CROSSDRO

Deliverable

3.1. Cross-sectorial market economic impacts

Table of Contents

1. Elbe basin

1.1 Population and Economy

According to Eurostat's 1 km grid of the 2011 census (Eurostat 2016) the GEB housed 17.622 million people (5.372 M of them were living in the Havel area). The population concentrates in the big cities with Berlin (3.292 M), Hamburg (1.707 M), Dresden (0.512 M), and Leipzig (0.503 M) ranking on top (Statistische Ämter 2014). As the next census has been postponed to 2022, more recent updates are only available as extrapolations for administrative divisions: Assuming homogeneous population densities within each of the 2532 municipalities in the GEB, there were 18.160 million residents in the domain on 31 December 2019 (5.836 M of them in the Havel area). Especially Berlin attracted many people during the 2010s from in- and outside Germany: At the end of 2019 the German capitol officially counted 3.669 million inhabitants, thus contributing 70 % to the population growth in the GEB (81 % in the Havel area) between 2011 and 2019 (DESTATIS 2020a, VG250-EW 2021).

Looking back into the 1990s and the first decade of the 21st century there was an exodus of younger people from the more rural regions of East Germany who saw their employment perspectives deteriorate after the old industries of the former socialist economy had been closed down. Between 1994 and 2017, most districts in East Germany lost 10–25% of their population while similar relative increases concentrated around the big cities Hamburg and Berlin. Albeit the net out migration from East Germany has meanwhile come to a halt, further population losses from the rural areas are expected until 2040 (Maretzke et al. 2021).

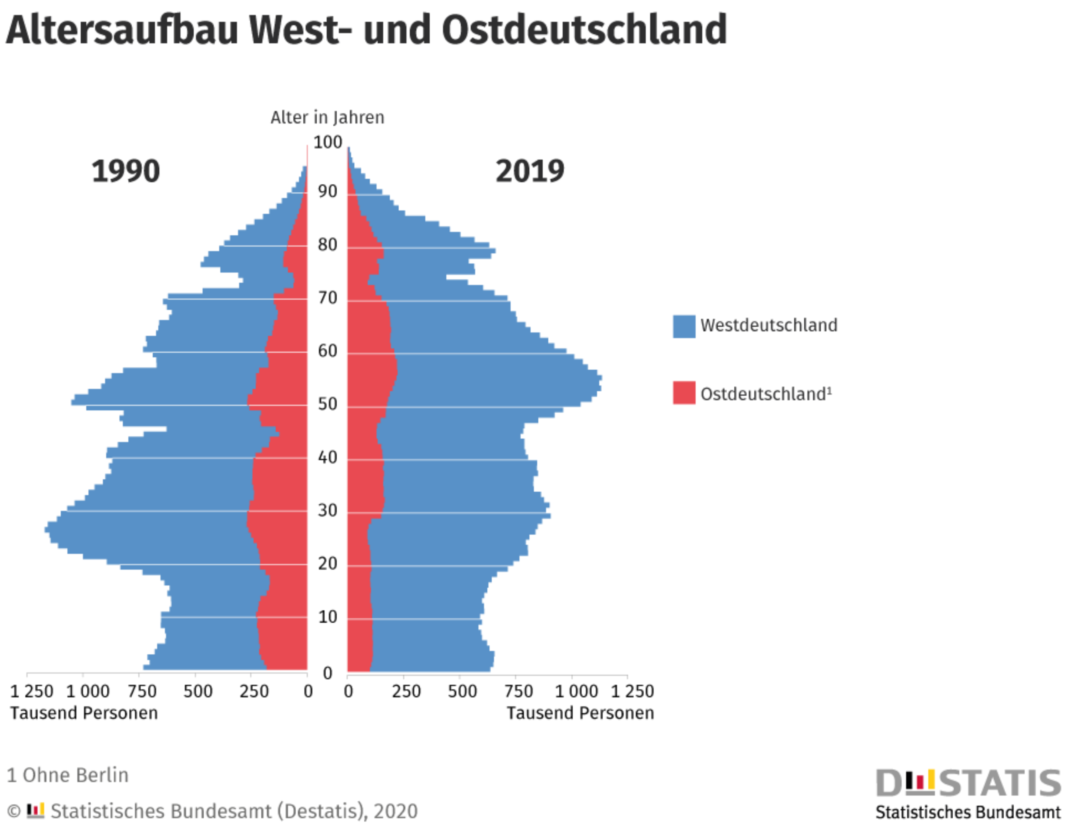

Figure 1: Age distributions of the population in West- (blue) and East Germany without Berlin (red) in 1990 and 2019. Graphic © Statistisches Bundesamt (Destatis) 2020, obtained in April 2021 via URL https://www.destatis.de/DE/Themen/Querschnitt/Demografischer-Wandel/_Grafik/_Statisch/demografischer-wandel-30-jahre-de-altersaufbau.png.

This can be explained by the age structure, see Figure 1: Especially young people were leaving East Germany and the fertility among the population remaining in this part of the country was (and still is) unsustainably low, at about 1.0 children per woman in the 1990s, now stabilizing at 1.6 (DESTATIS 2019a). The recent immigration of (mostly younger) refugees hardly altered the picture: outside the big cities with up to 4 % refugee share regularly only 1.0–1.5 % of the population is backed up by refugees. Consequently there are now about two people in the age bracket of 50–70 years per child or young adult up to the age of 20 living in East Germany, and Maretzke et al. (2021) expect an aged population in the rural parts still in the year 2040 with averages above 50 years.

The elderly are more sensitive to heat waves than younger people, especially those suffering from coronary heart diseases. Without the support of younger family members living nearby and confronted with a deteriorating health system in the countryside, substantial life hazards can emerge for this group from drought periods in the rural parts of the GEB; more about this issue in section 1.2, p.5.

The economy in the GEB has undergone a process of deindustrialization since the German reunification. With the exception of the metropolitan regions of Hamburg, the international port city, and Berlin, the federal capitol, the GEB comprises the poorest regions of Germany measured by average available income and personal net worth of the inhabitants. However, a 25 % share of the secondary sector in gross value added (GVA) and the general prosperity of the region are still comparable to EU averages. Table 1 summarizes the situation; the year 2019 was chosen for reference because 2020 data are still preliminary and affected by the onset of the global pandemic.

Table 1: National accounts and other economic key figures for the year 2019 (disposable incomes for 2018). Federal state codes: BE = Berlin, BB = Brandenburg, SN = Saxony, ST = Saxony-Anhalt, TH = Thuringia. GVA = Gross value added. NACE sector A = Agriculture, forestry, and fishing; NACE sectors B–F = Industry including mining, utilities, and construction; NACE sectors G-U = all other economic activities (i.e. the service sector). Sources: Statistische Ämter (2021), Eurostat (2021a), and own calculations based on these data.

Reporting item and unit		Federal states representing the GEB						For comparison	
		BE	BB	SN	ST	TH	Combined	Germany	EU 28
Gross domestic product	bn €	156.8	74.8	128.9	64.1	63.3	488.0	3 449.1	16 492.1
GDP per inhabitant	1000 €	42.9	29.7	31.6	29.1	29.6	33.4	41.5	32.0
Disposable income per inhab.	1000 €	20.5	19.9	19.8	19.0	19.3	19.8	22.4	n/a
GVA share NACE sector A	%	0.0	1.5	0.9	1.9	1.4	0.9	0.8	1.6
GVA share NACE sectors B–F	%	13.9	26.8	31.1	32.6	33.5	25.4	29.7	24.5
GVA share NACE sectors G–U	%	86.1	71.7	68.0	65.5	65.1	73.7	69.5	73.9

1.2 Drought impacts on economic sectors

1.2.1 Agriculture, forestry and fisheries

1.2.1.1 Agriculture

Although the GEB is not a dry region compared to most of Southern Europe, every drought means losses in plant production. We confine our analysis to the recent 2018–2019 drought impact because of the superior data availability. The data sources assessed are Statistische Ämter (2020, 2021), DESTATIS (2011–2021), and VG1000 (2018). Federal states data have been aggregated from four states only (BB, SN, ST, TH), because Berlin has practically no agriculture.

The maps in Figure 2 show that the GEB was indeed the regional centre of yield losses in 2018. Some farmers experienced even complete failure of their crops and consecutive personal hard ships which remain unaccounted by the integrated economic impact analysis.

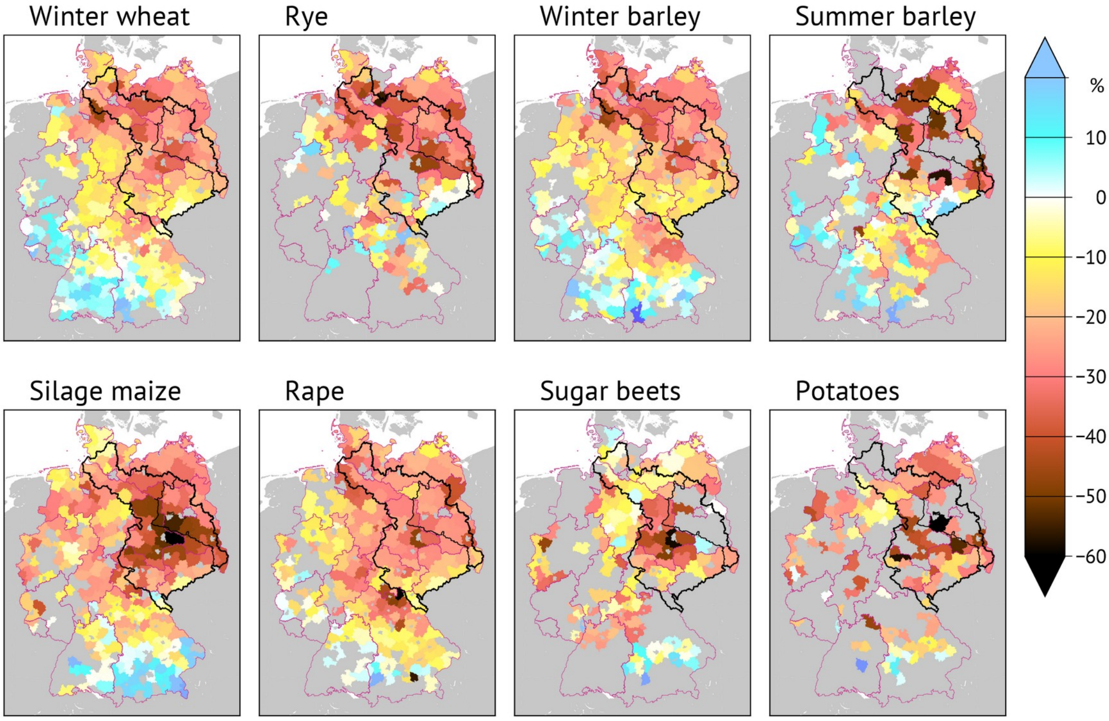

Figure 2: Crop yields of 2018 relative to the 2012–2017 averages in German district-level administrative units; grey areas indicate missing data. GEB and Havel area are outlined in black. Map geometries © 2018 GeoBasis-DE/BKG (VG1000, 2018).

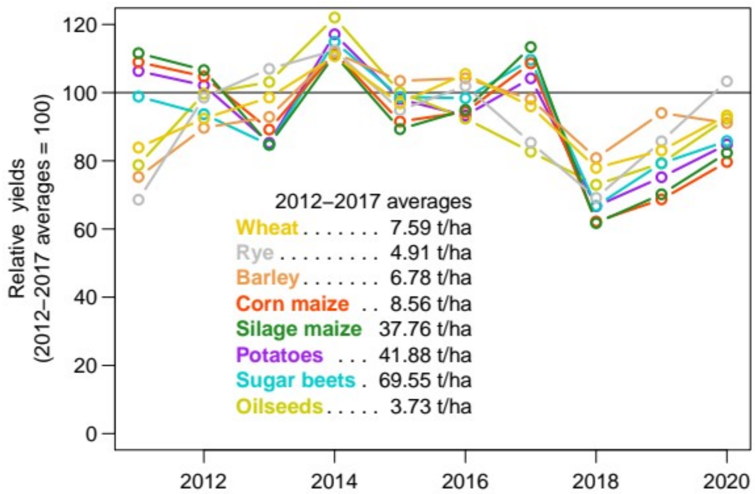

Figure 3: A decade of relative yield levels for eight crops in the GEB (approximated by the federal states Brandenburg, Saxony, Saxony-Anhalt, and Thuringia). The crop-specific values are normalized based on the 2012–2017 yield averages listed with the colour legend.

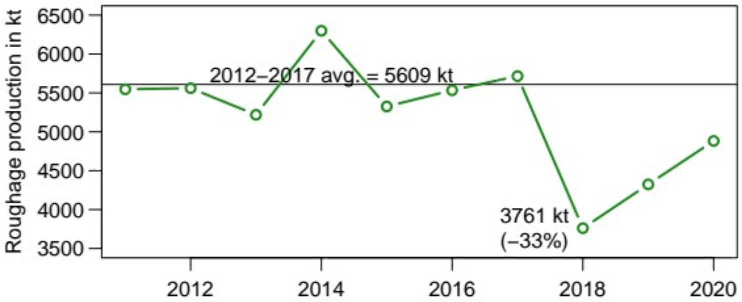

Figure 4: A decade of roughage harvests in the GEB (four-state approximation), absolute production values for dry matter.

Figures 3 and 4 show the 2018 slump in plant production in perspective to the general yield variability of the last decade. GEB averages show typical losses by 20–40 % compared to their pre-drought levels; wheat and barley are at the moderate, silage and corn maize at the extreme end of the spectrum. While wheat and barley are largely grown on richer soils with higher available water content, maize has a much longer vegetation period and can not recover once the soils are continuously dry. The prolonged harvest time also explains the significant loss in fodder production (Figure 4).

Although many animal producers and dairy farmers had to buy expensive extra fodder from abroad, the drought is not visible in livestock numbers or slaughtering rates. In order to quantify the economic impact for the agricultural sector it might seem an idea to express the monetary losses by multiplying production gaps with producer prices. However, such a simple straightforward approach neglects the effects of fixed costs and price volatility. For example, bread wheat prices had stabilized at 150 €/t before 2018, jumped to 190 €/t when the drought hit and returned to pre-drought levels not before the late summer of 2020. Corn maize was mostly traded in the range of 150–170 €/t during the last three years and also spiked to 190 €/t in 2018 but came back to 175 €/t in due to world market reactions. Furthermore, the importance of plant production for agricultural activities in general remains unclear.

