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Increased economic drought impacts in Europe with anthropogenic warming

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While climate change will alter the distribution of water in time and space, quantifications of drought risk under global warming remain uncertain. Here, we show that in Europe drought damages could strongly increase with global warming and cause a 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 9 billion €/year currently, 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 current impacts in northern and northeastern regions. Keeping global warming well below 2°C would avoid most impacts in 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^{3,4}.

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^{5–8}. Since the 1950s, northern Europe shows wetting patterns while southern and eastern Europe show a drying tendency⁴. 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^{9,10}. Hence, with global warming droughts could become more frequent, severe, and longer-lasting in parts of Europe, especially in the south^{11–13}.

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 impacts¹⁴ and estimates of present annual drought losses in Europe vary substantially. Reported losses in MunichRe's NatCatSERVICE (<https://natcatservice.munichre.com>) database indicate direct 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 year¹⁵. 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 €¹⁵ – exemplified what the potential impacts could be if climate change leads to an increase in the frequency and intensity of droughts across Europe¹⁶.

Many studies have assessed the economic effects of drought, mostly at local and national scales and with focus on specific sectors, such as agriculture^{17,18}, energy¹⁹, or regulatory drought management²⁰. However, assessments at continental scale of future drought losses in view of climate change are rare in literature^{21–24}. Here, we present a 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 drought events. As the latter only represent direct drought losses, indirect effects on business production and the flow of goods and services are not included in our estimates. Long-term demographic, land use and sector productivity dynamics correspond to economic and budgetary projections for the EU²⁵. Drought hazard and impacts were calculated for each climate projection of the ensemble. We report the ensemble mean and the range of potential outcomes defined by the minimum and maximum scenario of the ensemble. In the estimation of drought losses, we further account for uncertainty in the damage function fitting (more details in Methods).

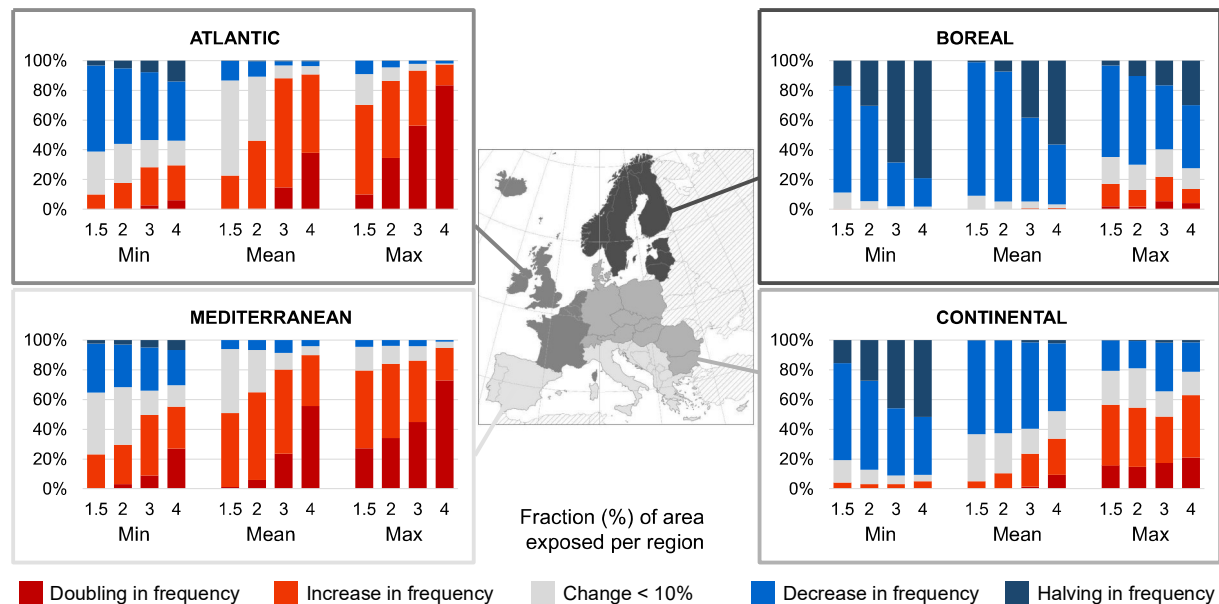


Figure 1. Fraction of area exposed to changes in drought occurrence for IPCC AR5 European sub-regions. Red (blue) shades indicate areas with an increase (decrease) in drought frequency, while dark red (dark blue) indicates areas with a doubling (halving) of the frequency of drought. Grey indicates the fractions with relative changes less than 10%. For each region, the ‘Mean’ outcome represents the ensemble mean results, whereas the ‘Max’ outcome represents the largest projected increase for that region by any model in the ensemble or the smallest decrease in case all models show a negative change, and the ‘Min’ outcome represents the model in the ensemble with the largest decrease or smallest increase in case all models project a positive 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

demand²⁶ and decreasing precipitation especially in summer²⁷. Drought conditions will also worsen in southern parts of the Continental region (Figure 1, Figure S5). With a GWL of 4°C, ensemble mean drought frequency is projected to double over nearly 60% [27-73%] of Mediterranean, 40% [6-83%] of Atlantic, and 10% [1-21%] of Continental Europe. The corresponding minimum and maximum scenarios, indicated between square brackets, shows that there is considerable variability in the projected changes among the climate realisations. Limiting global warming to 1.5°C would still result in an increase in drought frequency over half [23-80%] of the Mediterranean and one-fourth [10-70%] of the Atlantic region, but would avoid for nearly all climate realisations 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, which will likely outweigh the increase in evaporative demand due to warmer temperatures linked with climate change²⁸. In central and eastern Europe the projected mostly declining trends in drought intensity are less strong and show more climate variability (Figure S6 and S7).

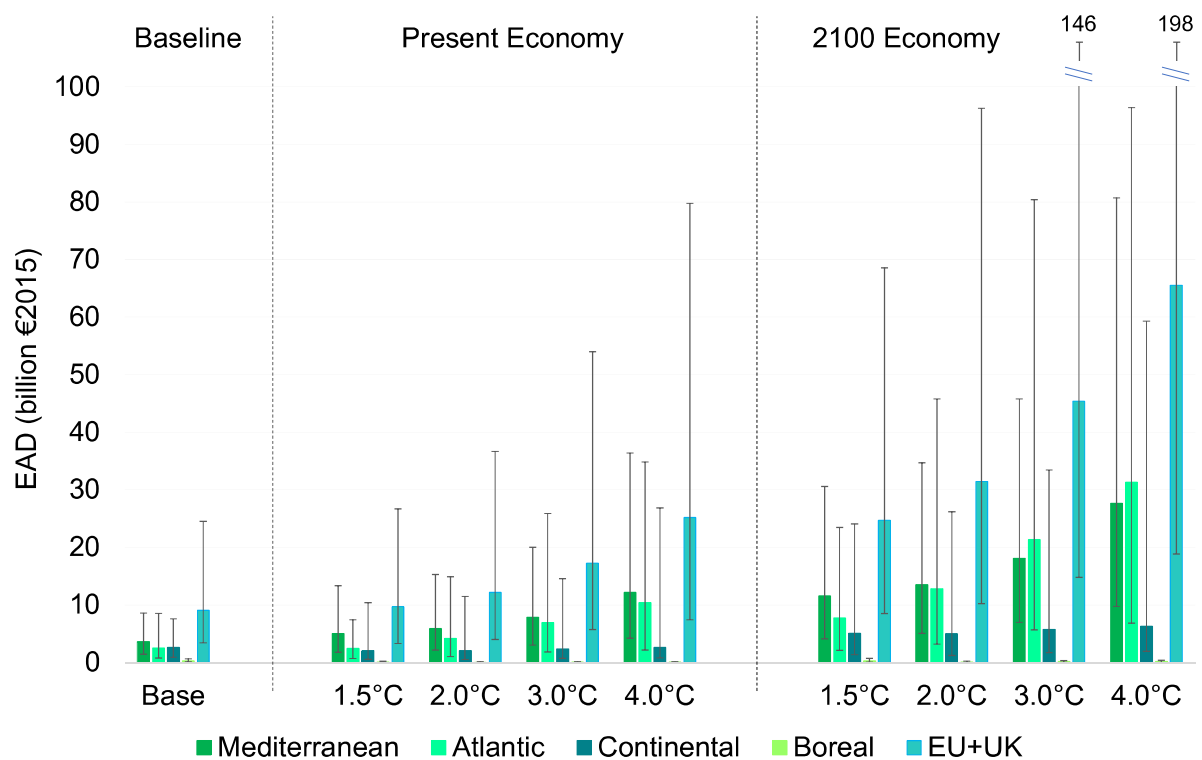


Figure 2. Expected Annual Damage (EAD, billion €2015) in the baseline and at global warming levels for EU + UK and IPCC AR5 European sub-regions, assuming static and 2100 economic conditions. The colored bars represent ensemble mean estimates, while the thin lines represent the spread in the results that includes the range of

damage estimates over the climate ensemble and the 90% uncertainty interval of the fitting of the damage function.

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 range (Table S6) on this estimate lies between 3.4 and 26.6 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% [0.03-0.19%] of 2015 EU+UK GDP (Table S7 and S8), compared to nearly 0.06% for river flooding²⁹ and 0.01% for coastal flooding³⁰. Our mean 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 EEA¹⁵, 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 event¹⁴ 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	6,112		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	27,677	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 market exchange rates) for countries, regions and EU + UK for the baseline and different scenarios. Average estimates over climate ensemble. The spread in the results that includes the range of damage estimates over the climate ensemble and the 90% uncertainty interval of the fitting of the damage function are tabulated in Table S6.

The highest absolute expected drought losses nowadays occur in Spain (1.5 [0.6-3.5] billion €/year), Italy (1.4 [0.5-3.3] billion €/year) and France (1.2 [0.3-4.6] billion €/year) (Table 1 and S6). Relative to the size of the economy (share of GDP), drought losses are highest in Romania (0.30% [0.11-0.70%]) and Bulgaria (0.24% [0.10-0.56%]), and lowest in Finland (0.04% [0.01-0.08%]), Sweden (0.04% [0.02-0.1%]) and the UK (0.04% [0.01-0.1%]) (Table S7 and S8).

