consumptive use percentages were used for sectors to split water abstraction into net water consumption and return flow. A more elaborate description of the different modelling techniques used for the water use projections can be found in[55].

For the historical drought hazard analysis, LISFLOOD was run for the period 1990-2016 with high-resolution (5x5 km) observation-based meteorological data derived from about 5,600 rain gauges and 8,900 temperature stations[56]. Drought events derived from this historical simulated streamflow discharge time series were used for the construction of the damage function.

For the analysis of changes in drought conditions in view of global warming, LISFLOOD was forced with an ensemble of 11 bias-corrected regional climate projections for RCP4.5 and RCP8.5 from 1981 up to 2100[57]. The models and the year of passing the GWLs are presented in Table S1. Drought hazard conditions for the baseline, 1.5 and 2°C warming were derived from an ensemble of 22 members, whereas the ensemble projections for 3 and 4°C warming is smaller as 10 out of 11 RCP4.5 climate simulations do not reach 3°C warming. The effect of pathway to GWLs on projected changes in low flows is negligible and the projections of the two pathways for the GWLs can be merged into a single ensemble without major loss of information[58].

Future water use was modelled based on projections of population (domestic), land use (agriculture), energy production (energy demand) and economic output of sectors (industry) according to the EU economic, budgetary, and demographic projections[20]. Spatial downscaling of the socioeconomic drivers of future water use was done similar as for the present (see above). The ECFIN socioeconomic projections are limited to the EU (including UK at that time), hence for non-EU countries water use was kept constant apart from climate-induced changes in irrigation requirements for irrigated crops.

In this study, the annual minimum river flow (q_{min}) was used as drought indicator[10,49]. In order to exclude low flows caused by the temporary storage of precipitation as snow in cold or mountainous regions, we considered flows only between April and October. We analysed qmin 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. In all river pixels considered we fitted a non-stationary Generalized Extreme Value (GEV) distribution through the annual minimum flows[59] for the historical analysis, and for the baseline and 30-year time slices centred on the GWLs. The fitted distributions provide a link between the intensity of a drought event in that river pixel and its expected probability of occurrence (expressed in return period). It is important to note that for future time windows (centred on the warming levels) the intensities of drought events were converted to return periods consistent with baseline streamflow conditions. This means that when a flow of X m^3/s happens once in 10 years at a warming level and such a flow happens once in 15 years in the baseline, a return period of 15 year is used instead of 10 years in the application of the damage function for this warming level (further below). Hence, while the damage function (see below) is expressed in probability (return period), in each location there is a unique link between impact and intensity.

Sensitivity

Droughts can have wide-reaching economic, social and environmental impacts. This study used recorded losses from major international disaster databases (see further below), which report country damages without further sectorial disaggregation of the impacts. In order to be able to construct a damage function, it was required to understand what sectors are mostly affected and what the main channels are through which the impacts are transmitted. The European Drought Impact report Inventory (EDII) provides a unique research database that has collected close to 5,000 impact reports from 33 European countries[13]. The data are classified into 15 categories, with entries related to agriculture and public water supply that dominate drought impact reports for most countries. However, impacts reported in EDII on energy supply, industry, several ecosystem services, but also conflict, human health and tourism exemplify the diversity of drought impacts.

For a number of climate hazards, including drought, Forzieti et al. [60] derived sensitivities for the thematic priorities of the EU Cohesion Policy Funds (CPF) to the considered climate hazards. The CPF investments cover 86 priority themes across a wide range of sectors, including environment, transport, energy, industry and infrastructure. A qualitative sensitivity matrix was established using a survey run among ∼2000 experts, complemented by an extensive literature review [27,60]. For each sector a sample of about 50 experts (out of 500 potential respondents) was collected from private companies, authors, and editorial boards of peer-reviewed climate change and sector-specific journals. Experts anonymously assigned a degree of sensitivity (high, moderate, low, no) of sectors to each climate hazard. Exposure and personal bias was removed and modes of the resulting Likert distributions were considered to be representative of the sensitivity[27]. A summary of the survey results for drought is presented in Table S2. The CPF does not specifically focus on agriculture, which in the EU is dealt with in the Common Agricultural Policy (CAP). Reports in Stahl et al.[13], and a wide body of literature suggest a high sensitivity to drought of this sector. We use the sensitivity of biomass (energy) as a proxy of the sensitivity of agricultural crop yield in general, including forage and fodder crops for livestock production.