Therefore Figure 5 shows the developments of gross value added (GVA) and workforce in the agricultural sector. Both graphs expose the most recent decade of a continuous downtrend: Not only the relative but also the absolute economic significance of agriculture in the region is constantly shrinking. The GVA graph reveals the positive effect of the record harvest in 2014, but in the following year there was obviously a combined negative effect of (moderate) yield losses and storage clearances. The 2018 drought drop is less extreme – probably due to the buffering effect of increased prices –, but still implies a relative loss of 19 % in sector GVA compared to 2017.

The constant decline in agricultural workforce, partly owing to the ongoing process of rationalization and introduction of new technologies, was clearly accelerated by the drought. In 2020 the COVID-19 travel restrictions prohibited many seasonal workers from taking up their jobs accelerating this downtrend even more. This might explain why the GVA remained very low still in 2020 despite a partial recovery of the yield levels.

In absolute numbers, the 2017–2018 GVA loss amounted to 606 million euros (in 2015 prices), approximately 0.2 % of the entire economy of the region. Hence it can be concluded that while the 2018 drought meant bankruptcy for some farms and individuals, the agricultural sector effects are hardly traceable in the general economy.

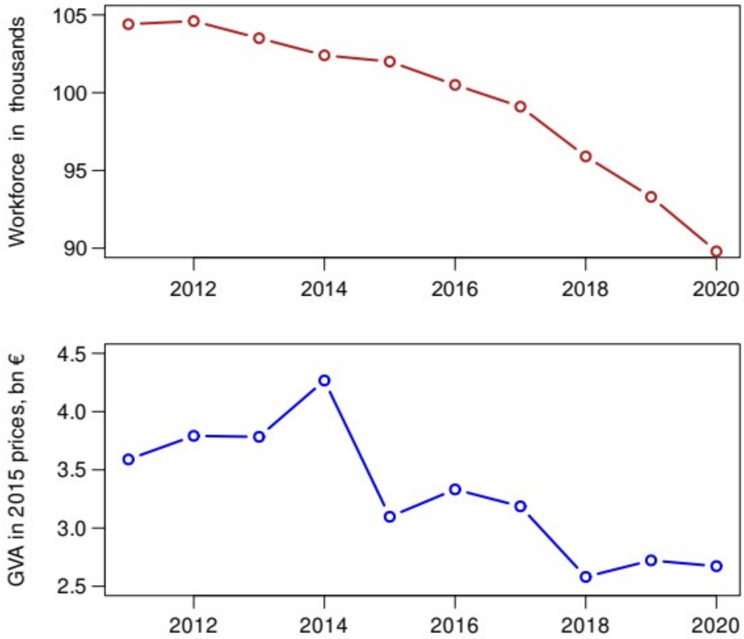

Figure 5: A decade of gross value added (GVA) of and workforce in agriculture and (relatively irrelevant) fisheries. Four-state approximation for the GEB.

1.2.1.2 Forestry

As already detailed above, 28.3 % of the GEB surface is forested according to CLC 2018 (Copernicus 2020). For the statistical aggregate of the five federal states Berlin, Brandenburg, Saxony, Saxony-Anhalt, and Thuringia a similar share of 29.7 % was recently determined (DESTATIS 2021b). According to the third federal forest stocktaking (*Bundeswaldinventur*) of 2012 – the fourth pass of this assessment is underway but results are not expected before 2024 – 37.6 % of all forests in the five states are state owned, 10.0 % belong to public corporations, and 52.4 % are private property (TI 2014); this is something to consider when looking at the drought-related economical damages in forestry.

The forests in Germany are generally extensively managed, and earlier national assessments showed a continuous increase in biomass after regional diebacks in the 1980s caused by air pollution. What happened to the forests since 2018 can be traced by the official harvest assessments aggregated and visualized for the five-states in Figure 6.

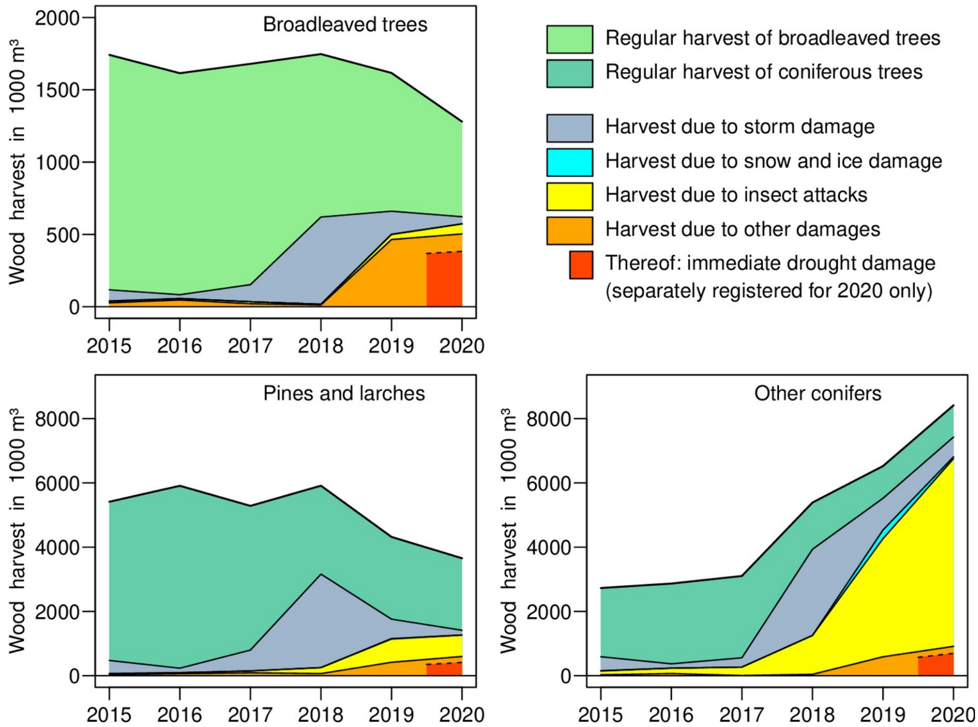

Figure 6: Recent annual wood harvests in the five-state aggregate separated by species groups. Indicated are also volume shares of cutting caused by certain actual damages. Data source: DESTATIS (2021c,d).

Before the fatal year of 2018, approximate annual harvest rates amounted to 1.7 million m³ of wood from broadleaved and 8.5 million m³ from coniferous trees, the preferred species group in Eastern Germany. Damaged wood accounted for minor shares in the harvest statistics. The situation changed quickly already before the drought when a series of gales struck:

Xavier, a fast moving cyclon hit especially the Berlin–Brandenburg region on 5th October 2017 with gusts reaching 30 m/s and more (Beaufort 11; Haeseler 2017). The author of these lines remembers well the scenery of derooted trees in and around Potsdam's science park "Albert Einstein". Xavier was quickly followed by Herwart, a similar system crossing the Elbe area on 29th October 2017 with highest wind speeds over Thuringia and Saxony (Haeseler & Lefebvre 2017). Finally, an intense low pressure system named Friederike passed Northern Germany on 18th January 2018. Gusts of 33 m/s and more (Beaufort 12) were registered in Thuringia, Saxony, and the southern half of Saxony-Anhalt (Haeseler et al. 2018).

The effect of these gales whose temporal clustering and intensity had not been observed in Northern Germany for decades can be seen in Figure 6 by the 2018 humps of the grey colour bands, the many wood harvests clearing wind damages. Explicit drought damages, the dieback of trees caused by lack of water, were not relevant in 2018, the first drought year. These damages are included in the orange bands of "other damages" (separate data are only available for 2020), but their relevance and hysteresis are obvious. Broadleaved trees are affected most because their leaves are prone to high transpiration losses and they are more frequent in the lowlands where the climatic water balance can be negative.

An indirect – and therefore even more hysteretic – drought impact is the explosive growth of damages caused by insects, especially in "other conifers". These are typically spruce trees in mountainous areas, and the harmful insects are bark beetles. The current bark beetle attacks are the most severe since those of the 1980s where many high altitude areas in the Ore Mountains had been cleared. Especially for spruce forests the general damage situation has never been worse since (BMEL 2021). Complete spruce diebacks can now be observed again in some locations although there is some hope for a turnaround in 2021 (SMUL 2021).

Regarding the economic consequences, on a short time scale the drought event in 2018 had positive economic impacts on forestry. Due to high calamity rates, more wood was cut down and sold for prices on relatively stable levels. However, reforestation and substantial losses in wood capital in the forests will most probably outweigh those short surpluses (Seintsch, Englert and Dieter, 2020).

Möhring et al. (2021) estimated the total economic loss for German forestry during the drought years 2018–2020. Since 27 % of damaged forests and 24 % of the fallen timber during this period belongs to the federal states BB, SY, ST and TH which make up 24 % of the German forest area (DESTATIS 2021b), the estimations represent the losses in the Elbe-River basin. Overall they suggest losses of 12.75 billion EUR for the years 2018–2020. The biggest share (31 %) is due to lower sales values and higher logging costs for calamity wood. Economic losses for the outset of value added (27 %) and early harvesting of mature wood resources causing yield losses (18 %) are following. Furthermore, reforestation (11 %), non-sellable woods (9 %) and higher costs for administration (5 %) constitute the economic pressure on forestry.

In 2018, forest fires alone affected more than 20 km² in the federal states BB, SN, ST and TH (see Tab. X.4). Keeping the high level in 2019 with 15 km² affected, the situation eased in 2020 with only about 1.7 km² affected which is below the average of the non-drought years 2015–2017 (Lachmann 2016–2021).

The economic loss of wood resources through forest fires is estimated from the German ministry of Food and Agriculture. Since data for BB do not include losses in forests owned by the federal state which make up most of the area, the estimations only represent economic losses for SN, ST and TH. In 2018 economic losses in the three states are estimated to 1.65 million euro, more than tenfold the average of the non-drought years 2015–2017. Estimations for economic losses in 2019 (0.49 million euro) and 2020 (0.37 million euro) are still on a high level, especially considering that 80 %, 93 % and 70 % of the affected areas belonged to BB in 2018, 2019 and 2020, respectively (Lachmann 2016–2021; Table 2). However, in comparison to the primary sector (agriculture, forestry, and fisheries) GVA of SN, ST and TH – 2.6 billion euro in 2018 and 2.9 billion in 2019 – the fire losses were still without consequences for the general economy.

Table 2: Area affected by forest fires in the four federal states. Source: Lachmann (2016–2021).

Year	Affected forest area in the federal states in ha				
	Brandenburg	Saxony	Saxony-Anhalt	Thuringia	All four states
2015	328.3	16.5	31.4	6.4	382.6
2016	157.4	5.4	30.8	2.0	195.6
2017	285.4	4.9	5.1	1.2	296.6
2018	1674.1	305.5	113.9	11.2	2104.7
2019	1388.6	56.8	20.6	21.6	1487.6
2020	118.7	32.8	8.9	9.0	169.4

1.2.1.3 Fisheries

Inland fisheries are such a minor economic activity that the Federal Statistical Office limited their data collection to aquacultures some years ago. A more comprehensive report of the situation of the German inland fisheries and aquaculture is ordered annually by the supreme fishery authorities of the federal states. The most recent issue for 2019 (Brämick n.d.) counted 166 professional fishing and 290 aquaculture enterprises for the five-state aggregate. Catches from rivers and lakes most of which are located in Brandenburg amount to approximately 1200 t per year, and the aquaculture production, centred in Saxony, reached about 4250 t/year. Using rough estimates of 15.00 €/kg and 7.50 €/kg as average retail prices for wild and aquaculture-produced fish, respectively, yields a gross revenue estimate of about 50 million euros.

Due to the direct consequence of the lack of water on fisheries, this sector is directly endangered by drought conditions. The case of the Seddin Lake (*Großer Seddiner See*; 52°16.5′N, 13°02.0′E; approx. 30 km south-west of Berlin) whose fisherman had to close shop due to low water levels was however more likely caused by sub-optimal water management than by drought alone (RBB 2020).

With SN and BB producing 47 % of carp in Germany, carp farming is a traditional kind of aquaculture in the Elbe River basin (Edebohls et al. 2021). Carp ponds are shallow water bodies with water depths around one meter. The ponds are drained in an annual cycle in order to harvest the carps. The water bodies differ in terms of water provision. In SN 25 % of the ponds are fed only from precipitation in mostly small basins. Other ponds are fed by above ground streams or groundwater (Ballmann et al. 2017). Salmonids are produced in flowing water sites. They prefer cold water temperatures and high oxygen levels. The most produced salmonid in Germany is the rainbow trout.

Brämick (n.d.) reports increased fish mortality for 2018 and 2019 owing to high temperatures causing lack of oxygen, and dried-out ponds limiting the production. In this case the fishes are usually harvested before complete losses would be inevitable. Furthermore, the amount of fish is reduced due to better hunting conditions for predators in low water depths (MDR.DE 2020; Proplanta 2020; Sächsische.de 2020). However, carps are a warmwater species tolerating low oxygen levels (Ballmann et al. 2017). Therefore sites which held a minimum amount of water and level of oxygen had low economic losses.

The production volume of carp in Saxony stayed relatively stable during the drought years 2018–2020. With the minimum of 1674 tonnes of carp reached in 2017 the production was between 5 % and 7 % lower than the average value of the years 2012–2017. The number of businesses producing carp in SN decreased about 20 % from an average of 156 in the years 2015–2017 to 125 in 2020. The loss for rainbow trout producers were higher. The production of the temperature sensitive fish declined by 39 % respective the average between 2012 and 2017 (DESTATIS 2012–2021).