Impacts with warming under present socioeconomic conditions

Future drought impacts will be the result of the combined effects of climate change and socioeconomic dynamics, including adaptation policy implementation and the development of drought management plans³¹. Because assumptions of demographic and economic developments over long-time spans are highly uncertain^{32,33} 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 [3.3-26.7] but rise faster with further warming to reach 12.2 [4.0-36.7] billion €/year at 2°C GWL, 17.3 [5.7-53.9] billion €/year at 3°C GWL and 25 [7.4-79.8] at 4°C GWL (Figure 2, Table 1 and S6). This corresponds to 0.08% [0.03-0.21%] (1.5°C), 0.10% [0.03-0.29%] (2°C), 0.14% [0.05-0.43] (3°C) and 0.20% [0.06-0.63%] (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

Droughts affect ecosystems and societies in many different ways because water is essential to life and important for many of our activities. They induce a complex web of impacts that span many sectors of the economy, including farming and livestock, public water supply, energy, tourism, human health, transportation, biodiversity and ecosystem services³⁴. Drought reports^{1,2,14}, expert judgement³⁵ and a wide body of literature indicate that drought losses in Europe 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 and indirect economic effects are typically not monetized and included in damage reports, they are 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.

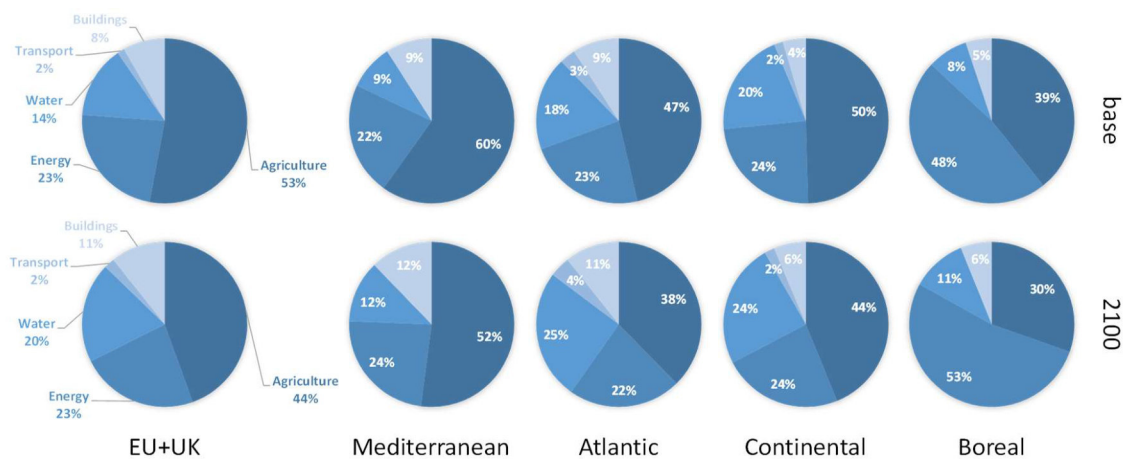


Figure 3. Sector shares in total drought damages under base (2015) and 2100 socioeconomic conditions for EU + UK and IPCC AR5 European sub-regions. Shares represent averages over different warming levels.

Direct 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 chains³⁶ but relative impacts for the transport sector as a whole are small. While structural damage to buildings is an undervalued aspect of drought³⁷, its impact is negligible compared to the total stock value of buildings.

Impacts with warming under future socioeconomic conditions

In addition to a scenario with static socioeconomic conditions, we also consider a scenario with socioeconomic dynamics based on the EU economic, budgetary, and demographic projections²⁵. For this scenario, overall absolute drought losses for EU+UK in 2100 grow to 25 [8-68] billion €/year at 1.5°C GWL and 31 [10-96] 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 [15-146] billion €/year (+400%) and to 65 [19-197] (+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 than nowadays. 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 decades³⁸. Continuous advances in drought-sensitive sectors, such as the development of stress-resistant crops to improve yield stability under water shortage conditions³⁹ or improved water use efficiency in power production⁴⁰, 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 complex⁴¹. There is a clear negative relation between wealth (GDP per capita) and drought vulnerability³⁸ and we estimate changes in vulnerability by applying this relation with the projected GDP per capita for each country²⁵. 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 now. 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 droughts⁴².

Discussion

Our damage estimates account for uncertainty in the impact modelling and climate uncertainty. We use an ensemble of climate projections from 11 GCM-RCM combinations²⁷, which may not fully capture total climate uncertainty and potentially undersample high impact events⁴³. Our estimates do not account for other potential sources of uncertainty, such as in the hydrological and water use model.

Intercomparison studies show that climate model related uncertainty generally outweighs uncertainty

from using multiple hydrological models^{44,45}, and that the sensitivity of global and regional hydrological models to climate variability is comparable in most basins under study⁴⁶.

Although that there is a large spread 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. Relatively few quantitative drought cost estimates are available for Europe and a comparison is hampered by differences in scale and sectors considered. An evaluation of drought damages at EU level⁴⁷ reported an average annual economic loss of around 6 billion € in the early 2000s, but not all EU countries were included in that appraisal, compared to our baseline estimate of 9 billion €. Average drought costs to the US economy during the last decade are estimated at 8 billion US\$/year with event damages that range between 2 to 43 billion US\$, depending on the area affected and the intensity of the drought⁴⁸. At country level in Europe, García-León et al.¹⁸ estimated economic agriculture losses in Italy of around 0.55 to 1.75 billion €/year, or 0.01-0.10% of the Italian GDP, which is in line with our estimates (Table S7). Martín-Ortega et al.⁴⁹ appraised total economic losses of the drought that affected the Spanish region of Catalonia during 2007 and 2008 at 1.6 billion €, which corresponds to 0.48% of the Catalanian GDP. As far as future projections are concerned, there are no studies that can serve as a reference for comparison of multi-sector direct economic costs in Europe. However, large-scale sectoral assessments show strong decreases in crop productivity in southern Europe⁵⁰ in the absence of adaptation, while increases in the length of growing seasons and water availability could improve the suitability for growing crops in northern Europe³. A north-south divide was also found for hydropower production^{51,52}, with an overall increase in hydropower potential in the north of Europe and strong declines in the south. At country level, Jenkins⁵³ estimated that drought losses in Spain could increase from around 0.65 billion US\$/year (2015 values) in 1955-2002 to between 1.8 and 3.1 billion US\$ in 2003-2050 and between 5.1 and 8.8 billion US\$ in 2051-2098, depending on the scenario. Our baseline estimate for Spain of 1.5 billion €/year for the period 1981-2010 is considerably higher, but exposure (i.e. economic value of drought sensitive sectors) has increased considerable since the 1950s, while the projected damages compare well with our future estimates for Spain (Table 1).

Our damage estimates are conditional on loss records of disaster risk databases, with the known difficulties in reporting them⁵⁴, but they are not comprehensive. Droughts can induce indirect effects within the entire socioeconomic system through market adjustments^{17,18} that are not captured in the loss records. Severe droughts impact vegetation productivity⁵⁵ and trigger tree mortality⁵⁶. The loss of

ecological, economic and social benefits of ecosystems, including carbon sequestration that is crucial for climate change mitigation⁵⁷, 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 wildfires⁵⁸. Increasing frequencies and intensities of uncorrelated climate hazards like floods in view of climate change^{29,30} could further increase the likelihood of consecutive climate extremes with overlapping and potentially amplified impacts while recovery is still under way⁵⁹.

Recently, some events in the US⁶⁰, Africa⁶¹, China⁶² and Australia⁶³ have shown that under persistent extreme weather conditions droughts can develop very rapidly and intensify at a high rate. While much focus of these flash droughts has been on rapid soil moisture decline and reduced crop yield, they can also result in the depletion of water storage, low river flows and associated consequences for water supply systems and hydropower production, though perhaps with some delays⁶⁴. Some short duration flash droughts resulting in soil moisture anomalies may not translate into extreme streamflow minima, but more severe flash droughts likely result in extreme low streamflow conditions and are therefore captured in our analysis. Multi-annual droughts, on the other hand, are implicitly accounted for in our analysis as a cumulative impact of consecutive drought years.

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 drought⁶⁵. 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.

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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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Competing interests

The authors declare no competing interests

Figures Legends

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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 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. 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 wealth³⁸.

The projections of socioeconomic development in Europe are based on the ECFIN 2015 Ageing Report²⁵. 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 platform⁶⁶. The sector composition of the economy and Gross Value Added (GVA) was modelled by GEM-E3 at country level⁶⁷, while energy demand was estimated with the POLES model⁶⁸ (see SI S1).

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.

We note that we treat each climate realisation separately throughout the whole modelling chain, from hydrological modelling and drought indicator analysis to the drought impact estimation. Hence we consider the whole spectrum of future drought conditions as projected by the ensemble of climate projections. Once we estimated annual economic losses over the period 1981-2100 for all climate realisations we calculated statistics (average and spread) for 30 year periods around each warming level over the ensemble of climate realisations that reach this warming level.

Drought hazard modelling

We used annual minimum river streamflow as an indicator of drought hazard^{11,69–72}. 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 model⁷³. 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 routing of surface runoff in the river network. The model also includes water use for industry, energy, domestic, livestock and irrigation water demand (see SI S2).

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 stations⁷⁴. 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 2100⁷⁵. The models and the year of passing the GWLs are presented in Table S1. Studies suggest that a sample of 11 RCM-GCM combinations for two RCP scenarios constitutes a sufficiently large sample to capture the main climate signals in Europe (see SI S3).