Based on the above studies, and the underlying literature, we included in this study the sectors and channels tabulated in Table S3. This includes damage to infrastructures due to drought-induced subsidence, which is an undervalued aspect of drought in literature but of relevance for insurance companies[29]. The sectors and channels in Table S3 are not exhaustive but likely cover a large share of the recorded economic losses from droughts. It should be noted that Stahl et al.[13] show that for several drought events there have been a considerable number of reports related to forest fires and ecosystems (aquatic and terrestrial). The survey of Forzieri et al.[60] also indicates that ecosystems are sensitive to drought. The damage data that were used in this study do not include those of forest fires, as this is typically considered a different hazard in the disaster databases for which there is a separate entry, while consequences on ecosystems are not monetized and included in damage records and therefore also not in our estimates.

Exposure

Present exposure

We use GVA of sectors in a country as a proxy of the potential output at risk for each sector. GVA was obtained from Eurostat and the average over the period 2008-2017 was taken. GVA is not available for all sectors (e.g. water supply is categorized under 'industry'). As GVA is highly correlated with the Total Fixed Assets (TFA) that is available for a wider coverage of sectors, a further sectorial breakdown of GVA was based on TFA, where sub-sectors were assigned a value of GVA based on their share of TFA to the total TFA of a sector. The TFA data were also obtained from Eurostat over the same period. For the transport and energy sector, we applied a further breakdown of the economic value over different transport modes and energy supply sources. This was done based on harmonized intensity values[61] that express the relative importance of sub-sectors in the energy and transport sector based on a common unit, tonnes of oil equivalent and tonnes of freight transported, respectively.

Sectors or sub-sectors that were assigned 'no' or 'low' sensitivity (e.g., management of household and industrial waste, road transport, or solar power production) were assumed to not contribute to the drought damage. For sectors or sub-sectors with 'medium' or 'high' sensitivity (e.g., agriculture, river navigation or thermal power production) the GVA of that (sub-)sector was weighted by the ratio of medium and high sensitivity answers to the total answers (Table S2). Although that the survey-derived sensitivities are not a quantitative measure of vulnerability, the weighting allows to account for that fact that certain sub-sectors are considered by experts to be more sensitive to drought.

For damage to buildings and infrastructures due to drought-induced soil subsidence, we use Total Construction (TC) values for all sectors from Eurostat (2008-2017) as a proxy of the potential value at risk to subsidence. As TC was not available for all sectors in all countries, gaps were filled based on TFA, Total Construction Formation (TCF) and Total Fixed Assets Formation (TFAF), all obtained for the same period from Eurostat. Only a fraction of the TC is actually at risk, as subsidence depends on the soil properties, building types and the structure of the surrounding area. Especially fine-grained clay-rich soils are susceptible to hydric swelling and shrinking of soils[62,63]. We used spatially information (1x1 km) on clay content in soils from the European Soil Database[64] and applied a threshold of 30% clay content to delineate areas with potential subsidence, and further assigned a susceptibility weight based on percentage clay content. Surveys have shown that detached buildings are more affected[65]. Following Corti et al.[66] we aggregated land cover classes of the refined European land cover map[54] into urban centres, urban discontinuous, and rural (100x100 m), and assigned them a susceptibility of 0.0, 0.5 and 1.0, respectively. The spatial soil and land use information was combined with build-up area (100x100 m) obtained from the Global Human Settlements Layer[67] for the year 2014 in order to estimate the actual amount of build-up area susceptible to subsidence. The fraction of the TC that is at risk was then obtained as the share of the build-up area that is susceptible to the total build-up area in a country.

The corresponding sensitive economic values exposed for the different sectors considered in our analysis are listed in Table S4. Agriculture accounts for the largest share, followed by energy and water supply. The share of transport is limited as only river navigation is sensitive to drought. Building stock value sensitive to subsidence accounts for approximately 7% of the total sensitive economic value. In France this is 11%, which is in line with subsidence losses that were estimated to be around 890 €million in France during the 2003 drought[66], with total losses to the EU economy of that event estimated to be around 8.7 €billion[14].