In Brandenburg the relative loss in carp and rainbow trout production was higher than in SN. The production declined by 19 % in 2018 and 26% in 2019 for carp and 34% (2018) and 33% (2019) for rainbow trout compared to the averages of the years 2013–2017 (Statistik BB 2016–2020, DESTATIS 2012–2021). In TH the average production of trout from aquacultures diminished by 19 % during the drought years 2018 and 2019 compared to the 2012–2017 period. Carp production was 13 % below the 2012–2017 average (DESTATIS 2012–2021).

1.2.2 Mining and Quarrying

The millennial history of mining in the mountainous areas, mainly for non-ferrous and noble metals and after WWII for uranium in the Ore mountains, ended with the 20th century. Still in operation are only a few open-cast mining areas for lignite, remains of two furthering regions (*Mitteldeutsches Revier, Lausitzer Revier*) that reached their production peak already in the 1980s. and are now characterized by remodelled landscapes, disused mining pits often being transformed into lakes.

Water was practically always more a disturbance than an advantage for mining activities (with the exception of early mechanical hydropower applications, e.g. for hammer mills). The open-cast lignite mining requires constant groundwater withdrawals through electric pumps to keep the excavation areas dry. Consequently, the recent drought was no problem at all for mining as such.

The planned emergence of lakes and waterways in the former mining area landscapes was however hampered by the drought. A water management centre in Lusatia, the border region of Brandenburg and Saxony, has been installed to carefully balance the filling of the new lakes with the minimum runoff requirements of the Spree River crossing Berlin. Shifting the goal of fully restored groundwater storages and filled artificial lakes (currently the year 2090 is aimed for the final lake fill; Scholz & Totsche 2021) further into the future is less problematic than a foul, stagnant water body below the Federal Chancellor's office (which could still be avoided).

1.2.3 Manufacturing

There are only few studies separating drought-related stresses on the economy from general climate change effects. The German Federal Ministry commissioned a study about climate adaption in enterprises and municipalities (Mahmmadzadeh et al. 2013) for which industry representants were asked for their risk perception. Heat was an issue of concern for only 23 %, and drought by only 13 % of only those enterprises which generally cared about climate change; frost, storms, and floods were more frequently named. Higher climate risks were anticipated for the future (2030) with heat now in the pole position (46 %) but drought still as also-ran.

A study commissioned by the German Federal Ministry for Economic Affairs and Energy (Lühr et al. 2014) focuses on possible supply chain disruptions. In procurement, extreme heat (which is strongly correlated with summer drought) can cause traffic disruptions (damaged traffic lanes, higher probability for accidents, water-level limited navigation), and much more directly, drought can lead to water shortages. Process risks include reduced employee productivity through high temperatures and UV radiation, problems in cooling of IT components and workplaces, and heat damages of stocked goods. On the demand side, there is again the risk of traffic disruptions, and there may be shifts in product demand. Due to the international interlinkage of supply chains, drought risks are not confined to production sites within the focus area. The analysis of Lühr et al. (2014) shows the metal industry as especially drought sensitive because of their high water and energy demand. (Regarding drought effects on electricity generation, see Section X.4.4 below.)

Virtually the same points of concern regarding drought and manufacturing – stress on production processes, logistics, and management; high energy demands for cooling confronted with increased probabilities for energy shortages; shortages in freshwater supply; and impacts on retail markets – are named by Buth et al. (2015) who also made some efforts to differentiate the risks spatially albeit without giving a clear picture for the Elbe region let alone concrete cost estimations.

For the Dresden region Auerswald & Vogt (2010) identified especially water or energy intensive sectors of manufacturing. The result, shown in Table 3, should be generally transferrable to the GEB. Interestingly, paper making or printing is not classified as energy sensitive, albeit paper mills and rotation presses would immediately stop without electricity. The same holds for the tools used in manufacture of machinery equipment, a sector named economically important for the Dresden region but neither classified energy nor water sensitive.

Table 3: Especially water or energy sensitive sectors of manufacturing (Auerswald & Vogt 2010)

Economical (sub-)section	Energy sensitive	Water sensitive
Food and tobacco processing		X
Paper, publishing, and print		X
Chemicals and chemical products	X	X
Rubber and plastic products	X	
Non-metallic mineral products (glass, ceramics, etc.)	X	X
Metals and metal products (except machinery)	X	

The water demand for manufacturing generally exceeds that of private housholds. A full separation of the sectors is only available on national level. Since the year 2000, 27 % of the industrial water demand could be saved due to new technologies which also allowed for higher productivity (IMAA 2019). The most current statistics is available for 2016 (DESTATIS 2019c). In that year, the water intake of the German manufacturing sector amounted to 5226 million m³ while private households used 3118 million m³ of freshwater.

Published federal states' figures include only aggregates for mining and manufacturing. Given the national water demand of coal mining (lignite) of 955 million m³ (DESTATIS 2019c) and the fact that the coal production in the GEB is about half of the national amount (Kohlenstatistik 2021), the 2016 water demand of mining and manufacturing in the five-state aggregate of 954 million m³ (Statistische Ämter 2021) may be split quite equally between the sectors. The private household demand in the five states amounted to 492 million m³, another figure in the same ballpark.

Although private water withdrawals from rivers and lakes were forbidden in the dry summers of 2019–2021 in many parts of Brandenburg and Saxony (see section X.4.5 below) no news reports about throttled industry production due to water shortages could be found for the Elbe region. Obviously the big industrial water demand could be constantly met, at least where no cooling was involved: Permittances for the discharge of warm water were reduced in the hot summers of 2003, 2006, and 2018 (IMAA 2019), but in the GEB this may only have been an issue for the heat-driven power stations (see the following section X.4.4).

It is not sure whether the stable water supply for manufacturing will still be secured for future decades. Elon Musk's Tesla factory currently being erected at Grünheide near Berlin has been critisized for its planned water demand of 3.6 million m³ per year. This is not so much compared to the entire manufacturing sector demand across the region, but the problem is that it needs to be fulfilled on site. The regional water coorperation's president anticipates severe shortages if the plans be realized (ZDFheute 2021). And in many parts of the GEB there is the lingering problem of receding groundwater levels.

1.2.4 Energy supply

The gross electricity production in the five-state aggregate approximately equalled 138.2 TWh in the years 2015 and 2016, jumped to 145.3 TWh in 2017 and kept this level with 145.9 TWh in 2018, the first drought year (LAK Energiebilanzen 2021; more recent data were not available in September 2021). Hence this sector seems relatively insensitive to drought on the first glance. Figure 7 shows the history of electricity production including the composition of renewables which emerged over the last two decades in line with the national trend.

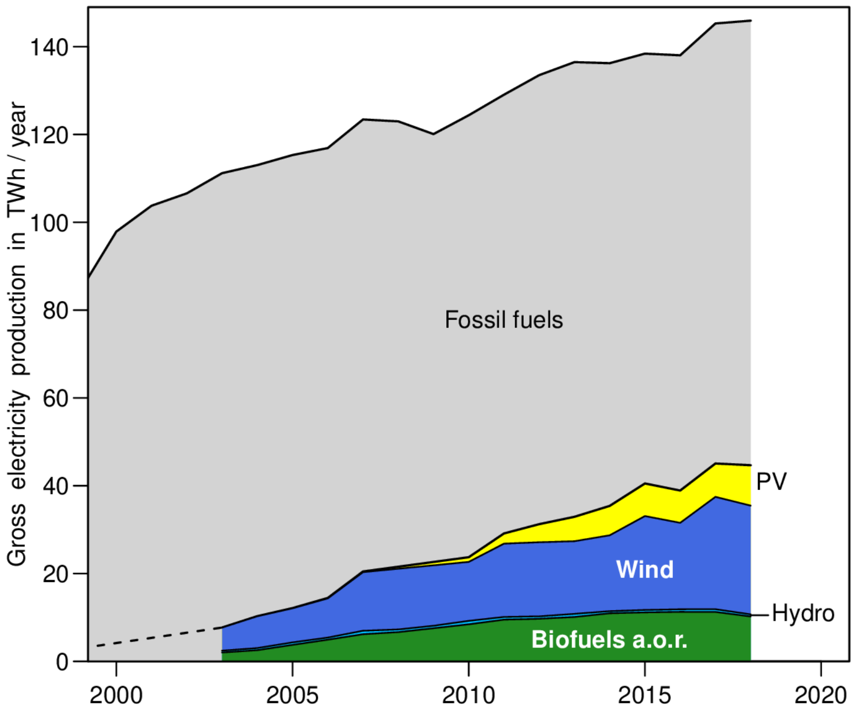

Figure 7: Gross electricity production in the five star aggregate separated by contributions of fossil fuels and renewable sources. Data source: LAK Energiebilanzen (2021).

Lignite fueled power plants in Lusatia (Brandenburg and Saxony) alone deliver nearly half of this electrical energy, approximately 65 TWh per year; there are also other lignite power stations and other fossile sources (especially hard coal and gas).

A negative effect of the 2018 drought on the energy supply can be spotted in the biofuel share (green band in Fig. X.23): After several years of relatively stable contributions it decreased from 10.9 TWh in 2017 to 10.0 TWh in 2018 – obviously crop failures led to fuel limitations. It is also traceable in the electricity output of Berlin's hardcoal plants: only 2.8 TWh in 2018 after 3.7, 3.5, and 3.4 TWh in the three previous years; these plants had to be throttled due to limitations in cooling water.

The drought had a positive effect on the five-state figures for photovoltaics (PV, yellow band in Fig. X.23). The output jumped to 9.2 TWh in 2018 after 7.4, 7.4, and 7.6 TWh in the three previous years. Hydropower shows of course the opposite, but it is of negligible importance despite the mountainous areas of the GEB being fully covered by the five states: 482 GWh in 2018 after 545, 579, and 616 GWh in the years 2015–2018 (LAK Energiebilanzen 2021).

All nuclear power plants in the GEB are either shut down, phased out, or already in their controlled disassembly phase. The fossil-fuel driven thermal plants are still the backbone of the regional electrical energy supply, and under drought conditions they could theoretically face the challenge of cooling water shortages which would limit their output capacity. Koch et al. (2014) analyzed the problems for electricty production in the Elbe basin under a dry climate scenario, and the reality of the recent drought seems to follow the projections – but the cooling water shortage problem was generally limited to the thermal power plants in the city of Berlin: The big lignite-fueled power plants near the open-cast mining areas of the GEB are not affected at all because the groundwater uptake from the mining areas always delivers enough water with suitable temperatures (approx. 11°C). Furthermore these power plants, namely Boxberg, Jänschwalde, and Schwarze Pumpe, use water-saving closed-loop systems with cooling towers as heat exchangers which makes them practically fully resistant against heat and drought.

There is a non-free database of the Energy sector collecting member reports on power production reductions and the reasons for them (KISSY, VGB Power Tech e.V.). The most recent free excerpt shows temperature-related production shortages of thermal power plants on the national level (IMAA 2019), but the annual time series released here does not contain the years after 2017. Until then, the highest shortages were in 2003 with 2500 GWh and in 2006 with 1775 GWh. Power plants along the Elbe river had however no share in the 2003 reductions which centered on nuclear plants in Western Germany. For 2018, there are a number of press reports about throttled power generation in Germany (e.g. LR Online 2018), but the two nuclear plants on the lower part of the Elbe River, Brunsbüttel and Stade, had already been shut down then.

Taking together the drought-competence of the lignite-fueled power plants, the increased output from photovoltaics and the practically non-existent share of hydropower it can be concluded that the electricity sector of the GEB seems virtually resistant against negative drought effects. This may however change in the future when fossil fuels are phased out which is currently planned for the year 2038. At some point in the future the general system stability might depend on water availability; we will discuss that further in the concluding section.

1.2.5 Water supply

During the recent drought water use was restricted for the public: Following a ministry recommendation many districts of Brandenburg forbade to withdraw water from rivers and lakes – often used for private gardening –, but only one local water cooperation decided to restrict tap water use for that purpose (Tagesspiegel 2019a). Similar witdrawal restrictions were introduced in Saxony, and the situation repeated more or less equally in 2020 and 2021 (Bussgeldkatalog.org 2020, RBB24 2021).

Actual tap water supply problems affected only very few municipalities, though. The village Harsefeld, approximately 25 km west of Hamburg, was confronted with pressure breakdowns in late afternoon when the demand for garden watering spiked. Meanwhile this problem is being resolved by new pipe installations (Kreiszeitung-Wochenblatt 2021). A real shortage of the natural supply was reported only outside the Elbe area: The case of Lauenau in Lower Saxony where people had to buy bottled water for drinking and fetch raw water for other uses from tank cars hit the news in summer 2020 (RND 2020).

While the recent drought did not cause any relevant outages in industrial and drinking water supply, record low groundwater levels and the perspective of decreasing water balances and groundwater recharge under climate change pose the question whether the high reliability of the system can still be guaranteed in the future. The associations of engineers, utility companies and water suppliers (the latter usually being public corporations in Germany) did their homework analysing the situation (Simon et al. 2019, EWP 2021) and drafted a demand charter (BDEW-DVGW-VKU 2021). The German association of cities and municipalities took the same line (DStGB 2021), and the federal government published the draft of a national water strategy (BMU 2021).

The proposals build on the compound power of numerous measures drawn from the engineer's space of possible solutions. Tap water security is definitely given a high priority, and large sums of public money and water fees will be invested over time, for instance in new wells, additional pipe connections, forest conversions, rainwater processing plants, or intelligent demand monitoring and charging systems. In the long term, the price of tap water (and probably also taxes) will consequently rise a lot, and that will be the economic drought burden – not directly connected to any particular drought event.

Tap water fees change between supply areas, often municipalities. In 2019, an average German household paid approximately € 240 per year for their water (DESTATIS 2020c), fees were tendentially higher in Hamburg and Thuringia, about that level in Saxony, and lower in the other parts of the Elbe basin. Interestingly, the average annual household fee is only € 157 in the German capital. In addition to that private end-users have to pay fees for the sewage water removal, usually a similar amount, so the average total freshwater supply fees are currently about 400–500 € per household and year. This may probably rise by 20–30 % in the 2020s to finance the investments deemed necessary for continued supply security. A surplus water fee of 125 € per year and household could grant about 5 billion € annually for infrastructure investments (1 billion € per year for the GEB), but there are no cost estimations yet.