Drought hazard and impacts were calculated for all climate model runs and we report ensemble average estimates as well as the range defined by the minimum and maximum change scenarios within the climate ensemble. These should not be interpreted as probabilities^{76,77} but as indicative of the range of outputs from the set of EURO-CORDEX simulations used. For the drought loss estimates we also take into account the uncertainty in the fitting of the damage function by considering the 5 and 95% uncertainty bounds on the damage function (see Figure S4). Hence, the ranges for the drought losses include the full variability in the climate ensemble used and the 90% uncertainty on the damage function. Reporting the potential range of outcomes is informative for risk assessments.

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 information⁷⁸.

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 projections²⁵. 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 ($q_{\min}$) based on 7-day moving window average of the daily discharge data was used as drought indicator^{11,69} (see SI S4). In all river pixels considered we fitted a non-stationary Generalized Extreme Value (GEV) distribution through the annual minimum flows for the historical analysis and for the whole simulation period of 120 years (from 1981 to 2100). We applied the

Transformed Stationary (tsEva) approach developed by Mentaschi et al. (2016)⁷⁹. It transforms a non-stationary time series into a stationary one, to which the stationary EVA theory can be applied, and then reversely transforms the result into a non-stationary extreme value distribution. This has the advantage of increasing the size of the sample used for the EVA, implying smaller uncertainty in the estimation of return levels, especially for higher return periods. 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 $X \text{ m}^3/\text{s}$ 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.

Based on the European Drought Impact report Inventory (EDII) and literature (see SI S5) 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 companies³⁷. 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.¹⁴ 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.⁸⁰ 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) (see Figure S3) 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 values⁸¹ 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 of all types of infrastructure 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 (see SI S6). 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^{82,83}. We used spatially information (1x1 km) on clay content in soils from the European Soil Database⁸⁴ 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 affected⁸⁵. Following Corti et al.⁸⁶ we aggregated land cover classes of the refined European land cover map⁸⁷ 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 Layer⁸⁸ 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 drought⁸⁶, with total losses to the EU economy of that event estimated to be around 8.7 €billion¹⁵.

Future exposure

Exposure by the end of this century was obtained by scaling present sensitive exposure value of each sector according to the projected change in the size of the sector economy in 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 Munich Re's NatCatSERVICE (<https://natcatservice.munichre.com>) 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. The quantities recorded as overall losses in the NatCatSERVICE database include only direct losses, while indirect and consequential losses are not included. Most of the aggregate loss entries are based on official sources such as governments, statistical and financial authorities. In the absence of official reports, overall losses are estimated on the grounds of insurance claims or other relevant loss indicators. Where known insured loss figures are not available, the overall loss is estimated on the basis of other parameters. These include the affected region (urban or rural), population density, level of prosperity, damaged property, infrastructure and public services. For further information on the loss recording and estimation we refer to Kron et al⁸⁹.

It was assumed that the reported direct 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.²¹ 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 damage function was estimated as

$$\frac{D_{i,j}(\phi)}{\text{sensitive exposure}_j} = a \cdot \phi_{i,j}^b + \varepsilon \quad (1)$$

where D represents the expected damage scaled by the country's sensitivity exposure value as a function of the drought probability ϕ (or inverse return period) for a given event i and country j , while a and b are the damage function coefficients and ε is the random error component. The upper and lower boundaries for the fitted damage function (dotted lines in Figure S4) were estimated from the uncertainty related to the power law coefficients (a and b). The resulting damage function, including the 90% confidence interval from the fitting of the power law, is shown in Figure S4.

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^{54,90}. 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.

Impact modelling

Estimates of direct 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 km² in a country. This value is then plugged into the damage function (central estimate in Figure S4, 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*. For each climate realisation the country Expected Annual Damage (EAD) at the GWLs was then obtained by taking the average loss over the 30 years of estimated annual losses in the respective periods. 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. The uncertainty in the fitted damage function (dotted lines in Figure S4) 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 total uncertainty in our damage estimates thus reflects the variability in future climate at the warming levels as defined by the climate ensemble and the uncertainty in the relation between damages and drought hazard.

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.

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Increased economic drought impacts in Europe with anthropogenic warming

Supplementary information

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S1. Modelling sector composition of the economy with GEM-E3

GEM-E3 is a macroeconomic, multi-country and multi-sectorial computable general equilibrium model. This study used GEM-E3 country-level projections regarding the sector composition of the economy and Gross Value Added (GVA) consistent with the macro projections of the 2015 Ageing Report to compute the dynamic drought damages¹. The GEM-E3 model was not used to compute the overall drought damages in a general equilibrium setting, as done for example by Dottori et al.² for river flood losses using the Climate Assessment General Equilibrium (CAGE) version of GEM-E3. Rather, GEM-E3 model was run without an external shock and uses projections of the social account matrixes of each country, including sectoral input-output tables, that were derived with the PIRAMID methodology (PIRAMID stands for Platform to Integrate, Reconcile and Align Model-based Input-output Data), which integrates data from external models and databases³.

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 projections⁴, and they were explicitly considered in the computation of the economic growth figures (more details can be found in Bisselink et al.⁵).

S2. LISFLOOD modelling framework

LISFLOOD is a spatially distributed hydrological model that simulates all the main hydrological processes occurring in the land-atmosphere system⁶. The surface runoff generated in each cell is channelled to the nearest river network cell by means of a routing component based on a four-point implicit finite-difference solution of the kinematic wave. 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.

Water use for industry, energy, domestic, livestock and irrigation water demand 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 AQUASTAT⁷ 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 literature⁸. Water demand for the household sector is simulated based on water use per capita and high-resolution population density⁹. 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 2000-2013¹⁰. 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 map¹¹. 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 Bisselink et al.⁵.

Several studies have used the LISFLOOD model to assess streamflow droughts across Europe in present¹² and future climate^{13,14}. For the present assessment, Figure S2 compares streamflow minima for different return periods derived from a hindcast simulation and long records (26 years) of streamflow observations at 437 gauging stations across Europe. The validation shows a satisfactory performance with Nash-Sutcliffe efficiency (NSE) equal to 0.99 (Nash-Sutcliffe Efficiency equals 1 for a perfect model) and percent biases below 7%.

S3. Climate uncertainty

The climate projections used herein cannot be considered independent projections of future climate. Especially in a GCM-RCM matrix where the same GCM has been downscaled by more than one RCM, or the same RCM has been used to downscale multiple GCMs. However, this is true for every ensemble. Different model development teams share code, and even if the code is rewritten from scratch, the underlying algorithms and methods are often linked¹⁵. Furthermore, many concepts and fundamental theories are common across models. Annan and Hargreaves¹⁶ discuss in length the

meaning of independence in climate science. They state that the strong assumption of independence is not required in order to make use of them, and that a more plausible assumption might be to interpret the ensemble as merely constituting independent samples of a distribution which represents our collective understanding of the climate system. For instance, Dosio et al.¹⁷ show that given a GCM-RCM ensemble, subsampling according to the RCM or GCM hardly makes a difference on the climate change signal. They conclude that a sub-selection of model results based on either GCM or RCM does not reduce the uncertainty significantly, nor change the overall message. These studies suggest that a sample of 11 RCM-GCM combinations for two RCP scenarios constitutes a sufficiently large sample to capture the main climate signals in Europe. Moreover, there is a number of papers that already analysed the climate change signal with the same ensemble used here^{18,19}.

There is still large uncertainty in global warming-induced circulation pattern changes²⁰. In our analysis we do not derive drought diagnostics from climate models directly, but we use simulated fields of temperature, precipitation, radiation, wind speed etc. from Regional Climate Models (EURO-CORDEX) to force a hydrological model. Daily streamflow simulations of the latter are used to derive drought diagnostics. Our drought diagnostics thus reflect the direct effects of temperature rise on evaporative demand and atmosphere moisture content, as well as potential changes in circulation patterns as projected by the GCM-RCM models. Uncertainty in the representation of circulation patterns and changes therein with global warming are represented in our framework as part of the climate model uncertainties.

S4. Drought indicator

We applied a 7-day averaging of the daily river flows to cancel day-to-day fluctuations in river flow, which are often arbitrary or artificial in low-flow periods²¹. 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 note that it is only in the selection of the annual minima that winter low flows are not considered but that the hydrological modelling is done for every day of the year. This implies that our analysis considers precipitation in winter that replenishes subsurface storage (soils and aquifers) and is released to streams slowly. The hydrologic modelling further considers storage in reservoirs over winter (wet periods) and release in summer (dry periods). Studies show that in Europe in regions with no considerable storage of water as snow during cold periods, the lowest river discharges are typically in summer^{13,22}, when demand for water is highest and most drought impacts are reported²³. We analysed $q_{\min}$ for all river cells with at least 1,000 km² 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.

S5. Sensitivity to drought

The European Drought Impact report Inventory (EDII) provides a unique research database that has collected close to 5,000 impact reports from 33 European countries²³. 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,²⁴ 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^{24,25}. 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 sensitivity²⁵. 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.²³, 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.

S6. Total construction gap filling

Information on Total Construction (TC) was not available for Bulgaria, Croatia, Ireland and the UK. For Ireland and the UK, TC was derived based on TFA, which was available for all 28 countries except for Bulgaria and Croatia. TC for Ireland and the UK was approximated by scaling its TFA with the average

share of TC in TFA for all countries with TC and TFA available (24 out of 28 countries). The share of TC in TFA ranges between 74-91%, with an average of 81%. For Bulgaria TC was derived from TCF, available in all countries but Croatia, based on the EU average ratio of TCF to TC (average 4%, range between 3 and 8%). In Croatia, TCF was first approximated based on TFAF using the EU average ratio between TCF and TFAF (average of 51% with range between 42% and 59%), and then converted to TC as for Bulgaria.