Future exposure

Exposure by the end of this century was obtained by scaling present sensitive exposure value according to the ECFIN socioeconomic projections. For agriculture, energy and transport, GVA projections are only available at sector level and it was assumed that all sub-sectors relevant here (i.e. that are drought sensitive) follow the same trend in economic output as the sector. Projections of GVA for the water supply sector were not available and baseline exposure was scaled according to the projections in GDP. Projections of TC were also not available. Given that TC and GDP are strongly correlated, baseline TC was adjusted according to the projected changes in GDP. The resulting sensitive economic values exposed for all countries are presented in Table S5.

Damage function

We appraised vulnerability to droughts based on damage records collected from the Emergency Events Database (EMDAT[b]) and Munich Re's NatCatSERVICE[c] disaster database during the period 1990-2016. All data were converted into €2015 based on the country's Harmonized Index of Consumer Prices (HICP) obtained from Eurostat. The reported damage for each drought event corresponds to the overall economic loss recorded in a country. Loss reports may include a very brief description of the event in textual form and list affected sectors, but no sectoral disaggregation of the economic losses is provided. It was assumed that the reported damage of an event is spread over the sectors in a country according to the sensitive exposure value for the sectors listed in Table S4. As in Naumann et al.[16] we obtained a damage function by fitting a power law between the damage reported for an event scaled by the country sensitive exposure value and the drought probability (inverse return period) derived from the historical drought analysis. For the latter we used the median probability within a country linked to the time of the reported event, which can be justified as impactful droughts typically stretch out over large spatial extents. The resulting damage function is shown in Figure S2, including the 90% confidence interval from the fitting of the power law.

The considerable width of the confidence interval confirms the high uncertainty in the quantification of drought impacts. Although NatCatSERVICE is one of the most comprehensive sources of reported disaster losses, recorded impacts very likely deviate from the true numbers[36,68]. The data that populate the database originate from different sources and are collected by multiple actors. This is especially true for droughts, as they induce a complex web of impacts, many of which may only occur long after the onset of the event. Further, our estimates of exposed sensitivity value are uncertain due to the combination of a qualitative appraisal of sector sensitivities with socioeconomic proxies of sector exposure. Finally, the estimation of drought intensity and corresponding occurrence probability is uncertain due to observation and interpolation error in the meteorological data, uncertainty in the hydrological and water use modelling, and the aggregation of the hazard to country level.

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[b] https://www.emdat.be/

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

Impact modelling

Estimates of economic damages are expressed in €2015 values and they were obtained as follows. For all climate realisations of the ensemble we combine for each 30-year time window (baseline and periods centred on the GWLs) the hazard, exposure and damage function in the following way. For each year of a 30-year time window, the median frequency of the simulated annual minimum flow is obtained over all river pixels with upstream area > 1,000 km^2 in a country. This value is then plugged into the damage function (Figure S2, x-axis) to determine the loss as a fraction of the exposed sensitive value. So in country A an event in year i with a probability to happen once every five years (frequency = 0.2, or return period of 5 years), would result in a 10% loss of the exposed sensitive value in that country. Multiplication with the present (baseline, Table S4) or future (end of century, Table S5) exposed sensitive value for country A then provides a quantitative estimate of the drought losses for country A in year i. The uncertainty in the fitted damage function (dotted lines in Figure S2) was translated into impact estimates through loss estimations for the 5 and 95% uncertainty bounds of the fitted vulnerability function for each climate realisation. The country Expected Annual Damage (EAD) and confidence bounds for the baseline and at the GWLs was then obtained by taking the average loss over the 30 years of annual losses in the respective periods and over the climate realisations. The total uncertainty in our damage estimates thus reflects the uncertainty in future climate at the warming levels and in the relation between damages and drought hazard. We note that when considering extremes it is important to take the average impact over all simulated events and not the median, as there is large skew in the impact distribution (inherent to extreme events) and the low probability high impact events have an important weight in the expected annual losses.

Data availability

The data that support the findings of this study are available from several databases listed in the Methods of the manuscript and the referred studies. Data are available from the authors on reasonable request and following data restrictions from the sources.

Code availability

The code that supported the findings of this study is available from the corresponding author upon reasonable request.