1.2.6 Construction

The freshwater use of the construction sector is relatively low, less than 1.5 % of the private household demand (DESTATIS 2019c), and with practically no tap water restrictions there were no water shortage problems.

Weather is nevertheless a bigger issue in construction; some outdoor works cannot be done in bad weather conditions, but sunny days with strong radiation and high temperatures limit the human productivity outdoors. A global study (ILO 2019) found construction among the most affected branches but quantified the climate-change related productivity losses in Western and Eastern Europe in small fractions of a percent; losses during hot summer days may be balanced by shorter bad weather breaks in winter (IMAA 2019).

A special factor to take into account for construction workers is the additional heat stress through the protective clothing. Other stresses, namely increased ozone levels and uv radiation, need also to be taken into account. For construction workers in Germany skin cancer is a recognised occupational disease.

One of the most comprehensive summaries about heat effects on outdoor workers has been published in the online magazine of the statutory accident insurance institution (*Berufsgenossenschaft*) for the German construction sector (Templiner et al. 2021). However, estimations for productivity losses are only available for the entire economy in Germany: 3–12 % during heat periods or 540 million to 2.4 billion euro compared to years without heat days (IMAA 2019, but see section X.4.8.1 questioning these figures). And there are direct nonmonetary losses: Accidents and fatalities become more frequent under high temperatures. This was tragically demonstrated *in extremo* by the death toll for the construction of football stadiums for the 2022 FIFA world cup in Qatar, but the effect is also statistically evident in the United States (Templiner et al. 2021) and thus very probably a neglected problem in Germany, too.

1.2.7 Trade and transportation

Among the different traffic routes, river waterways are directy and strongly affected by drought; navigation on the Elbe River had to be limited or shut down completely due to low water levels for many times in the past. On the least affected opposite side is aviation, and road and railroad transport are more indirectly affected in-between.

Railroad tracks are prone to loosing calibration and buckling through heat expansion ("sun kink"). In Germany respective damages were reported from Bavaria (Merkur 2018) and Mecklenburg-Western Pomerania (WiWo 2019). In order to minimize the effect the national railways, Deutsche Bahn AG, tested white coloured rails at Magdeburg, Saxony-Anhalt (FR 2019). A more prominent problem for German train passengers were however failing air conditions which led to numerous train drop-outs in the hot summers of 2018 and 2019 (Spiegel 2019b). According to a climate study commissioned by the Deutsche Bahn AG (Edenhofer & Hoffmann 2021) the Berlin traffic region was a centre of heat-related failures. This study was part of a new initiative for climate resilience of Germany's major rail operator (ZEIT ONLINE 2021).

The hauling capacity of the German transport sectors is reported on national basis only and kept a relatively stable level for railroad transport between 2016 and 2019 with annual values ranging between 128.9 and 131.2 billion ton-kilometers. Road transport increased from 473.4 billion ton-kilometers in 2016 to 499.2 and 498.6 billion ton-kilometers in the drought years 2018 and 2019, respectively (DESTATIS 2021e). Thus economic drought consequences seem negligible among the land transport sub-sectors. However, road traffic on hot summer days is characterized by average accident rates but higher shares of injuries and fatalities, because dry weather encourages fast driving and many people walk or cycle in public space (IMAA 2019).

We already hinted at the direct vulnerability of inland navigation: The hauling capacity on German waterways dropped from 55.5 billion ton-kilometers in 2017 to 46.9 billion ton-kilometers in the first drought year (DESTATIS 2021e). These numbers have however to be set into perspective of a generally shrinking navigation sub-sector, see Figure 8, p. 20: If we assume a linear extrapolation of the downtrend from the pre-drought years for the expected hauling under normal runoff conditions, the drought losses of 2018 and 2019 would sum up to 8.9 billion ton kilometers, approximately 8 % below the two years' expectations.

But how about the situation in the GEB? The Elbe River upstream its tidal part with the big international port of Hamburg is much less important for navigation. There are at least load data for the goods transported on waterway sections, Table 4 shows a comparison for the year 2017:

Table 4: Cargo loads transported in 2017 on GEB inland waterways in comparison to other routes of navigation within Germany. Data sources: DESTATIS (2021f,g), Port of Hamburg (2021).

Cargo loads transported on major inland waterways of the GEB	
Elbe upstream Magdeburg	3 797 413 t
Elbe, Magdeburg–Schnackenburg	1 136 464 t
Lower Havel Waterway (Berlin–Elbe River)	3 434 159 t
For comparison: Cargo loads transported on German sections of the River Rhine	
Rhine, Mannheim–Bingen (includes Main River junction towards Frankfurt)	59 258 267 t
Rhine, Lülsdorf–Orsoy (passes cities of Cologne, Düsseldorf, and Duisburg)	148 278 673 t
For comparison: Offshore cargo handling through the Elbe River estuary	
Port of Hamburg, according to DESTATIS (2021g)	118 760 726 t
Port of Hamburg, according to Port of Hamburg (2021)	136 400 000 t

These figures leave no doubt that water transport inside the GEB makes up only a tiny fraction of the national hauling capacity. The authors can confirm that from their personal experiences: Whenever you walk over the Hohenzollern bridge in Cologne you will very probably see some cargo vessels cruising the Rhine below you, but you may as well spend a full hour standing on the Strombrücke (lit. “stream bridge”) in Magdeburg watching the waves on the River Elbe, very likely undisturbed by any hull. But we would like to quantify the drought effect on GEB navigation using the load statistics. Using the load averages of 2011–2017 for normalization, we created index time series for the three selected waterways (Elbe River up- and downstream Magdeburg and Havel downstream Berlin). Their time series are shown in Figure 9.

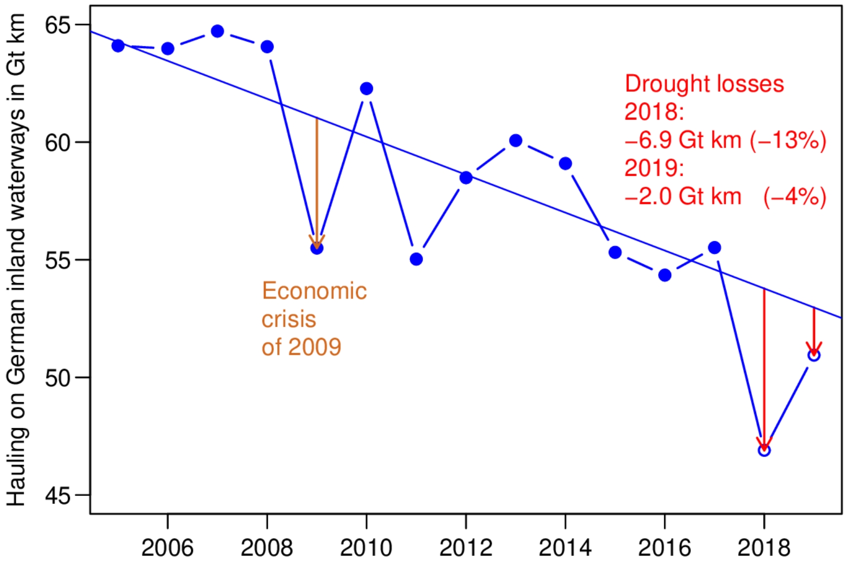

Figure 8: General downtrend in German inland navigation with special setbacks in single years. The trend line has been fitted to the pre-drought data of 2005–2017 (filled circles).

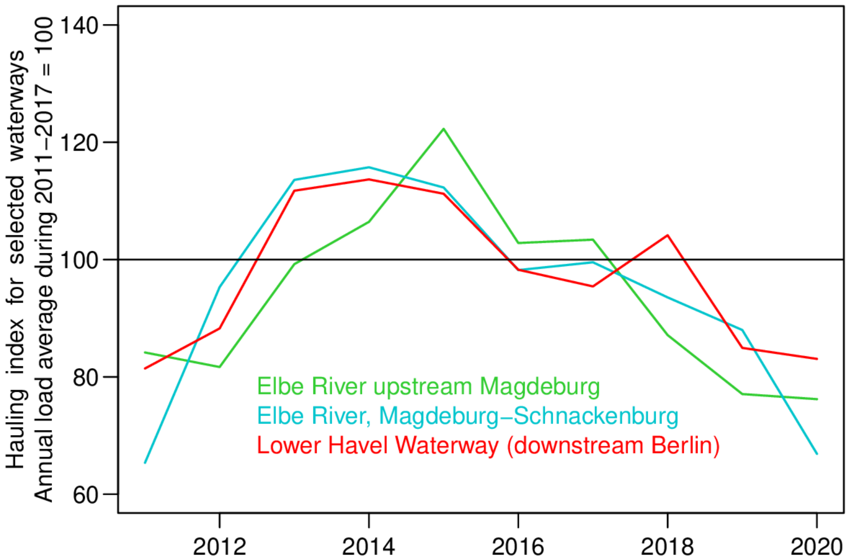

Figure 9: Recent hauling trends on three principal navigable waterways in the German Elbe basin.

The picture which Figure 9 conveys is somewhat indifferent regarding the drought consequences to inland navigation inside the GEB. There are also general downtrends since 2015, and no particular disturbance in the drought years can be traced. Cargo loads on the Lower Havel Waterway did in fact increase in 2018 – but there are many deep lakes and locks to secure navigation in this part of the river. The strongest drought effect can be assumed for the shallower upstream part of the Elbe river, and this is in line with the data (light green line in Figure 9). However, the economic losses are negligible in comparison to the Rhine River navigation or the entire transport sector in the GEB.

1.2.8 Services

1.2.8.1 Service activities in general

These include accommodation and food service; information and communication; financial and insurance activities; real estate activities; professional, scientific and technical activities; administrative and support services; and public administration. The service sector as a whole dominates the economy with 73.7 % of the gross value added (GVA) in the five-state aggregate, practically the same share as in the EU as a whole (see Table X.2 in section X.1); this however includes trade and transportation (NACE sectors G and H) already discussed above. Their 2019 shares in gross added value of the five-state aggregate were 8.1 % and 4.3 %, respectively.

Of the remaining service activities, about 2.0 % of the GVA can be attributed to defence (estimated from the federal defence budget, BMF n.d., taking into account the rather even distribution of garrisons across Germany and the weaker economy of the GEB compared to the national average), 5.8 % to education, and 1.8 % to arts, entertainment and recreation (percentages for the five-state aggregate, Statistische Ämter 2021a). These special sectors are discussed below, hence this section about services in a narrower sense, mainly "white collar" office work, covers about half of all economic value generation.

Offices are indoor working environments usually sheltered from weather influences, although the first sentence of Hooyberghs et al. (2017) states exactly the opposite: "Indoor climatic conditions are strongly influenced by outdoor meteorological conditions." Whatever – we have already shown above there were no outages in electricity and tap water supply caused by the recent major drought, so could office work be affected by the recent droughts? Yes, through the accompanying heat during summer, because – in contrast to other world regions with comparable seasonal temperature extremes, e.g. East Asia or the United States – air conditioning is more an exception than the rule in the GEB, and many indoor work places became uncomfortably hot in the summers of 2003, 2018 and 2019.

The economic effect of heat-related performance losses in office work is however hardly quantifiable. Zhao et al. (2021) reviewed 30 scientific articles on heat-related labour productivity losses and identified four different methods to quantify the economic impacts. The results from different world regions varied significantly and are not transferrable to the Elbe region. A similar meta-analysis of 35 studies was provided by Porras-Salazar et al. (2021) and came up with the shattering conclusion: "We could not find a relationship between temperature and office work performance neither for the range of temperatures measured in most of the office buildings (20°C–30°C) or a wider range (18°C–34°C). [...] The lack of relationships does not necessarily refute that temperature affects the performance of office work." While the latter statement seems self-evident, both meta studies show that a generally applicable formula for the relationship between temperature and productivity of office workers is not on the horizon yet.

These findings question the validity of any single study such as the one estimating 3–12 % from which IMAA (2019) derived 540 million to 2.4 billion euro heat stress-related productivity losses for the entire German economy (already quoted in section X.4.6). IMAA (2019) cites Hübler & Klepper (2007) as source for the percentages, who in turn named Bux (2006) as their source. However, Bux (2006) also discusses inconsistent findings in the literature and mentions the 3–12 % range without context, just as example for the typical uncertainty! (Despite the unreliabilty of any specific productivity loss function, economists have not flinched from comparing costs of work and workplace cooling, Hooyberghs 2017, or even estimating a cost-minimizing optimum room temperature, Dai et al. 2014.)

The German weather service (DWD) uses the "Klima-Michel" model for the thermal comfort of a reference person walking *outdoors* with moderate speed (Jendritzky et al. 1979, Jendritzky 1990). It is based on heat balance calculations for the human body and considers not only air temperature but also humidity, wind speed and radiation. A "perceived temperature" was developed as related index; values above 20 degrees indicate heat stress, different intensity levels are defined (Staiger et al. 1997). New insights about biometeorology and the temperature regulation of the human body led to the development of an overhauled index, UTCI (Jendritzky et al. 2010, http://www.utci.org).

A comparably refined thermal comfort index for *indoor* conditions would probably be needed to reliably describe and parameterize the relationship between thermal environment and human productivity in offices. Air humidity is still a neglected factor in productivity research, but also air movements from ventilation and heat radiation sources may be influential for office environments. Furthermore, different tasks are affected differently by heat stress (Lan et al. 2009), hence we have to conclude that no reliable forward estimation of productivity losses under heat waves is possible yet.

Econometric time series on the narrower service sector's productivity in the five-state aggregate (BE, BB, SN, ST, and TH; Statistische Ämter 2021a) are shown in Figure 10, p.23, and 11, p. 23. "Narrower" refers to the NACE sectors J–Q, these are: (J) Information and communication; (K) Financial and insurance activities; (L) Real estate activities; (M) Professional, scientific and technical activities; (N) Administrative and support service activities; (O) Public administration and defence, compulsory social security; (P) Education; and (Q) Human health and social work activities.

Comparing the index of the sector-specific GVA to the total GVA index in Figure 10 shows primarily a more or less parallel growth of services and the entire economy. A strong resilience against the financial crisis of 2008/2009 is also clearly visible; it has to be noted that many service jobs are permanent positions with fixed standard wages, especially in the public administration and public health sector, and that catering trade is not considered here. Consequently it can be assumed that the red graph will also not bend down as the blue one does due to the Corona crisis once the respective data are released by the statistical offices.