S7. Additional Figures and Tables

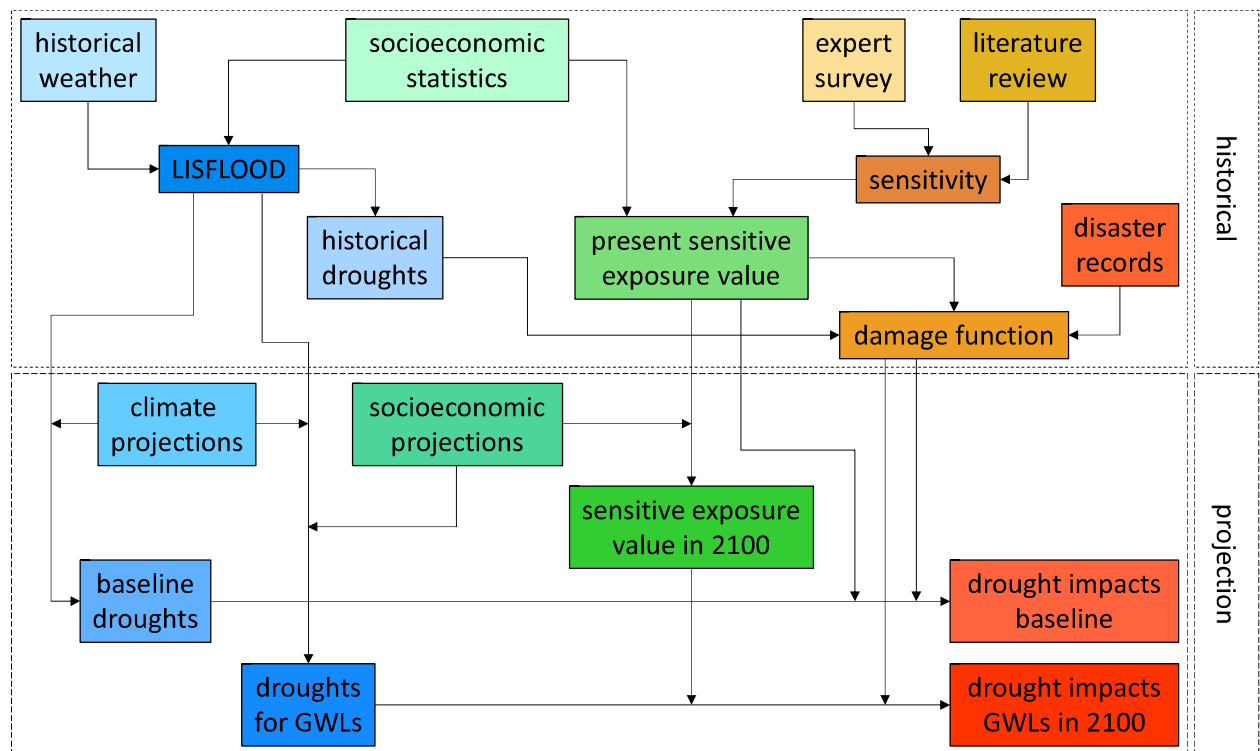


Figure S1. Schematic overview of the methodological approach. Components of hazard, exposure, and vulnerability are displayed in shades of blue, green, and brown, respectively, while impacts are shaded in red. The flow diagram refers to a scenario with static vulnerability.

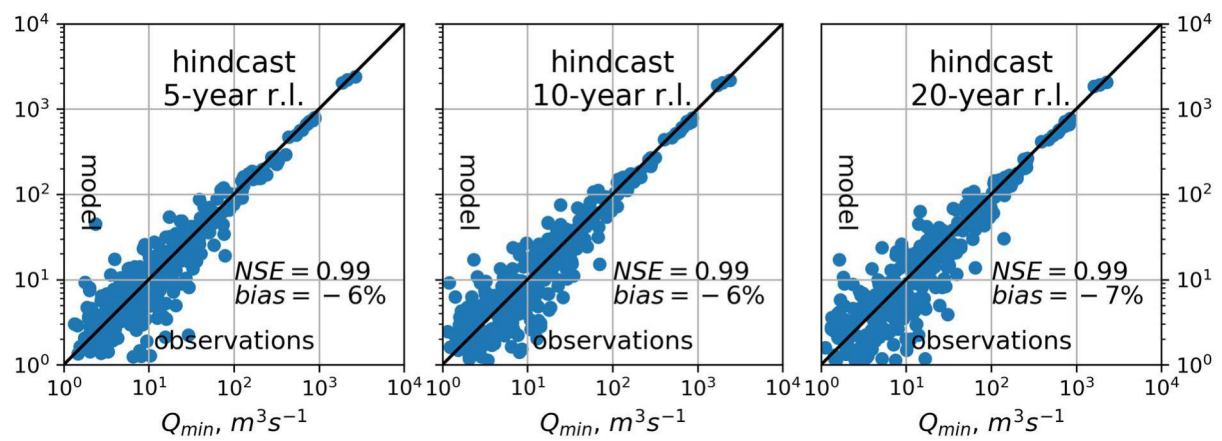


Figure S2. Observed versus simulated return levels for the annual minima of 7-day average flow during the control period (1990–2015) at each of the 437 stations distributed across the continent.

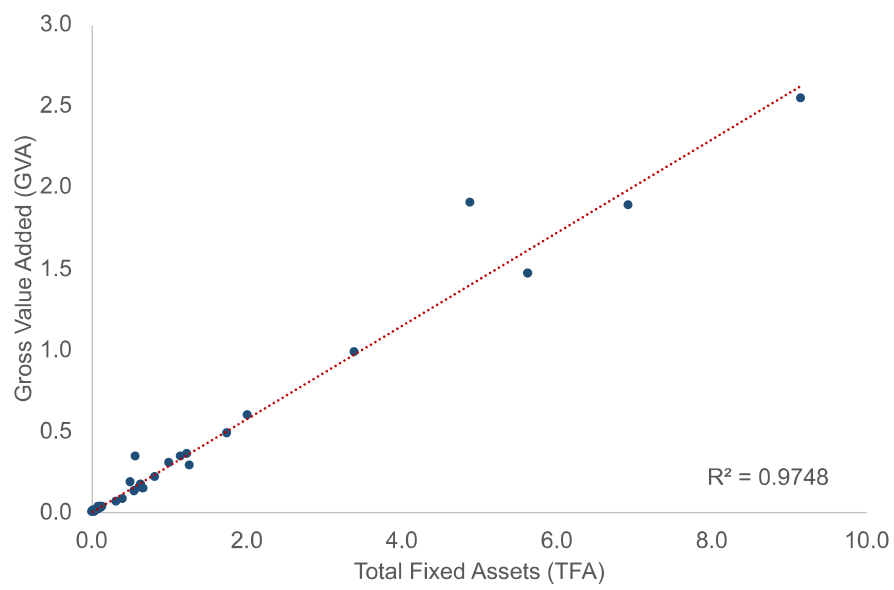


Figure S3. Correlation between country Total Fixed Assets (TFA) in current replacement costs and Gross Value Added (GVA) in current prices, both expressed as trillion euro.

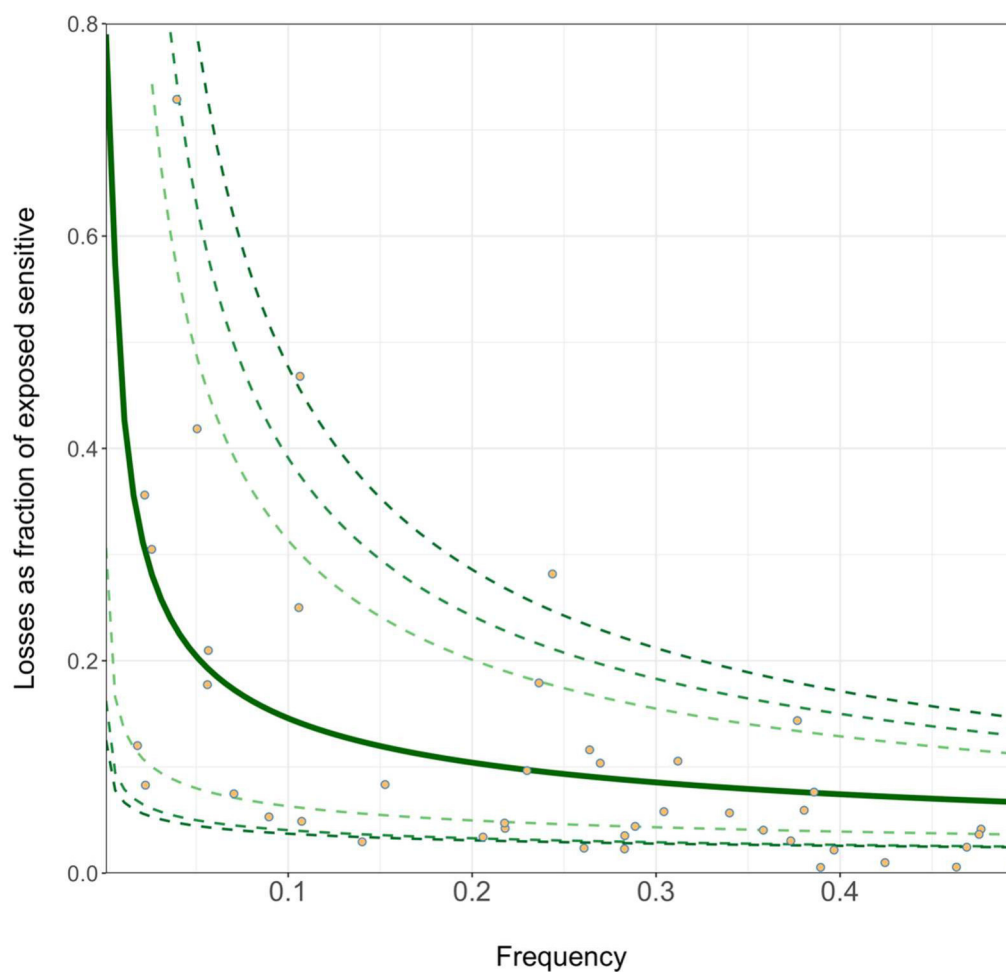


Figure S4. Drought damage function depicting the relationship between country median drought frequency and loss as a fraction of the exposed value of sensitive sectors. Dotted lines represent the uncertainty in the fitted model, expressed by the 90%, 95% and 97.5% confidence interval.