Furthermore, neither any influence of the 2003 heat wave nor of the 2018–2019 drought on the narrower service sector can be spotted in Figure 10, even the slight slowdown of the general economy during the recent drought is not mirrored in the service sector development. A similar picture is conveyed from the percentages of this sector in the total economy measured in actual prices as seen in Figure 11: The services share even climbed a new record during the recent drought; the long-term trend of slowly deteriorating importance of the primary and secondary economic sectors seems unbroken.

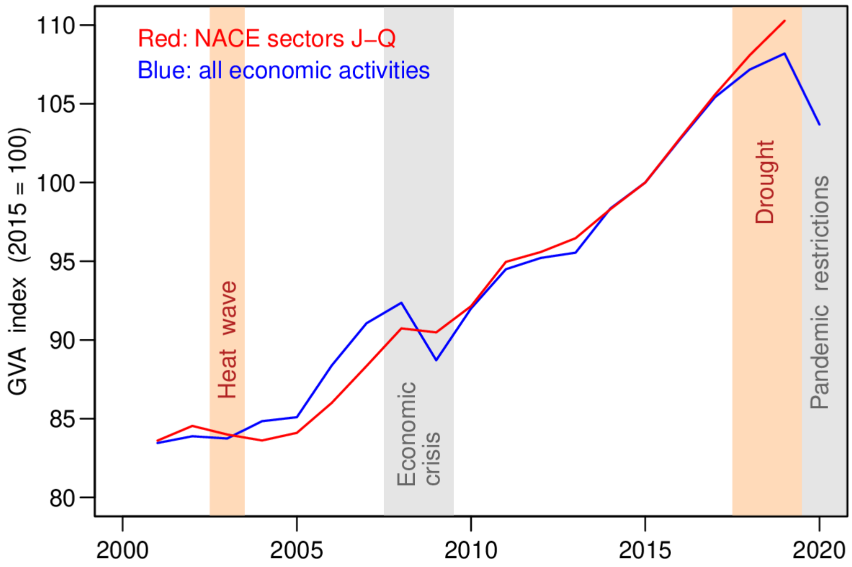

Figure 10: Relative developments of the gross value added for the narrower service sector (red) and the entire economy (blue) in the five-state aggregate. Index values, chained and corrected for inflation. Data source: Statistische Ämter (2021a).

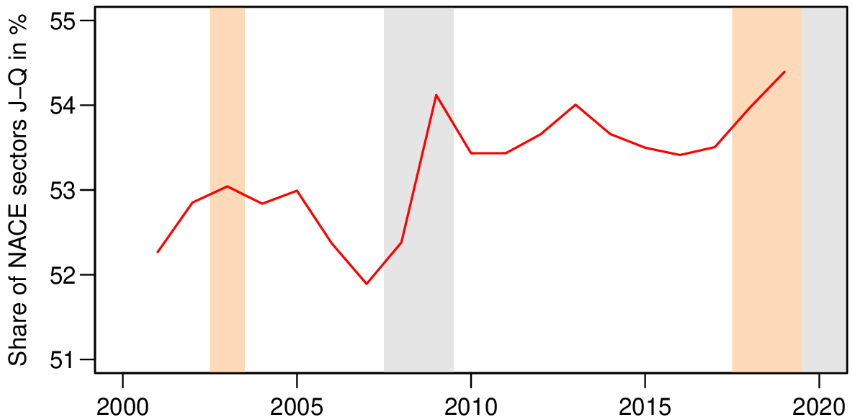

Figure 11: Share of the the narrower service sector in the total GVA of the five-state aggregate, calculated from absolute GVA figures in actual prices. Data source: Statistische Ämter (2021a).

We close this subsection by peeking into the market for air conditioning systems in Germany which may serve as indicator for uncomfortable heat in offices. There is a highly detailed statistics about production and trade in the EU maintained by Eurostat, PRODCOM (Eurostat 2021b). It subdivides the NACE classification of economic activities further down to product groups. The way to air conditioning leads from NACE sector C (Manufacturing) and its group 28 (Manufacture of machinery and equipment n.e.c.) via subgroup 28.2 (Manufacture of other general-purpose machinery) to class 28.25 (Manufacture of non-domestic cooling and ventilation equipment). Non-domestic means the exclusion of household devices, but professional ice-making and gas liquefying machines are still included as well as isolated heat pumps. The so-called PRODCOM list details further subcategories, and 28.25.12 is the one limited to air conditioning machines, however those for motor vehicles and special types are still included here. So finally we end up at PRODCOM code 28.25.12.20 – Window or wall air conditioning systems, self-contained or split-systems. Figure X.28 shows the sales volumes of German manufacturers and Germany's international trade in this kind of workspace air conditioning.

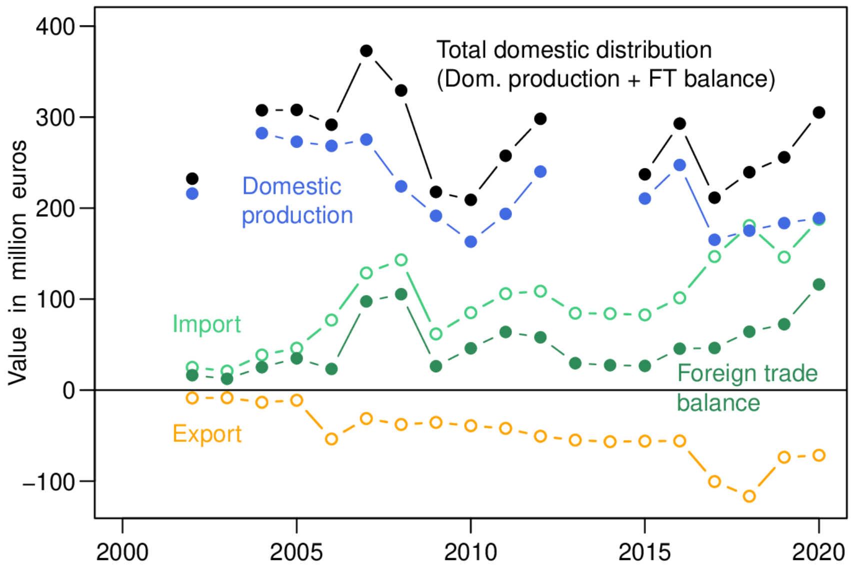

Figure 12: Visualisation of the PRODCOM statistics on sold production and foreign trade of professional window or wall air conditioning systems for Germany (Source: Eurostat 2021b).

The import/export values have a high coherence and reliability, because German customs scrutinize every parcel crossing the border. The net balance of the foreign trade reveals a clear but hysteretic response to the 2006 heat wave: In 2007 and 2008 the imports exceeded the exports by approx. 100 million euro p.a. The same hysteresis can be observed for the recent drought: It took until 2020, two years after drought onset, to return to the same elevated level of annual net imports.

The sales from domestic producers are however sketchy and incomplete, because this part of the statistics relies on individual enterprise reports. The black graph on top of the others in Figure 12 should provide the combined inland distribution of domestically produced and imported air conditioning units; no clear response to sunny and dry summers can be seen any more from these numbers, though. At least there is the impression of a tendency towards lower production output from German manufacturers, but this is misleading as Figure 13 demonstates.

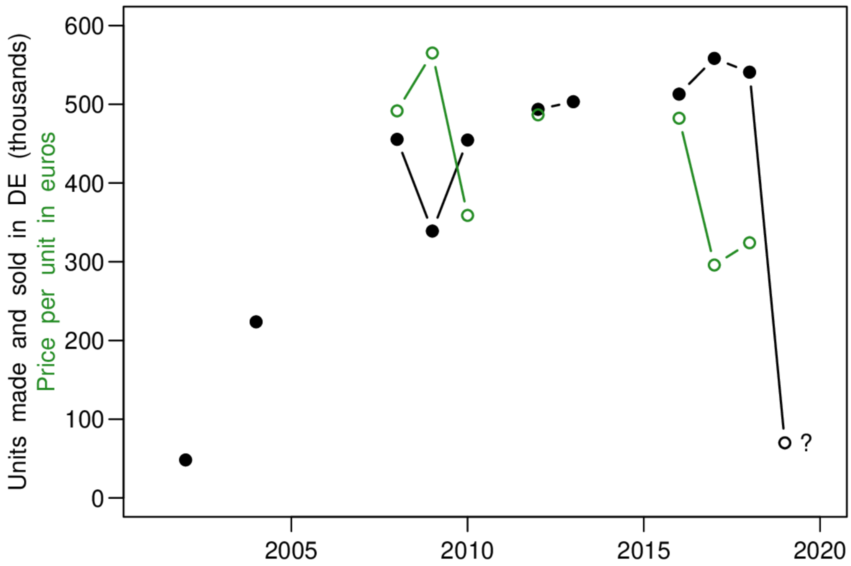

Figure 13: Annual counts of air conditioning units made and sold in Germany (black), and the average price per unit (green). Source: Eurostat (2021b).

Here we have some actual counts of individual air conditioning devices (units) produced and sold by German manufacturers plus their average prices calculated from the associated production values shown in Figure 12. The production breakdown in 2019 shown in Figure 13 is very probably an error, note the stable development in production value in Figure 12; Eurostat has already been contacted regarding that inconsistency.

Aside from that, it seems that the production of air conditioning sets in Germany gained momentum in the first years of the millenium, and there might be still an increasing trend in output while the average prices fell from about 500 €/unit ten years ago to about 300 €/unit recently. So a general market emergence owing to climate change is temporally topped with elevated demand in years following summers that were exceptionally dry and hot, the latter being matched through foreign trade. Hence office air condition will probably become less extraordinary in the GEB in the near future.

1.2.8.2 Defence

The only military stationed in Eastern Germany, and consequently in most of the GEB, is the German army (*Bundeswehr*), other NATO allies have to stay outside this region as stipulated in Article 5 of the reunification treaty, officially “Treaty on the Final Settlement with respect to Germany” (BGBl. 1990 II S. 1317). The Ministry of Defence in Berlin and the military headquarters near Potsdam are also located in the GEB. How the defence readiness condition is affected by drought belongs to the domain of state secrets, though. But there were some news regarding military operations and drought-furthered forest fires:

Wildfires driven by the extreme drought event in 2018 and 2019 involved the German army. This was the case when military supported the fighting of a wildfire near Potsdam with helicopters and tanks (ZEIT ONLINE 2018a, Spiegel 2018).

Some wildfires the troops were fighting were obviously started by themselves. This happened in 2018 in Saxony during a maneuver, the fire was successfully fought by the military fire fighters at the same day (T-Online 2018a). Another wildfire burning more than 900 ha of forest started in 2019 on the former military training range Lübtheen (about 53°17N, 11°09E). Due to the site's contamination with ammunition (it had been in military use during 1936–2013) army troops and regular firefighters could not fight the fire from a short distance which made the operation difficult (Spiegel 2019a).

1.2.8.3 Education

Schools responded to the extreme heat events during summer months of 2018 and 2019 with shortened lessons or cancellation of afternoon courses (MOZ.de 2018, 2019, LVZ 2019, Nordkurier 2019). In BB and ST changes in the timetables are regulated by temperature measurements in classrooms or on the schoolyard at a certain time, whereas in SN and in TH this decision is made without concrete temperature measurements (Süddeutsche Zeitung 2019a).

1.2.8.4 Arts, entertainment and recreation (including tourism)

The extreme drought conditions increased the potential of wildfires during 2018 and 2019 and thereby forced music and art festivals to delay or cancellation (RP ONLINE 2018; MAZ Online 2018, Niederlausitz Aktuell 2018, WELT 2018, Tagesspiegel 2018, T-Online 2018b). Traditional Easter fires were cancelled for the same reason in 2019 (PNN 2019, Tagesspiegel 2019b).

As another consequence, entering forest areas during nights was not allowed in the Saxon national park "Sächsische Schweiz" during spring and summer of 2019 (Sächsische.de 2019a,b).

The drought events affected tourism in the GEB in multiple ways. Forms of tourism depending on water availability in the first order were most affected. For instance, boating trips could not take place on the Elbe River during the recent extreme drought event (Süddeutsche Zeitung 2019c). In 2020 the drought had impacts on canoeing tourism because locks had to be kept close in order to avoid drainage of the river system (Tagesspiegel 2020).

Camping tourism is generally affected by changing weather conditions. Statistics of camping tourism in the four federal states agree in an increase in arriving visitors and overnight stays in 2018 and 2019. The increase in arriving visitors amounts to 17 % in 2018 and to 31 % in 2019 compared to the three-year average of 2015–2017. Overnight stays increased by 14 % in 2018 and 28 % in 2019 respectively.

The 2018 and 2019 reports for TH (Statistik TH 2016–2020) suggest the majority of increasing visitors of camping sites and overnight stays to be domestic tourists. The relative increase of domestic visitors was 13.5 % (9.4 %) and 1.9 % (2.6 %) for visitors from foreign countries in 2018 (2019). This is in line with data from BB (Statistik BB 2016–2021). Tourism reports for SN and ST do not cover the tourists' country of origin (Statistik SN 2020, Statistik ST 2020). The increased share of local tourists at campsites during 2018 and 2019 suggests more spontaneous camping trips which may have been attracted by the sunny weather conditions.

Swimming pool operators clearly benefitted from the warm and dry swimming season in 2018. Several visiting records have been thrown during the warm and dry period covering all summer months in 2018 (Cellesche Zeitung 2018, Sächsische.de 2018).

1.3 Conclusions

Electricity and tap water supplies could still be maintained, and despite an increased heat load on large parts of the workforce no drought-related disruptions in industry and service sectors could be observed in this part of Germany. Some special branches were even benefitting from the sunny weather, e.g. winemaking or domestic tourism. Only the global financial crisis of 2008/2009 and the global pandemic of 2020ff left significant dents in the principal econometric time series of the last two decades. There will for sure be some long-term consequences of the recent extreme drought like low groundwater levels, reforestations, investments in water procurement, scattered deployments of air conditioning systems; but it seems the GEB is very drought resilient – still.

Pfister (2018) analysed the extreme Central European drought of 1540: Disregarding a million of deaths from diarrhea – because wells were dried out and people resorted to polluted water bodies – the pre-industrial society proved to be astonishingly resilient. This study however points out that a drought of this magnitude may threaten a modern society through long-lasting power blackouts caused by lack of cooling water. We have seen that the backbone of the electricity supply in the GEB, lignite-fired power stations, use sump water from the nearby open-cast mining areas and closed-loop systems for cooling and are thus not affected. So, can any substantial drought dangers for the GEB emerge in the future, any effects dwarfing the 2018/2019 experiences?

What we have not seen in the GEB so far are cascading drought effects to which the CROSSDRO research project promised to pay particular attention. A glimpse on connected failures was however already possible in Western Germany: Navigation on the Rhine River was hampered by low water levels in 2018, and this caused interruptions and price spikes in petrol and diesel fuel supplies; parts of the national oil reserve were released with limited relaxing effect. Furthermore, parts of the BASF chemical production at Ludwigshafen and a Thyssen-Krupp steel mill in Duisburg had to be shut down in October (ZEIT ONLINE 2018b). The financial losses amounted to 250 million euro for BASF alone (WELT 2019), and were estimated at about two billion euro for all industries affected along the river (IKSR 2020).

This might not seem relevant for the Elbe river, because there are only few industries and there is no such dependency on navigation as along the Rhine. But the drought-resistant lignite power plants will soon be phased out together with every other coal plant in Germany – 2038 according to the current plan, probably even earlier in order to achieve the national greenhouse gas emission reduction targets. And this will elevate the risk for extended power outages, because a regulating reserve of conventional power plants is urgently needed to balance the variable contributions from wind and photovoltaics. This is a major threat that extends beyond the GEB:

The share of renewable sources in the German gross electricity production is steadily increasing. In 2010 it was at 17.7 %, and in 2019 40.9 % were reached (Eurostat 2021a). Germany's 2018 renewables' share, 36.0 %, was higher than the the EU28 average of 33.0 % which in turn exceeded the 30.6 % share of the five-state aggregate in that year (the last one reported by LAK Energiebilanzen 2021, see Fig. X.23). However, the fossil fuel dominance in the GEB area will suddenly crumble away with the coal ban, leaving only a gas-fueled production of currently less than 20 TWh/year. The German nuclear plants will go into permanent shutdown already at the end of 2021 which will make all of Germany dependent on nuclear and fossil power plants in the neighbour states. And heat and drought-related throttlings and shutdowns were also reported from these: In 2018, two Swiss nuclear plants and three French reactors were affected (IKSR 2020, La Tribune 2019).

Extreme droughts in Central Europe will certainly become more frequent under climate change (Hari et al. 2020) while the resilience of the European electricity grid is challenged by the ongoing transition towards renewable energy sources. The possible blackout scenario could easily extend to larger parts of Europe causing cascading consequences way beyond what is currently associated with "drought effects". Respective studies, e.g. Pescaroli et al. (2017), and especially the comprehensive assessment for Germany by Petermann et al. (2011, English language version) are recommended reads.

1.4 References

Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Zickfeld (2018) Framing and Context. Chapter 1 in: Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change, Geneva. URL https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter1_Low_Res.pdf – Last accessed in May 2021

Auerswald, H., G. Vogt (2010) Zur Klimasensitivität der Wirtschaft in der Region Dresden. ifo Dresden berichtet 17 (3) 15–23. ISSN 0945-5922, ifo Institut, Dresden. URL https://www.econstor.eu/bitstream/10419/169915/1/ifo-db-v17-y2010-i03-p15-23.pdf – Last accessed in August 2021.

Ballmann, H., S. Bärisch, A. Böhm, J. Franke, G. Füllner, A. Hausmann, I. John, K. Kuhn, A. Thiem, A. Völlings, R. Schreyer (2017) Auswirkungen des Klimawandels auf die Perspektiven in der sächsischen Teichwirtschaft. Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG), Dresden. URL https://publikationen.sachsen.de/bdb/artikel/28070 – Last accessed in September 2021.

BDEW-DVGW-VKU (2021) Bedarfe der Wasserversorgung in Zeiten des Klimawandels – Maßnahmenvorschläge des BDEW, DVGW und VKU zur Sicherung der Wasserversorgung. DVGW Deutscher Verein des Gas- und Wasserfaches e. V., Bonn, Bundesverband der Energie- und

Wasserwirtschaft e. V., Berlin, and VKU Verband kommunaler Unternehmen e. V., Berlin, 4 pp. URL https://www.bdew.de/media/documents/210621_BDEW_DVGW_VKU_Positionspapier_Klimawandel_und_Trockenheit.pdf – Last accessed in August 2021.

Beguería, S., S. M. Vicente-Serrano, F. Reig, B. Latorre (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. International Journal of Climatology 34 (10) 3001–3023. doi:10.1002/joc.3887

Beguería, S., S. M. Vicente-Serrano (2017) Package 'SPEI' – Calculation of the Standardised Precipitation-Evapotranspiration Index. R software package, version 1.7. URL: https://CRAN.R-project.org/package=SPEI – Last accessed in May 2021.

BGBl. 1990 II S. 1317 – Gesetz zu dem Vertrag vom 12. September 1990 über die abschließende Regelung in bezug auf Deutschland. Bundesgesetzblatt 1990, Part II, pp 1317–1329. URL http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl290s1317.pdf – Last accessed in September 2021. This is actually the German law ratifying the treaty. The four-language text of the treaty is included, and the English version of Article 5 is split between pages 1322 and 1324.

BMEL (2021) Ergebnisse der Waldzustandserhebung 2020. Bundesministerium für Ernährung und Landwirtschaft (BMEL), Bonn. 72 pp. URL: https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/ergebnisse-waldzustandserhebung-2020.pdf – Last accessed in August 2021.

BMF (n.d.) Haushaltsrechnung des Bundes für das Haushaltsjahr 2019, vol. 1. Bundesministerium der Finanzen, Berlin, 4+127 pp. URL https://www.bundeshaushalt.de/fileadmin/de.bundeshaushalt/content_de/dokumente/2019/ist/HR_2019_Band1.pdf – Last accessed in September 2021.

BMU (2021) Nationale Wasserstrategie – Entwurf des Bundesumweltministeriums. Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit (BMU), Bonn, 76 pp. URL https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Binnengewaesser/langfassung_wasserstrategie_bf.pdf – Last accessed in August 2021. An English summary is available via URL https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Binnengewaesser/kurzfassung_wasserstrategie_en_bf.pdf

Brämick, U. (n.d.) Jahresbericht zur Deutschen Binnenfischerei. Vols 2018 and 2019, 58 and 61 pp, respectively. Institut für Binnenfischerei e.V., Potsdam-Sacrow. URL https://ifb-potsdam.de/de-de/ver%C3%B6ffentlichungen/downloads.aspx – Last accessed in August 2021.

Brázdil, R., P. Dobrovolný, M. Bauch, C. Camenisch, A. Kiss, O. Kotyza, P. Oliński, L. Řezníčková (2020) Central Europe, 1531–1540 CE: The driest summer decade of the past five centuries? Climate of the Past 16 (6) 2125–2151. doi:10.5194/cp-16-2125-2020

Büntgen, U., O. Urban, P. J. Krusic, M. Rybníček, T. Kolář, T. Kyncl, A. Ač, E. Koňasová, J. Čáslavský, J. Esper, S. Wagner, M. Saurer, W. Tegel, P. Dobrovolný, P. Cherubini, F. Reinig, M. Trnka (2021) Recent European drought extremes beyond Common Era background variability. Nature Geoscience 14 (4) 190–196+12 pp. doi:10.1038/s41561-021-00698-0

Bussgeldkatalog.org (2020) Wassernotstand in Deutschland – Bußgeld für Wasserentnahme. Online news, 26th August 2020. URL https://www.bussgeldkatalog.org/news/wassernotstand-in-deutschland-bussgeld-fuer-wasserentnahme-2880364/ – Last accessed in August 2021.

Buth, M., W. Kahlenbom, J. Savelsberg, N. Becker, P. Bubeck, S. Kabisch, C. Kind, A. Tempel, F. Tucci, S. Greiving, M. Fleischhauer, C. Lindner, J. Lückenkötter, M. Schonlau, H. Schmitt, F. Hurth, F. Othmer, R. Augustin, D. Becker, M. Abel, T. Bornemann, H. Steiner, M. Zebisch, S. Schneiderbauer, C. Kofler (2015) Vulnerabilität Deutschlands gegenüber dem Klimawandel. Climate Change 24/2015, UBA-FB 002226. Umweltbundesamt, Dessau-Roßlau, 688 pp. URL https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_24_2015_vulnerabilitaet_deutschlands_gegenueber_dem_klimawandel_1.pdf – Last accessed in August 2021.

Bux, K. (2006) Klima am Arbeitsplatz – Stand arbeitswissenschaftlicher Erkenntnisse – Bedarfsanalyse für weitere Forschungen. Final report of the research project F 1987, Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, Dortmund, Berlin, and Dresden, 33 p. URL https://www.baua.de/DE/Angebote/Publikationen/Berichte/Gd45.pdf – Last accessed in September 2021.

Cellesche Zeitung (2018) Bis zu viermal so viele Badegäste. Online news, 12th October 2018, 15:25. URL https://www.cz.de/Celler-Land/Aus-dem-Landkreis/Bis-zu-viermal-so-viele-Badegaeste – Last accessed in September 2018.

Cherlet, M., C. Hutchinson, J. Reynolds, J. Hill, S. Sommer, G. von Maltitz (eds) (2018) World Atlas of Desertification – Rethinking land degradation and sustainable land management. 3rd edition. Publication Office of the European Union, Luxemburg. ISBN 978-92-79-75350-3. doi:10.2760/06292

Copernicus (2020) CORINE Land Cover (CLC) 2018, version v.2020_20u1, downloaded in March 2021. Source: Copernicus Land Monitoring Service, part of the European Earth monitoring programme (GMES). URL: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

DESTATIS (2011–2021) Wachstum und Ernte – Feldfrüchte. Fachserie 3, Reihe 3.2.1. Statistisches Bundesamt, Wiesbaden. URL https://www.statistischebibliothek.de/mir/receive/DESerie_mods_00000335 – Last accessed in August 2021.

DESTATIS (2012–2021) Erzeugung in Aquakulturbetrieben. Fachserie 3 Reihe 4.6. Statistisches Bundesamt, Wiesbaden. URL https://www.statistischebibliothek.de/mir/receive/DESerie_mods_00000531 – Last accessed in August 2021

DESTATIS (2019a) Bevölkerung im Wandel – Annahmen und Ergebnisse der 14. koordinierten Bevölkerungsvorausberechnung. Short report, 69 pp. Statistisches Bundesamt, Wiesbaden. URL https://www.destatis.de/DE/Presse/Pressekonferenzen/2019/Bevoelkerung/pressebroschuere-bevoelkerung.pdf – last accessed in April 2021.

DESTATIS (2019b) Öffentliche Wasserversorgung und öffentliche Abwasserentsorgung. Fachserie 19 Reihe 2.1.1., 78+22 pp. Statistisches Bundesamt, Wiesbaden. URL https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Wasserwirtschaft/Publikationen/Downloads-Wasserwirtschaft/wasser-oeffentlich-2190211169004.pdf – last accessed in June 2021.

DESTATIS (2019c) Umweltnutzung und Wirtschaft – Tabellen zu den Umweltökonomischen Gesamtrechnungen. Teil4: Wassereinsatz, Abwasser. Ausgabe 2019. Statistisches Bundesamt, Wiesbaden, 30 pp. URL https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/rohstoffe-materialfluesse-wasser/Publikationen/Downloads/umweltnutzung-und-wirtschaft-tabelle-5850007197006-teil-4.pdf – Last accessed in August 2021.

DESTATIS (2020a) Verwaltungsgliederung am 31.12.2019. Excel file, 46kB. Statistisches Bundesamt, Wiesbaden. URL: https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/Administrativ/Archiv/Verwaltungsgliederung/31122019_Jahr.html – last accessed in April 2021.

DESTATIS (2020b) Bodenfläche nach Art der tatsächlichen Nutzung 2019. Fachserie 3 Reihe 5.1, 409+24 pp. Statistisches Bundesamt, Wiesbaden. URL https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Flaechennutzung/Publikationen/Downloads-Flaechennutzung/bodenflaechennutzung-2030510197004.pdf – last accessed in August 2021

DESTATIS (2020c) Entgelt für die Trinkwasserversorgung in Tarifgebieten nach Tariftypen 2017 bis 2019. Webpage with data table, status 26th June 2020. Statistisches Bundesamt, Wiesbaden. URL https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Wasserwirtschaft/Tabellen/tw-07-entgelt-trinkwasserversorgung-tarifgeb-nach-tariftypen-2017-2019-land-bund.html – Accessed in September 2021.

DESTATIS (2021a) Schutzsuchende – Anteil an der Bevölkerung insgesamt in % – Stichtag 31.12.2019. Online map. Statistisches Bundesamt, Wiesbaden. URL: https://service.destatis.de/DE/karten/migration_integration_regionen.html#A2_Sch_i – last accessed in April 2021.

DESTATIS (2021b) Flächengröße des Waldes nach Bundesländern, Statistisches Bundesamt. Available at: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Wald-Holz/Tabellen/waldflaeche-bundeslaender.html (Accessed: 28 July 2021).

DESTATIS (2021c) Holzeinschlag: Bundesländer, Jahre, Holzsorten, Holzartengruppen, Waldeigentumsarten. Table 41261-0011 of the Genesis database. Online resource, Statistisches Bundesamt, Wiesbaden. URL: https://www-genesis.destatis.de/genesis//online?operation=table&code=41261-0011#astructure – accessed in August 2021.

DESTATIS (2021d) Schadholzeinschlag: Bundesländer, Jahre, Einschlagsursache, Holzartengruppen, Waldeigentumsarten. Table 41261-0012 of the Genesis database. Online resource, Statistisches Bundesamt, Wiesbaden. URL: https://www-genesis.destatis.de/genesis//online?operation=table&code=41261-0012#astructure – accessed in August 2021.