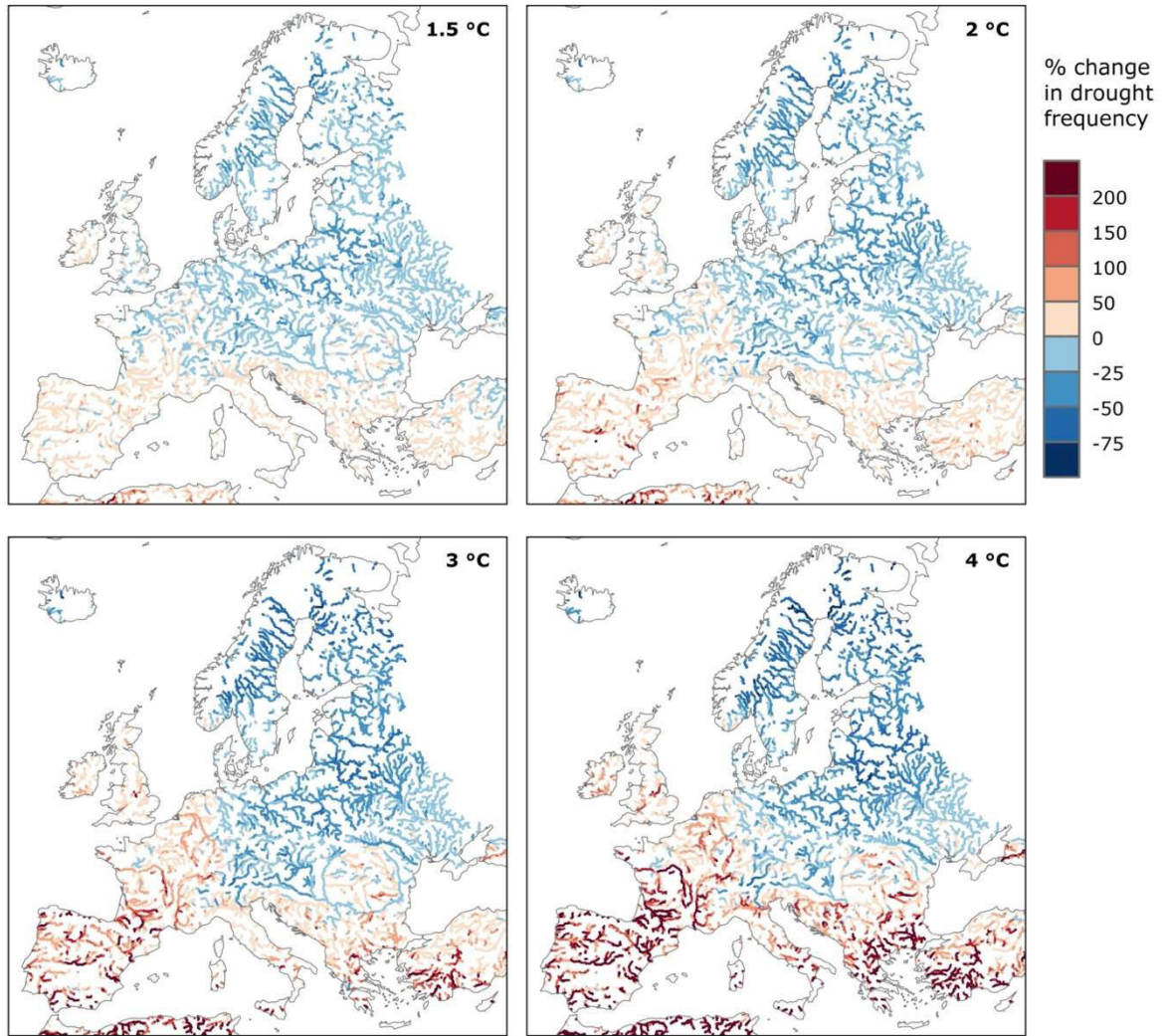


Figure S5. Ensemble average relative change in streamflow drought frequency compared to baseline for 1.5, 2, 3 and 4°C GWL. Grey indicates river cells where changes are less than 10%.

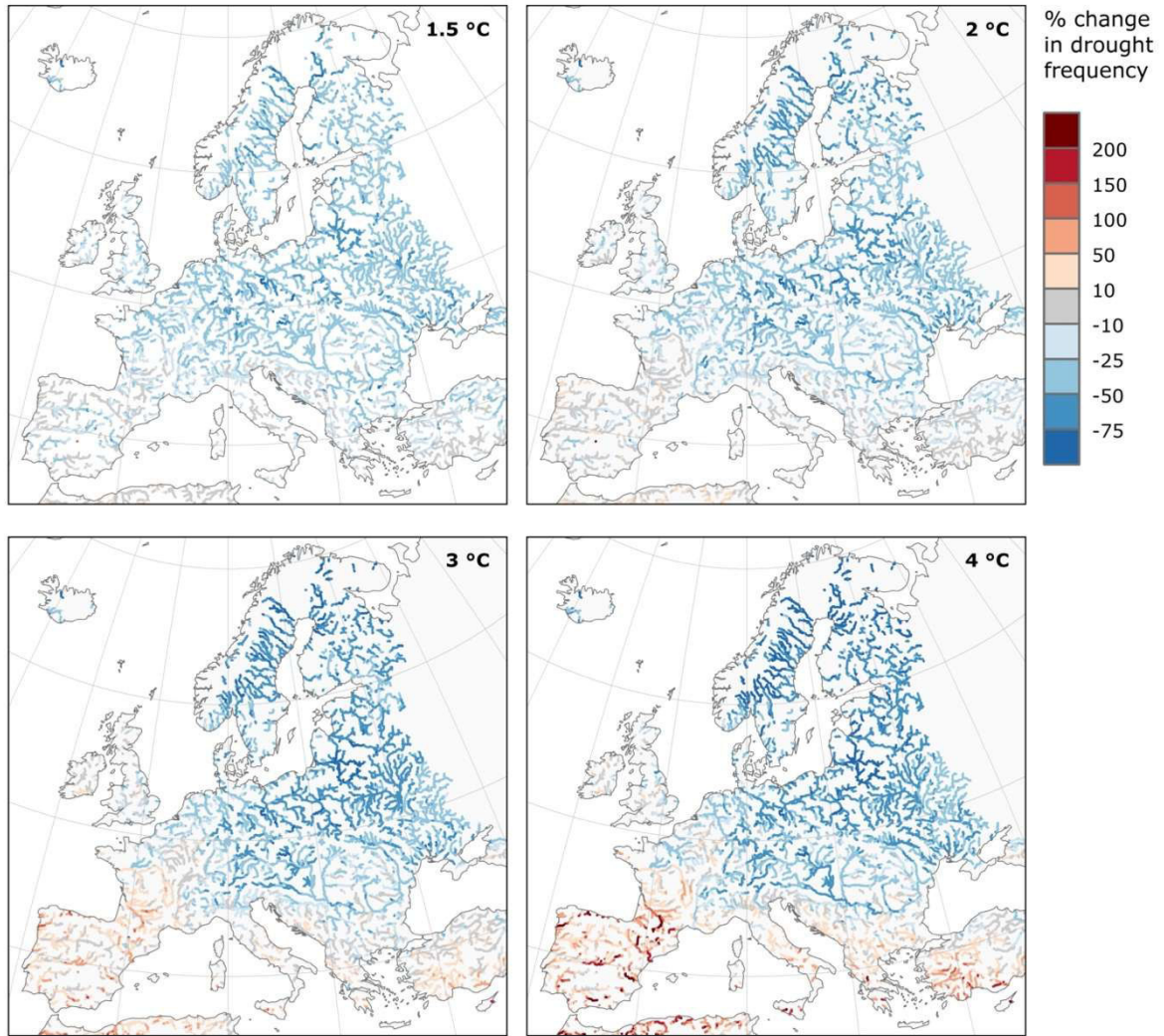


Figure S6. Minimum relative change scenario in streamflow drought frequency compared to baseline for 1.5, 2, 3 and 4°C GWL. Shown in each river cell is the largest decrease in drought frequency projected by any model in the ensemble, or if no models project a decrease at that GWL, it is the smallest projected increase. Grey indicates river cells where changes are less than 10%.