DESTATIS (2021e) Güterverkehr – Beförderungsmenge und Beförderungsleistung nach Verkehrsträgern. Website with data table, status of 11th November 2020. URL https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/gueterbefoerderung-lr.html – Accessed in September 2021.

DESTATIS (2021f) Beförderte Güter (Binnenschifffahrt): Deutschland, Jahre, Gefahrgut, Wasserstraßen, Güterverzeichnis (Abteilungen). Table 46321-0013 of the Genesis database. Online resource, Statistisches Bundesamt, Wiesbaden. URL: https://www-genesis.destatis.de/genesis//online?operation=table&code=46321-0013#astructure – accessed in September 2021.

DESTATIS (2021g) Empfang und Versand von Gütern (Seeverkehr): Deutschland, Monate, Ausgewählte Häfen, Ladungsarten. Table 46331-0007 of the Genesis database. Online resource, Statistisches Bundesamt, Wiesbaden. URL: https://www-genesis.destatis.de/genesis//online?operation=table&code=46331-0007#astructure – accessed in September 2021.

DESTATIS (2021h) Bevölkerung und Erwerbstätigkeit Bevölkerungsfortschreibung auf Grundlage des Zensus 2011. Fachserie 1, Reihe 1.3 – 2019. Statistisches Bundesamt, Wiesbaden. URL https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Publikationen/Downloads-Bevoelkerungsstand/bevoelkerungsfortschreibung-2010130197004.pdf – Last accessed in September 2021.

Dietrich, O., J. Steidl, D. Pavlik (2012) The impact of global change on the water balance of large wetlands in the Elbe Lowland. Regional Environmental Change 12 (4) 701–713. doi: 10.1007/s10113-012-0286-5.

DStGB (2021) Wassermanagement in Zeiten von Hitze & Dürre – 10 Thesen & Forderungen des DStGB. DStGB Deutscher Städte- und Gemeindebund, Berlin-Lichterfelde, 2 pp. URL https://www.dstgb.de/themen/wasser-und-abwasser/aktuelles/aktives-wassermanagement-erforderlich/hitze-duerre-160621.pdf – Last accessed in August 2021.

DWD (2021) Klimadaten Deutschland: Monats- und Tageswerte von 76 ausgewählten Messstationen in Deutschland. Deutscher Wetterdienst, Wiesbaden. URL https://www.dwd.de/DE/leistungen/klimadatendeutschland/klimadatendeutschland.html – Last accessed in September 2021.

DWD-CDC (2021a) DWD Climate Data Center (CDC): Grids of monthly averaged daily air temperature (2m) over Germany, version v1.0. ASCII files. Deutscher Wetterdienst, Wiesbaden. URL: https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/air_temperature_mean/ – last accessed in May 2021.

DWD-CDC (2021b) DWD Climate Data Center (CDC): Grids of monthly total precipitation over Germany, version v1.0. ASCII files. Deutscher Wetterdienst, Wiesbaden. URL: https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/precipitation/ – last accessed in May 2021.

DWD-CDC (2021c) DWD Climate Data Center (CDC): Grids of monthly total sunshine duration over Germany, version v1.0. ASCII files. Deutscher Wetterdienst, Wiesbaden. URL: https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/sunshine_duration/ – last accessed in May 2021.

DWD-CDC (2021d) DWD Climate Data Center (CDC): Historical heat warnings in Germany, version 001. Deutscher Wetterdienst, Wiesbaden. URL https://opendata.dwd.de/climate_environment/health/historical_alerts/heat_warnings/ – Last accessed in September 2021.

Edebohls, I., T. Lasner, U. Focken, C. Kreiß, S. Reiser (2021) Steckbriefe zur Tierhaltung in Deutschland: Aquakultur. Thünen-Institut, Bremerhaven, 26 pp. URL https://www.thuenen.de/media/institute/fi/Aktuelles/Steckbrief_Aquakultur_in_Deutschland_2021.pdf – Last accessed in September 2021.

Edenhofer, O., P. Hoffmann (2021) Analyse des Klimawandels für die Deutsche Bahn: Studie zur räumlichen Ausprägung in Deutschland. Slideshow of the press conference on 18th June 2021. URL https://www.deutschebahn.com/resource/blob/6249150/5b885297f5d854d53bae429c05de3908/20210618_PIK-Studie-Slides-data.pdf – Last accessed in September 2021.

Eurostat (2016) GEOSTAT 1km² population grid 2011. Version 2.0.1 of 01/02/2016. European Commission, Eurostat, Luxembourg. URL: https://ec.europa.eu/eurostat/cache/GISCO/geodatafiles/GEOSTAT-grid-POP-1K-2011-V2-0-1.zip – Last accessed in March 2021

Eurostat (2021a) Eurostat data base. URL https://ec.europa.eu/eurostat/data/database – Last accessed in April 2021.

Eurostat (2021b) PRODCOM – Overview. Web page with explanations and links to the relevant sections of the Eurostat data base and further documents. URL https://ec.europa.eu/eurostat/web/prodcom – Last accessed in September 2021.

EWP (2021) Wasserforschung zur Anpassung an den Klimawandel – Beiträge aus der DVGW energie | wasser-praxis. Special collection of articles, DVGW Energie | Wasser-Praxis, 66 pp. URL https://www.energie-wasser-praxis.de/fileadmin/heftarchiv/2021/ewp-dossier_wasserforschung.pdf – Last accessed in August 2021.

FGG Elbe (2015) Aktualisierung des Bewirtschaftungsplans nach § 83 WHG bzw. Artikel 13 der Richtlinie 2000/60/EG für den deutschen Teil der Flussgebietseinheit Elbe für den Zeitraum von 2016 bis 2021. Flussgebietsgemeinschaft Elbe, Magdeburg, xvii + 240 pp. URL: https://www.fgg-elbe.de/berichte/aktualisierung-nach-art-13.html – Last accessed in March 2021.

Forst Brandenburg (2020) Waldzustandsbericht 2020 des Landes Brandenburg. Ministerium für Landwirtschaft, Umwelt und Klimaschutz des Landes Brandenburg, Landesbetrieb Forst Brandenburg, Eberswalde, 38 pp. URL https://mluk.brandenburg.de/sixcms/media.php/9/Waldzustandsbericht-BB-2020.pdf – Last accessed in September 2021.

FR (2019) Klimawandel macht auch der Bahn zu schaffen. Online news. Frankfurter Rundschau, 5th August 2019, 15:05. URL https://www.fr.de/wissen/klimawandel-macht-auch-bahn-schaffen-12881785.html – Last accessed in September 2021.

Grünewald, U. (2001) Water resources management in river catchments influenced by lignite mining. Ecological Engineering 17 (2–3) 143–152. doi:10.1016/S0925-8574(00)00154-3

Grünewald, U. (2010) Wasserbilanzen der Region Berlin–Brandenburg. Diskussionspapier 7, Berlin-Brandenburgische Akademie der Wissenschaften, Interdisziplinäre Arbeitsgruppe »Globaler Wandel – Regionale Entwicklung«, Berlin, 57 pp. URL https://edoc.bbaw.de/files/278/diskussionspapier_7_gruenewald_online.pdf – last accessed in June 2021.

Haeseler, S. (2017) Sturmtief XAVIER zieht am 5. Oktober 2017 mit Orkanböen über Deutschland. Deutscher Wetterdienst, Abteilung Klimaüberwachung, Wiesbaden. 8 pp. URL https://www.dwd.de/DE/leistungen/besondereereignisse/stuerme/20171009_sturmtief_xavier_deutschland.pdf – Last accessed in August 2021.

Haeseler, S., C. Lefebvre (2017) Sturmtief HERWART sorgt am 28./29. Oktober 2017 für Orkanböen über Deutschland. Deutscher Wetterdienst, Abteilung Klimaüberwachung, Wiesbaden. 6 pp. URL https://www.dwd.de/DE/leistungen/besondereereignisse/stuerme/20171030_herwart_europa.pdf – Last accessed in August 2021.

Haeseler, S. C. Lefebvre, P. Bissolli, J. Daßler, B. Mamtimin (2018) Orkantief FRIEDERIKE wütet am 18. Januar 2018 über Europa. Deutscher Wetterdienst, Abteilung Klimaüberwachung, Wiesbaden. 6 pp. URL https://www.dwd.de/DE/leistungen/besondereereignisse/stuerme/20180123_friederike_europa.pdf – Last accessed in August 2021.

Hari, V., O. Rakovec, Y. Markonis, M. Hanel, R. Kumar (2020) Increased future occurrences of the exceptional 2018–2019 Central European drought under global warming. Nature Scientific Reports 10, 12207 (10 pp). doi:10.1038/s41598-020-68872-9

Hayes, M., M. Svoboda, N. Wall and M. Widhalm (2011) The Lincoln Declaration on Drought Indices: Universal Meteorological Drought Index Recommended. Bulletin of the American Meteorological Society, 92 (4) 485–488. doi:10.1175/2010BAMS3103.1

Heklau, H., G. Jetschke, H. Bruelheide, G. Seidler, S. Haider (2019) Species-specific responses of wood growth to flooding and climate in floodplain forests in Central Germany. iForest - Biogeosciences and Forestry 12 (3) 226–236. doi:10.3832/ifor2845-012

Hooyberghs, H., S. Verbeke, D. Lauwaet, H. Costa, G. Floater, K. De Ridder (2017) Influence of climate change on summer cooling costs and heat stress in urban office buildings. Climatic Change 144 (4) 721–735. doi:10.1007/s10584-017-2058-1

Hoymann, J., J. Dekkers, E. Koomen (2016) Szenarien zur Siedlungsflächenentwicklung. In: Wechsung, F., V. Hartje, S. Kaden, M. Venohr, B. Hansjürgens, P. Gräfe (eds) Die Elbe im globalen Wandel – Eine integrative Betrachtung. Vol. 9 in series Konzepte für die nachhaltige Entwicklung einer Flusslandschaft. Chapter 2.6, pp 135–175. Schweizerbart Science Publishers, Stuttgart, Germany. ISBN 978-3-510-65306-5.

Humphries, P. and Baldwin, D. S. (2003) Drought and aquatic ecosystems: an introduction. Freshwater Biology 48 (7) 1141–1146. doi:10.1046/j.1365-2427.2003.01092.x

Hünefeld, L., A. Hünefeld (2019) Arbeiten im Freien – Beschäftigte vor UV-Strahlung schützen: BIBB/BAuA-Faktenblatt 29. doi:10.21934/baua:fakten20190628.

IKSR (2020) Bericht zum Niedrigwasserereignis Juli–November 2018. Report no. 263. Internationale Kommission zum Schutz des Rheins (IKSR), Koblenz, 18 pp. URL https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/DE/rp_De_0263.pdf – Last accessed in September 2021.

ILO (2019) Working on a warmer planet – The impact of heat stress on labour productivity and decent work. International Labour Office, Geneva, 103 pp. ISBN 978-92-2-132967-1 (print), ISBN 978-92-2-132968-8 (web pdf). URL https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_711919.pdf – Last accessed in August 2021.

IMAA (2019) Monitoringbericht 2019 zur Deutschen Anpassungsstrategie an den Klimawandel. Interministerielle Arbeitsgruppe Anpassungsstrategie der Bundesregierung (IMAA). Ed. by P. van Rüth, K. Schönthaler, M. Buth. Umweltbundesamt, Dessau-Roßlau, 272 pp. URL https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/das_monitoringbericht_2019_barrierefrei.pdf – Last accessed in August 2021.

Jendritzky, G. (1990) Bioklimatische Bewertungsgrundlage der Räume am Beispiel von mesoskaligen Bioklimakarten. In: Jendritzky, G., H. Schirmer, G. Menz, W. Schmidt-Kessen: Methode zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima-Michel-Modell). Beiträge der Akademie für Raumforschung und Landesplanung 114, pp 7–69. Akademie für Raumforschung und Landesplanung, Hannover. ISBN 3-88838-207-6

Jendritzky, G., W. Sönning, H. J. Swantes (1979) Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt- und Landschaftsplanung („Klima-Michel-Modell“). Beiträge der Akademie für Raumforschung und Landesplanung 28. Schroedel, Hannover, 85 pp. ISSN 0587-2642, ISBN 3-507-91498-0

Jendritzky, G., P. Bröde, D. Fiala, G. Havenith, P. Weihs, E. Batchvarova, R. DeDear (2010) Der Thermische Klimaindex UTCI. Klimastatusbericht 2009, pp 96–101. Deutscher Wetterdienst, Offenbach. ISSN 1437-7691 (print) / 1616-5063 (online), ISBN 978-3-88148-447-3. URL https://www.dwd.de/DE/leistungen/klimastatusbericht/publikationen/ksb2009_pdf/artikel11.pdf – Last accessed in September 2021.

Kabisch, N. and R. Kraemer (2020) Physical activity patterns in two differently characterised urban parks under conditions of summer heat. Environmental Science & Policy 107, 56–65. doi: 10.1016/j.envsci.2020.02.008.

Koch, H., M. Kaltofen, U. Grünewald, F. Messner, M. Karkuschke, O. Zwirner, M. Schramm (2005) Scenarios of water resources management in the Lower Lusatian mining district, Germany. Ecological Engineering 24 (1–2) 49–57. doi:10.1016/j.ecoleng.2004.12.006

Koch, H., S. Vögele, M. Kaltofen, M. Grossmann, U. Grünewald (2014) Security of Water Supply and Electricity Production: Aspects of Integrated Management. Water Resources Management 28 (6) 1767–1780. doi:10.1007/s11269-014-0589-z

Kohlenstatistik (2021) Statistik der Kohlenwirtschaft. Website. Statistik der Kohlenwirtschaft e.V., Bergheim. URL https://kohlenstatistik.de – Last accessed in August 2021.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, F. Rubel (2006) World Map of the Köppen–Geiger climate classification updated. Meteorologische Zeitschrift 15 (3) 259–263. doi:10.1127/0941-2948/2006/0130

Kreiszeitung-Wochenblatt (2021) Beiträge zum Trinkwasserverband Stader Land. Online news collection. Wochenblatt-Verlag Schrader, Buchholz, and Neue Buxtehuder Verlagsgesellschaft, Buxtehude. URL https://www.kreiszeitung-wochenblatt.de/tag/trinkwasserverband-stader-land – Accessed in August 2021.