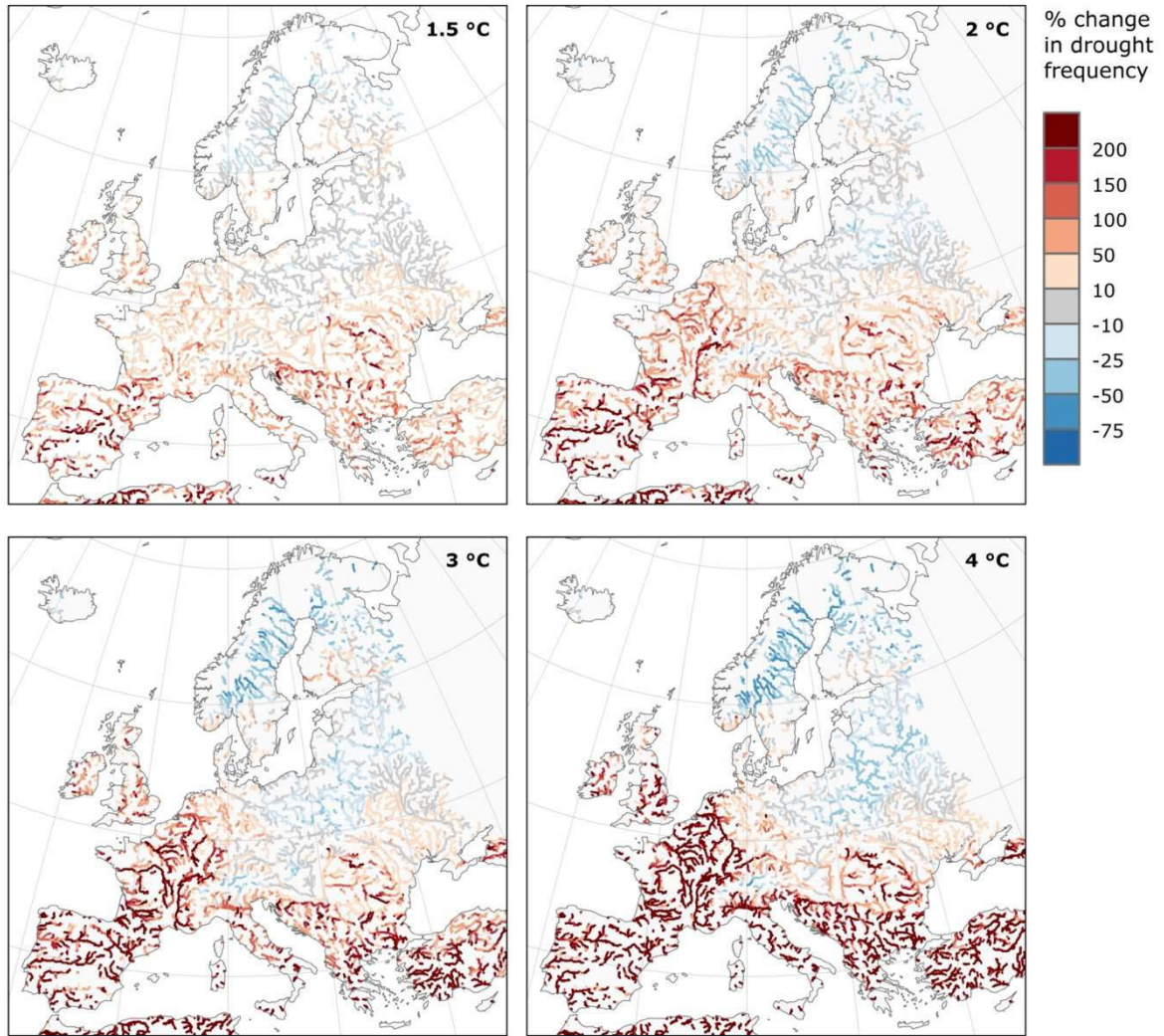


Figure S7. Maximum relative change scenario in streamflow drought frequency compared to baseline for 1.5, 2, 3 and 4°C GWL. Shown in each river cell is the largest increase in drought frequency projected by any model in the ensemble, or if no models project an increase at that GWL, it is the smallest projected decrease. Grey indicates river cells where changes are less than 10%.

RCM (R)	Driving GCM (G)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
		1.5 °C		2 °C		3 °C		4 °C	
CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044	-	2067	-	2089
	ICHEC-EC-EARTH	2033	2026	2056	2041	-	2066	-	2090
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044	-	2067	-	2089
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043	-	2065	-	2086
WRF331F	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035	-	2054	-	2073
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042	-	2065	-	2087
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044	-	2067	-	2089
	ICHEC-EC-EARTH	2033	2026	2056	2041	-	2066	-	2090
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035	-	2054	-	2073
	MOHC-HadGEM2-ES	2021	2018	2037	2030	2069	2051	-	2071
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044	-	2067	-	2089

Table S1. Regional climate projections used in the drought hazard analysis and corresponding years of exceeding 1.5, 2, 3 and 4°C global warming. There are some climate projections that reach 4°C a few years after 2085. 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.

Sector	Responses per sensitivity class				Sensitivity
Environment	No	Low	Medium	High	
Promotion of biodiversity and nature protection (including Natura 2000)	1	9	16	21	high
Promotion of natural assets (for tourism)	1	8	18	16	medium
Protection and development of natural heritage (for tourism)	1	9	18	15	medium
Industries					
Management of household and industrial waste	7	29	8	3	low
Management and distribution of drink water	1	6	6	34	high
Water treatment (waste water)	3	14	23	6	medium
Refineries	9	12	10	6	low
Production and processing of metals	10	12	10	5	low
Chemical industry	10	11	9	7	low
Mineral industry	6	13	11	6	low
Buildings					
Infrastructure (education, health, childcare, housing)	4	14	15	4	medium
Transport					
Railways	32	12	4	1	no
Roads (motorways, national, regional and local)	29	15	4	1	no
Airports	30	18	1	0	no
Ports	18	19	9	3	no
Inland waterways	4	7	13	25	high
Energy					
Nuclear and thermal (coal, gas, oil) power plants	4	9	16	14	medium
Electricity transmission/distribution	23	18	3	0	no
Gas & oil pipelines	28	15	1	0	no
Renewable energy: wind	31	9	3	0	no
Renewable energy: solar	26	12	2	2	no
Renewable energy: biomass	5	9	6	23	high
Renewable energy: hydroelectric	2	1	7	34	high

Table S2. Summary of sensitivity survey among experts: number of responses per class (no, low, medium, and high), followed by assigned sensitivity. From Forzieri et al. (2015).

Sector	Description
Agriculture (crops and livestock)	Droughts adversely affect rainfed and irrigated crops, and can result in reduced productivity of livestock farming. Industries linked with farming activities may lose business when drought damages crops or livestock.
Public water supply	Drought conditions decrease supply and increase demand for various usages (e.g., domestic/municipal use).
Power generation (hydropower, biofuel, thermal and nuclear)	Lower hydropower potential due to reduced water volumes. Reduced availability of cooling water can decrease power generation and even cause the shutdown of thermal or nuclear power plants. Droughts induce feedstock loss for biofuel.
Transport (commercial shipping)	During low-flow conditions, barges and ships may have difficulty in navigating streams, rivers, and canals, affecting businesses that depend on water transportation for receiving or delivering goods and materials.
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. The effects of drought could be aggravated due to aquifer over-exploitation.

Table S3. Sectors sensitive to droughts in Europe and covered in this assessment. Description of main channels through which impacts are transmitted.

Country	agriculture	energy	water supply	transport	subsidence	total
Austria	3,092	4,515	2,272	79	249	10,206
Belgium	2,175	1,722	1,612	986	91	6,586
Bulgaria	1,388	393	151	13	147	2,092
Croatia	1,102	344	140	6	130	1,722
Cyprus	292	67	25	0	31	415
Czechia	2,642	1,698	928	3	111	5,382
Denmark	2,622	792	884	0	9	4,306
Estonia	438	62	58	0	1	560
Finland	3,351	2,878	651	1	640	7,521
France	23,646	12,844	5,827	504	5,185	48,007
Germany	16,527	13,622	16,858	1,555	2,703	51,266
Greece	4,518	1,080	356	0	612	6,566
Hungary	2,749	416	555	22	324	4,067
Ireland	1,606	1,352	1,427	0	33	4,419
Italy	24,741	12,896	3,704	9	4,589	45,938
Latvia	596	217	64	0	0	877
Lithuania	867	134	147	0	0	1,149
Luxembourg	99	109	79	47	85	419
Malta	88	0	20	0	10	118
Netherlands	8,731	1,252	1,177	1,519	919	13,599
Poland	7,590	2,964	2,016	13	10	12,593
Portugal	2,704	1,606	495	0	230	5,034
Romania	5,433	1,414	692	154	390	8,083
Slovakia	1,851	904	236	53	220	3,265
Slovenia	528	739	163	0	134	1,564
Spain	19,639	5,511	3,197	0	2,873	31,220
Sweden	3,757	13,756	1,258	0	987	19,759
UK	9,823	4,183	8,035	21	2,891	24,953
EU + UK	152,595	87,472	53,030	4,986	23,605	321,688

Table S4. Present sensitive economic value exposed in million € (2015 values) per sector and total for each country.

Country	agriculture	energy	water supply	transport	subsidence	total
Austria	7,169	11,950	7945	297	754	28,117
Belgium	5,253	5,908	6877	4,413	290	22,742
Bulgaria	2,512	872	433	43	533	4,393
Croatia	2,250	619	409	18	426	3,722
Cyprus	696	205	119	0	119	1,139
Czechia	6,298	4,705	3793	13	431	15,241
Denmark	6,565	2,441	4085	0	35	13,126
Estonia	848	140	186	0	5	1,179
Finland	7,254	8,568	2375	4	2,053	20,255
France	57,116	33,102	23,852	2,061	18,695	134,826
Germany	32,090	31,532	43,267	3,486	7,561	117,937
Greece	7,120	1,732	800	0	1,670	11,322
Hungary	6,357	938	1,766	70	1,098	10,228
Ireland	5,670	5,823	6,805	0	135	18,433
Italy	55,869	35,270	11,765	27	13,065	115,996
Latvia	1,484	474	220	0	0	2,177
Lithuania	1,618	330	464	1	0	2,413
Luxembourg	298	346	506	279	276	1,705
Malta	188	0	76	0	35	298
Netherlands	19,887	3,151	3,903	4,819	2,934	34,693
Poland	14,310	7,041	5,963	40	32	27,385
Portugal	4,058	3,812	1,172	0	645	9,687
Romania	11,826	3,229	2,319	549	1,460	19,382
Slovakia	4,348	2,441	830	169	860	8,647
Slovenia	1,156	1,739	546	0	446	3,887
Spain	39,597	13,249	10,620	0	9,716	73,182
Sweden	11,925	53,977	7,027	0	4,222	77,151
UK	24,790	13,313	36,278	93	10,754	85,228
EU + UK	338,550	246,905	184,404	16,382	78,252	864,494

Table S5. End of the century sensitive economic value exposed in million € (2015 values) per sector and total for each country.

Country	Base economy					Economy 2100 static vulnerability			
	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
Austria	[80-728]	[39-455]	[25-515]	[21-165]	[36-304]	[107-1,254]	[69-1,420]	[58-454]	[98-837]
Belgium	[48-917]	[55-1,042]	[81-1,875]	[131-3,068]	[154-7,031]	[190-3,599]	[278-6,474]	[451-10,595]	[531-24,278]
Bulgaria	[35-209]	[35-339]	[44-378]	[55-627]	[93-1,305]	[74-711]	[92-794]	[115-1,317]	[195-2,740]
Croatia	[14-332]	[14-316]	[15-266]	[16-196]	[29-517]	[31-682]	[31-575]	[34-423]	[62-1,117]
Cyprus	[9-148]	[12-230]	[16-338]	[34-788]	[41-1,062]	[32-630]	[43-928]	[93-2,164]	[113-2,915]
Czechia	[51-489]	[27-372]	[18-352]	[29-276]	[30-239]	[77-1,052]	[52-997]	[82-782]	[85-675]
Denmark	[28-471]	[19-578]	[19-393]	[18-839]	[10-247]	[58-1,763]	[57-1,198]	[54-2,559]	[29-754]
Estonia	[5-42]	[2-17]	[1-12]	[1-10]	[0-3]	[5-36]	[3-25]	[2-21]	[1-6]
Finland	[24-151]	[4-62]	[1-31]	[1-52]	[0-29]	[12-166]	[4-84]	[3-139]	[0-77]
France	[331-4,608]	[246-3,049]	[435-7,521]	[775-13,582]	[962-19,719]	[692-8,562]	[1,222-21,123]	[2,177-38,144]	[2,703-42,297]
Germany	[329-3,357]	[129-2,697]	[110-2,545]	[218-2,490]	[243-2,324]	[297-6,203]	[254-5,856]	[501-5,728]	[559-5,346]
Greece	[130-771]	[168-1,589]	[193-2,148]	[274-3,045]	[400-8,622]	[290-2,740]	[332-3,704]	[472-5,251]	[690-14,866]
Hungary	[56-471]	[45-369]	[39-327]	[41-316]	[57-415]	[112-928]	[98-823]	[103-794]	[144-1,044]
Ireland	[31-354]	[33-780]	[42-1,377]	[99-3,047]	[92-2,521]	[139-3,253]	[177-5,746]	[415-12,709]	[382-10,517]
Italy	[546-3,304]	[563-3,886]	[652-4,086]	[776-5,295]	[1,222-9,224]	[1,421-9,813]	[1,645-10,318]	[1,960-13,370]	[3,087-23,290]
Latvia	[6-47]	[2-20]	[1-8]	[1-8]	[0-3]	[6-50]	[2-21]	[2-20]	[0-7]
Lithuania	[9-89]	[3-25]	[1-8]	[0-2]	[0-2]	[6-53]	[2-16]	[0-5]	[0-4]
Luxembourg	[0-142]	[0-24]	[0-159]	[1-167]	[3-368]	[0-96]	[0-645]	[5-681]	[10-1,498]
Malta	[5-27]	[7-31]	[8-34]	[9-40]	[15-113]	[18-76]	[19-80]	[23-101]	[37-279]
Netherlands	[79-833]	[80-898]	[132-2,033]	[200-2,577]	[253-3,176]	[205-2,291]	[336-5,186]	[510-6,575]	[645-8,102]
Poland	[128-802]	[62-461]	[36-333]	[25-184]	[15-110]	[134-1,003]	[78-725]	[55-400]	[32-238]
Portugal	[104-540]	[137-1,322]	[160-1,738]	[222-1,479]	[272-3,343]	[263-2,545]	[309-3,345]	[427-2,846]	[523-6,433]
Romania	[149-913]	[133-1,119]	[153-1,164]	[187-2,256]	[221-2,700]	[318-2,683]	[366-2,791]	[448-5,411]	[531-6,474]
Slovakia	[26-240]	[16-230]	[14-200]	[12-226]	[17-127]	[43-610]	[36-530]	[33-598]	[46-337]
Slovenia	[3-244]	[3-520]	[3-283]	[3-346]	[14-832]	[7-1,292]	[7-705]	[8-859]	[34-2,067]
Spain	[569-3,487]	[801-5,546]	[1,053-6,950]	[1,563-9,624]	[2,025-13,186]	[1,877-13,001]	[2,469-16,292]	[3,664-22,559]	[4,746-30,908]
Sweden	[60-357]	[8-70]	[0-19]	[0-38]	[3-75]	[31-273]	[0-74]	[0-147]	[13-292]
United Kingdom	[234-1,737]	[205-1,744]	[257-2,101]	[469-3,516]	[508-4,291]	[700-5,958]	[877-7,177]	[1,602-12,010]	[1,736-14,656]
Mediterranean	[1,440-8,607]	[1,784-13,335]	[2,184-15,307]	[3,024-20,032]	[4,222-36,384]	[4,106-30,578]	[5,044-34,696]	[6,980-45,770]	[9,758-80,700]
Atlantic	[766-8,514]	[679-7,436]	[1,025-14,896]	[1,808-25,873]	[2,188-34,830]	[2,109-23,465]	[3,176-45,789]	[5,662-80,379]	[6,828-96,363]
Continental	[912-7,274]	[562-6,496]	[507-6,900]	[706-8,092]	[822-8,486]	[1,365-15,990]	[1,222-16,823]	[1,712-19,730]	[1,963-20,196]
Boreal	[112-660]	[24-237]	[9-93]	[4-110]	[13-111]	[70-707]	[26-263]	[9-332]	[39-386]
EU+UK	[3,416-24,517]	[3,305-26,684]	[3,997-36,668]	[5,740-53,985]	[7,412-79,754]	[8,511-68,579]	[10,229-96,270]	[14,783-145,914]	[18,850-197,530]

Table S6. Range between minimum and maximum estimates of Expected Annual Damage (EAD) for the baseline and different scenarios. The range represents variability in climate projections in the ensemble and the uncertainty of the damage function. Corresponding average estimates are tabulated in Table 1.

Country	Base economy					Economy 2100 static vulnerability				Economy 2100 dynamic vulnerability			
	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	0.08	0.06	0.05	0.03	0.05	0.04	0.04	0.02	0.04	0.02	0.02	0.01	0.02
Belgium	0.06	0.07	0.11	0.18	0.33	0.06	0.09	0.14	0.27	0.03	0.05	0.08	0.14
Bulgaria	0.24	0.32	0.36	0.47	0.88	0.23	0.26	0.35	0.65	0.10	0.11	0.15	0.28
Croatia	0.16	0.19	0.17	0.15	0.30	0.14	0.13	0.11	0.22	0.06	0.06	0.05	0.10
Cyprus	0.23	0.34	0.48	1.00	1.32	0.20	0.27	0.58	0.76	0.09	0.13	0.27	0.35
Czechia	0.11	0.08	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02
Denmark	0.05	0.06	0.04	0.06	0.03	0.04	0.03	0.04	0.02	0.02	0.01	0.02	0.01
Estonia	0.09	0.05	0.03	0.03	0.01	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00
Finland	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00
France	0.06	0.05	0.11	0.18	0.31	0.04	0.07	0.13	0.21	0.02	0.04	0.06	0.11
Germany	0.04	0.03	0.03	0.04	0.04	0.02	0.03	0.03	0.03	0.01	0.01	0.02	0.02
Greece	0.16	0.25	0.32	0.44	0.92	0.20	0.24	0.34	0.70	0.09	0.12	0.16	0.34
Hungary	0.16	0.14	0.13	0.12	0.17	0.11	0.10	0.10	0.13	0.05	0.05	0.05	0.06
Ireland	0.07	0.12	0.17	0.34	0.30	0.10	0.15	0.30	0.26	0.05	0.07	0.15	0.13
Italy	0.09	0.11	0.11	0.14	0.23	0.08	0.09	0.11	0.18	0.04	0.05	0.06	0.09
Latvia	0.09	0.05	0.02	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Lithuania	0.10	0.04	0.01	0.00	0.00	0.03	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Luxembourg	0.05	0.01	0.05	0.06	0.12	0.01	0.03	0.04	0.08	0.00	0.02	0.02	0.05
Malta	0.19	0.22	0.23	0.29	0.48	0.15	0.16	0.20	0.33	0.07	0.08	0.09	0.16
Netherlands	0.04	0.05	0.09	0.12	0.16	0.04	0.07	0.10	0.13	0.02	0.03	0.05	0.06
Poland	0.09	0.05	0.04	0.02	0.01	0.03	0.03	0.02	0.01	0.02	0.01	0.01	0.00
Portugal	0.15	0.25	0.30	0.33	0.53	0.20	0.24	0.27	0.43	0.10	0.12	0.13	0.21
Romania	0.30	0.32	0.34	0.48	0.57	0.23	0.25	0.34	0.41	0.10	0.11	0.15	0.18
Slovakia	0.12	0.12	0.11	0.10	0.08	0.09	0.08	0.07	0.06	0.04	0.03	0.03	0.03
Slovenia	0.13	0.26	0.15	0.17	0.39	0.19	0.11	0.12	0.29	0.09	0.05	0.06	0.14
Spain	0.14	0.21	0.27	0.38	0.51	0.15	0.19	0.27	0.36	0.07	0.09	0.13	0.17
Sweden	0.04	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
United Kingdom	0.04	0.04	0.05	0.07	0.09	0.03	0.03	0.06	0.06	0.01	0.02	0.03	0.03
Mediterranean	0.12	0.16	0.19	0.26	0.40	0.12	0.14	0.19	0.29	0.06	0.07	0.09	0.14
Atlantic	0.05	0.05	0.08	0.14	0.21	0.04	0.06	0.10	0.15	0.02	0.03	0.05	0.08
Continental	0.06	0.05	0.05	0.06	0.07	0.04	0.04	0.05	0.05	0.02	0.02	0.02	0.03
Boreal	0.05	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00
EU+UK	0.07	0.08	0.10	0.14	0.20	0.06	0.07	0.10	0.15	0.03	0.03	0.05	0.07

Table S7. Expected Annual Damage (EAD) as % of GDP for the baseline and different scenarios.

Average estimates over climate ensemble, ranges between minimum and maximum estimates are tabulated in Table S8.

Country	Base economy					Economy 2100 static vulnerability			
	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
Austria	[0.03-0.21]	[0.02-0.13]	[0.02-0.18]	[0.01-0.06]	[0.02-0.10]	[0.02-0.10]	[0.01-0.14]	[0.01-0.04]	[0.02-0.08]
Belgium	[0.02-0.21]	[0.02-0.24]	[0.03-0.43]	[0.05-0.69]	[0.08-1.60]	[0.02-0.19]	[0.03-0.34]	[0.04-0.56]	[0.06-1.30]
Bulgaria	[0.10-0.52]	[0.13-0.78]	[0.14-0.89]	[0.18-1.42]	[0.29-2.93]	[0.09-0.57]	[0.11-0.65]	[0.13-1.04]	[0.21-2.15]
Croatia	[0.05-0.63]	[0.06-0.60]	[0.06-0.50]	[0.06-0.37]	[0.10-0.98]	[0.05-0.44]	[0.05-0.37]	[0.04-0.27]	[0.07-0.72]
Cyprus	[0.07-0.73]	[0.11-1.14]	[0.14-1.68]	[0.27-3.39]	[0.34-5.33]	[0.06-0.65]	[0.08-0.97]	[0.15-2.26]	[0.19-3.07]
Czechia	[0.04-0.27]	[0.03-0.20]	[0.03-0.19]	[0.03-0.18]	[0.03-0.16]	[0.02-0.14]	[0.02-0.13]	[0.02-0.12]	[0.02-0.11]
Denmark	[0.02-0.16]	[0.01-0.24]	[0.01-0.16]	[0.02-0.29]	[0.01-0.10]	[0.01-0.16]	[0.01-0.11]	[0.01-0.19]	[0.01-0.07]
Estonia	[0.04-0.22]	[0.02-0.11]	[0.01-0.06]	[0.01-0.06]	[0.00-0.02]	[0.01-0.07]	[0.01-0.04]	[0.01-0.04]	[0.00-0.01]
Finland	[0.02-0.07]	[0.01-0.03]	[0.00-0.02]	[0.01-0.03]	[0.00-0.02]	[0.01-0.03]	[0.00-0.01]	[0.01-0.02]	[0.00-0.01]
France	[0.02-0.19]	[0.02-0.13]	[0.04-0.32]	[0.06-0.57]	[0.09-0.85]	[0.01-0.09]	[0.03-0.22]	[0.04-0.39]	[0.06-0.67]
Germany	[0.02-0.18]	[0.01-0.13]	[0.01-0.10]	[0.01-0.10]	[0.01-0.09]	[0.01-0.08]	[0.01-0.09]	[0.01-0.09]	[0.01-0.08]
Greece	[0.07-0.34]	[0.10-0.66]	[0.12-0.88]	[0.16-1.25]	[0.27-3.49]	[0.08-0.51]	[0.09-0.68]	[0.12-0.96]	[0.20-2.68]
Hungary	[0.07-0.41]	[0.06-0.31]	[0.06-0.28]	[0.05-0.27]	[0.07-0.36]	[0.05-0.25]	[0.04-0.22]	[0.04-0.21]	[0.06-0.28]
Ireland	[0.03-0.17]	[0.04-0.38]	[0.05-0.68]	[0.09-1.51]	[0.09-1.25]	[0.04-0.34]	[0.04-0.59]	[0.08-1.32]	[0.08-1.09]
Italy	[0.04-0.19]	[0.05-0.22]	[0.05-0.23]	[0.06-0.30]	[0.10-0.51]	0.18][0.04-	[0.04-0.19]	[0.05-0.24]	[0.08-0.41]
Latvia	[0.04-0.20]	[0.02-0.10]	[0.01-0.04]	[0.01-0.04]	[0.00-0.01]	[0.01-0.07]	[0.01-0.03]	[0.01-0.03]	[0.00-0.01]
Lithuania	[0.04-0.25]	[0.02-0.08]	[0.01-0.02]	[0.00-0.01]	[0.00-0.01]	[0.01-0.05]	[0.00-0.02]	[0.00-0.01]	[0.00-0.00]
Luxembourg	[0.01-0.34]	[0.01-0.06]	[0.01-0.38]	[0.01-0.41]	[0.02-0.89]	[0.00-0.04]	[0.00-0.24]	[0.01-0.26]	[0.01-0.57]
Malta	[0.09-0.38]	[0.10-0.44]	[0.11-0.46]	[0.14-0.58]	[0.20-0.95]	[0.07-0.29]	[0.07-0.31]	[0.09-0.39]	[0.13-0.63]
Netherlands	[0.02-0.12]	[0.02-0.13]	[0.03-0.28]	[0.04-0.36]	[0.06-0.45]	[0.01-0.10]	[0.02-0.22]	[0.03-0.28]	[0.04-0.34]
Poland	[0.04-0.19]	[0.02-0.10]	[0.02-0.07]	[0.01-0.05]	[0.01-0.03]	[0.02-0.07]	[0.01-0.05]	[0.01-0.04]	[0.00-0.02]
Portugal	[0.07-0.29]	[0.10-0.67]	[0.12-0.88]	[0.14-0.77]	[0.19-1.71]	[0.08-0.54]	[0.09-0.71]	[0.11-0.62]	[0.15-1.38]
Romania	[0.13-0.63]	[0.14-0.72]	[0.15-0.76]	[0.18-1.44]	[0.21-1.70]	[0.10-0.52]	[0.10-0.55]	[0.13-1.03]	[0.15-1.22]
Slovakia	[0.05-0.29]	[0.04-0.33]	[0.04-0.29]	[0.03-0.32]	[0.03-0.18]	[0.03-0.25]	[0.03-0.22]	[0.02-0.25]	[0.03-0.14]
Slovenia	[0.03-0.68]	[0.05-1.46]	[0.03-0.79]	[0.03-0.97]	[0.08-2.33]	[0.04-1.08]	[0.03-0.59]	[0.02-0.72]	[0.06-1.73]
Spain	[0.07-0.29]	[0.09-0.46]	[0.11-0.58]	[0.16-0.84]	[0.20-1.18]	[0.07-0.32]	[0.08-0.41]	[0.11-0.59]	[0.14-0.84]
Sweden	[0.02-0.08]	[0.01-0.02]	[0.00-0.01]	[0.00-0.01]	[0.01-0.02]	[0.00-0.01]	[0.00-0.00]	[0.00-0.01]	[0.00-0.01]
United Kingdom	[0.02-0.08]	[0.02-0.08]	[0.02-0.10]	[0.03-0.17]	[0.04-0.20]	[0.01-0.06]	[0.02-0.07]	[0.02-0.13]	[0.03-0.15]
Mediterranean	[0.08-0.19]	[0.11-0.27]	[0.13-0.33]	[0.17-0.45]	[0.27-0.73]	[0.08-0.20]	[0.09-0.24]	[0.12-0.33]	[0.19-0.52]
Atlantic	[0.03-0.11]	[0.03-0.09]	[0.05-0.18]	[0.09-0.31]	[0.12-0.45]	[0.03-0.06]	[0.04-0.13]	[0.07-0.22]	[0.09-0.35]
Continental	[0.05-0.16]	[0.04-0.09]	[0.04-0.10]	[0.04-0.11]	[0.05-0.12]	[0.03-0.08]	[0.03-0.08]	[0.03-0.09]	[0.04-0.10]
Boreal	[0.03-0.07]	[0.01-0.02]	[0.00-0.01]	[0.01-0.01]	[0.01-0.02]	[0.01-0.02]	[0.00-0.01]	[0.00-0.01]	[0.00-0.01]
EU+UK	[0.06-0.11]	[0.06-0.11]	[0.08-0.15]	[0.11-0.22]	[0.15-0.33]	[0.04-0.08]	[0.06-0.11]	[0.08-0.16]	[0.11-0.25]

Table S8. Range between minimum and maximum estimates of Expected Annual Damage (EAD) expressed as share of GDP for the baseline and different scenarios. The range represents variability in climate projections in the ensemble and the uncertainty of the damage function. Corresponding average estimates are tabulated in Table S7.

Region	base	1.5°C	2.0°C	3.0°C	4.0°C
	Agriculture				
Mediterranean	3.05	4.26	5.03	6.77	10.45
Atlantic	1.90	1.83	3.17	5.23	7.85
Continental	2.15	1.80	1.77	2.09	2.34
Boreal	0.85	0.34	0.15	0.19	0.14
EU+UK	2.31	2.58	3.24	4.56	6.72
	Energy				
Mediterranean	0.241	0.329	0.377	0.492	0.772
Atlantic	0.157	0.152	0.263	0.445	0.679
Continental	0.152	0.117	0.116	0.127	0.139
Boreal	0.167	0.049	0.018	0.030	0.039
EU+UK	0.180	0.182	0.226	0.318	0.471
	Water supply				
Mediterranean	0.281	0.393	0.461	0.616	0.929
Atlantic	0.188	0.193	0.295	0.493	0.687
Continental	0.112	0.084	0.085	0.097	0.100
Boreal	0.069	0.025	0.010	0.014	0.013
EU+UK	0.154	0.152	0.190	0.273	0.370
	Transport				
Mediterranean	0.000	0.000	0.000	0.000	0.000
Atlantic	0.017	0.018	0.032	0.048	0.078
Continental	0.010	0.008	0.009	0.010	0.011
Boreal	0.000	0.000	0.000	0.000	0.000
EU+UK	0.009	0.009	0.014	0.020	0.031
	Damage buildings				
Mediterranean	0.004	0.005	0.006	0.008	0.012
Atlantic	0.002	0.002	0.003	0.005	0.007
Continental	0.001	0.001	0.001	0.001	0.001
Boreal	0.001	0.000	0.000	0.000	0.000
EU+UK	0.002	0.002	0.003	0.004	0.006

Table S9. Expected Annual Damage per sector expressed as a share (in %) of the sector Gross Value Added for the baseline and different warming levels considering present socioeconomic conditions. Average estimates over climate ensemble and uncertainty of damage function. Damages to buildings are expressed with respect to the value of total building stock.

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