Lachmann, M. (2016–2021) Waldbrandstatistik der Bundesrepublik Deutschland. Annual report. Bonn: Bundesanstalt für Landwirtschaft und Ernährung, Bonn. URLs https://www.ble.de/DE/BZL/Daten-Berichte/Wald/wald_node.html and https://www.bmel-statistik.de/forst-holz/waldbrandstatistik/ – Last accessed in September 2021.

LAK Energiebilanzen (2021) Energiebilanzen. Website with interactive tables of energy data for the German federal states. Länderarbeitskreis Energiebilanzen, Statistisches Landesamt Bremen. URL https://www.lak-energiebilanzen.de – Accessed in August 2021.

Lan, L., Z. Lian, L. Pan, Q. Ye (2009) Neurobehavioral approach for evaluation of office workers' productivity: the effects of room temperature. Building and Environment 44 (8) 1578–1588. doi:10.1016/j.buildenv.2008.10.004

LfU (2019) Luftqualität in Brandenburg – Jahresbericht 2019. Landesamt für Umwelt Brandenburg. Ministerium für Landwirtschaft, Umwelt und Klimaschutz (MLUK), Potsdam. URL https://lfu.brandenburg.de/sixcms/media.php/9/Luftqualitaet_BB_2019.pdf – Last accessed in September 2021.

Löpmeier, F.-J. (1993) Agrarmeteorologisches Modell zur Berechnung der aktuellen Verdunstung (AMBAV). Beiträge zur Agrarmeteorologie 1983 (7). Deutscher Wetterdienst, Zentrale Agrarmeteorologische Forschungsstelle Braunschweig, 55+22 pp.

Löpmeier, F.-J. (1994) Berechnung der Bodenfeuchte und Verdunstung mittels agrarmeteorologischer Modelle. Zeitschrift für Bewässerungswirtschaft 29 (2) 157–167.

Löpmeier, F.-J. (n.d.) Agrarmeteorologisches Modell zur Berechnung der aktuellen Verdunstung (AMBAV). DWD Climate Data Center (CDC), online PDF document, 39 pp. URL https://opendata.dwd.de/climate_environment/CDC/derived_germany/soil/daily/recent/AMBAV.pdf – Last accessed in June 2021.

LR Online (2018) Kühlwasser für Kraftwerke – Hitze bringt Energiebranche ins Schwitzen. Online news, Lausitzer Rundschau, 9th August 2018, 18:43. URL: https://www.lr-online.de/nachrichten/kuehlwasser-fuer-kraftwerke-hitze-bringt-energiebranche-ins-schwitzen-38089044.html – Last accessed in August 2021.

Ludewig, K., D. W. Donath, B. Zelle, R. L. Eckstein, E. Mosner, A. Otte, K. Jensen (2015) Effects of Reduced Summer Precipitation on Productivity and Forage Quality of Floodplain Meadows at the Elbe and the Rhine River. PLOS ONE, 10 (5) e0124140. doi:10.1371/journal.pone.0124140

Lühr, O., J.-P. Kramer, J. Lambert, C. Kind, J. Savelsberg (2014) Analyse spezifischer Risiken des Klimawandels und Erarbeitung von Handlungsempfehlungen für exponierte industrielle Produktion in Deutschland (KLIMACHECK). Study commissioned by the German Federal Ministry for Economic Affairs and Energy, Final report I C 4 - 02 08 15 - 30/12. Prognos AG in cooperation with Adelphi, Düsseldorf and Berlin, v + 110 pp. URL https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/analyse-spezifischer-risiken-des-klimawandels-und-erarbeitung-von-handlungsempfehlungen-fuer-exponierte-industrielle-produktion-in-deutschland-klimacheck.pdf – Last accessed in August 2021.

LVZ (2019) Heiße Woche in Sachsen: Hitzefrei an Schulen, Straßenschäden drohen. Online news, Leipziger Volkszeitung, 22nd June 2019, 09:34. URL https://www.lvz.de/Region/Mitteldeutschland/Heisse-Woche-in-Sachsen-Hitzefrei-an-Schulen-Strassenschaeden-und-Bahn-Probleme-drohen – Last accessed in August 2021.

Mahammadzadeh, M., E. Chrischilles, H. Biebeler (2013) Klimaanpassung in Unternehmen und Kommunen – Betroffenheiten, Verletzlichkeiten und Anpassungsbedarf. Analysen 83. Institut der deutschen Wirtschaft Köln Medien GmbH, Köln, 186 pp. ISBN 978-3-602-14904-9 (print), ISBN 978-3-602-45522-5 (e-book/PDF). URL: https://www.iwkoeln.de/fileadmin/user_upload/Studien/IW-Analysen/PDF/Bd._83_Klimaanpassung.pdf – Last accessed in August 2021.

Maltby, E., M. C. Acreman (2011) Ecosystem services of wetlands: pathfinder for a new paradigm. Hydrological Sciences Journal 56 (8) 1341–1359. doi:10.1080/02626667.2011.631014.

Maretzke, S., J. Hoymann, C. Schlömer, A. Stelzer (2021) Raumordnungsprognose 2040 – Bevölkerungsprognose: Ergebnisse und Methodik. BBSR-Analysen KOMPAKT 03/2021, 24 pp. Bundesinstitut für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung, Bonn, Germany. ISBN 978-3-87994-626-6. URL: https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/analysen-kompakt/2021/ak-03-2021-dl.pdf – Last accessed in March 2021.

Moravec, V., Y. Markonis, O. Rakovec, M. Svoboda, M. Trnka, R. Kumar, M. Hanel (2021) Europe under multi-year droughts: how severe was the 2014–2018 drought period? Environmental Research Letters 16 (3) 034062 (13 pp). doi:10.1088/1748-9326/abe828

MOZ.de (2018) Viele Schulen verkürzen Unterricht. Online news, MOZ.de/Märkisches Medienhaus GmbH & Co. KG, Frankfurt (Oder), 28th May 2018, 20:02. URL https://www.moz.de/lokales/oranienburg/hitzewelle-viele-schulen-verkuerzen-unterricht-48959500.html – Last accessed in August 2021.

MOZ.de (2019) Schulen gewähren Hitzefrei. Online news, MOZ.de/Märkisches Medienhaus GmbH & Co. KG, Frankfurt (Oder), 4th June 2019, 06:30. URL https://www.moz.de/lokales/beeskow/temperaturen-schulen-gewaehren-hitzefrei-48996618.html – Last accessed in August 2021.

de Martonne, E. (1926) L'indice d'aridité. Bulletin de l'Association de Géographes Français 9: 3–5. URL: https://www.persee.fr/doc/bagf_0004-5322_1926_num_3_9_6321 – last accessed in May 2021.

MAZ Online (2018) Festival wegen Waldbrandgefahr abgesagt. Online news, Märkische Allgemeine, 29th May 2018, 10:45. URL https://www.maz-online.de/Lokales/Maerkisch-Oderland/Festival-wegen-Waldbrandgefahr-abgesagt – Last accessed in August 2021.

McKee, T. B., N. J. Doesken and J. Kleist (1993) The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California,17–22 January 1993. Boston, American Meteorological Society, 179–184. URL https://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf – Last accessed in September 2021.

MDR.DE (2020) Schwere Zeiten für Sachsens Teichwirte. Online news, 8th November 2020, 15:25. https://www.mdr.de/nachrichten/sachsen/bautzen/bautzen-hoyerswerda-kamenz/teichwirte-haben-nicht-nur-wegen--corona-zu-kaempfen-100.html – Last accessed in July 2021.

Merkur (2018) Wegen Hitze-Sommer: Bahn meldet Schäden an Schienen bei Polling. Online news, Merkur.de, 5th October 2018, 16:42. URL https://www.merkur.de/lokales/weilheim/polling-weilheim-ort583340/polling-bahn-meldet-schaeden-an-schienen-wegen-hitze-10301636.html – Last accessed in September 2021.

Möhring, B., A. Bitter, G. Bub, M. Dieter, M. Dög, M. Hanewinkel, N. Graf v. Hatzfeldt, J. Köhler, G. Ontrup, R. Rosenberger, B. Seintsch, F. Thoma (2021) Abschätzung der ökonömischen Schäden der Extremwetterereignisse der Jahre 2018-2020 in der Forstwirtschaft. Ausschuss für Betriebswirtschaft (AfB) des Deutschen Forstwirtschaftsrates (DFWR), 16 pp. URL https://www.forstpraxis.de/wp-content/uploads/Langfassung-Schadensbewertung-AfB-DFWR-BMg.pdf – Last accessed in September 2021.

Möllers, F. (no date a) Jahresbericht 2018. Anglerverband Niedersachsen e.V., Hannover, 48 pp. URL https://av-nds.de/wp-content/uploads/2021/04/2018_AVN-Geschaeftsbericht_WEB.pdf – Last accessed in September 2021.

Möllers, F. (no date b) Jahresbericht 2019. Anglerverband Niedersachsen e.V., Hannover, 68 pp. URL https://av-nds.de/wp-content/uploads/2021/04/2019_AVN_Geschaeftsbericht_WEB.pdf – Last accessed in September 2021.

Mosley, L. M. (2015) Drought impacts on the water quality of freshwater systems; review and integration. Earth-Science Reviews 140, 203–214. doi:10.1016/j.earscirev.2014.11.010.

MULE (2021) Internationaler Tag der Feuchtgebiete: Renaturierung der Flutrinnen an der Elbe im Oberluch Roßlau. Web page, Ministerium für Umwelt, Landwirtschaft und Energie, Magdeburg, 1st February 2021. URL https://mule.sachsen-anhalt.de/newsarchiv/artikel-detail/news/internationaler-tag-der-feuchtgebiete-renaturierung-der-flutrinnen-an-der-elbe-im-oberluch-rosslau/ – Last accessed in July 2021.

MULE (n.d.) Waldzustandsbericht Sachsen-Anhalt 2020. Ministerium für Umwelt, Landwirtschaft und Energie Sachsen-Anhalt (MULE), Magdeburg, 40 pp. URL https://mule.sachsen-anhalt.de/fileadmin/Bibliothek/Politik_und_Verwaltung/MLU/MLU/03_Landwirtschaft/Forst/Waldschutz/201203_NFO_WZB-Sachsen-Anhalt-2020_BF_NEU_klein.pdf – Last accessed in September 2021

Niederlausitz Aktuell (2018) Wegen Waldbrandgefahr. Musik Open-Air am Deulowitzer See abgesagt. Online news, 15th August 2018. URL https://www.niederlausitz-aktuell.de/spree-neisse/guben/73489/wegen-waldbrandgefahr-musik-open-air-am-deulowitzer-see-abgesagt.html – Last accessed in August 2021.

Nordkurier (2019) Mehr als 33 Grad: Viele Schulen in MV machen Hitzefrei. Online news, 27th August 2019, 14:22. URL https://www.nordkurier.de/mecklenburg-vorpommern/viele-schulen-in-mv-machen-hitzefrei-2736557908.html – Last accessed in August 2021.

Orth, R., M. M. Vogel, J. Luterbacher, C. Pfister, S. I. Seneviratne (2016) Did European temperatures in 1540 exceed present-day records? Environmental Research Letters 11, 114021 (10 pp). doi:10.1088/1748-9326/11/11/114021

Pescaroli, G., S. Turner, T. Gould, D. E. Alexander, R. T. Wicks (2017) Cascading Effects and Escalations in Wide Area Power Failures – A summary for emergency planners. UCL IRDR and London Resilience Special Report 2017-01, Institute for Risk and Disaster Reduction, University College London, 15 pp. URL https://www.ucl.ac.uk/risk-disaster-reduction/sites/risk-disaster-reduction/files/report_power_failures.pdf – Last accessed in September 2021.

Petermann, T., H. Bradke, A. Lüllmann, M. Poetzsch, U. Riehm (2011) What happens during a blackout – Consequences of a prolongend and wide-ranging power outage. Final report, vol. 4 in Technology Assessment Studies Series. Office of Technology Assessment at the German Bundestag (TAB), Berlin. BoD, Norderstedt, 252 pp. ISBN 978-3-7322-9329-2. URL https://www.tab-beim-bundestag.de/en/pdf/publications/books/petermann-etal-2011-141.pdf – Last accessed in September 2021.

Pfister, C. (2018) The “Black Swan” of 1540: Aspects of a European Megadrought. In: Leggewie, C., F. Mauelshagen (eds) Climate Change and Cultural Transition in Europe. Vol. 4 in series Climate and Culture. Brill, Leiden. Chapter 5, pp 156–194. ISBN 978-90-04-35682-5 (e-book), 978-90-04-35642-9 (print). doi:10.1163/9789004356825_007

PNN (2019) Alle Osterfeuer in Potsdam abgesagt. Online news, Potsdamer Neueste Nachrichten, 18th April 2019, 13:30. URL https://www.pnn.de/brandenburg/hohe-waldbrandgefahr-alle-osterfeuer-in-potsdam-abgesagt/24235364.html – Last accessed in September 2021.

Porras-Salazar, J. A., S. Schiavon, P. Wargocki, T. Cheung, K. W. Tham (2021) Meta-analysis of 35 studies examining the effect of indoor temperature on office work performance. Building and Environment 203, 108037, 15 pp. doi:10.1016/j.buildenv.2021.108037

Port of Hamburg (2021) Seaborne cargo handling. Webpage. Port of Hamburg, Hamburg. URL https://www.hafen-hamburg.de/en/statistics/seabornecargohandling/ – Last accessed in September 2021.

Proplanta (2020) Trockene Teiche: Fischzucht in Dürre-Zeiten. Online news, Proplanta GmbH & Co. KG, Stuttgart, 10th August 2020, 11:00. URL https://www.proplanta.de/agrar-nachrichten/tier/trockene-teiche-fischzucht-in-duerre-zeiten_article1597050025.html – Last accessed in July 2021.

RBB (2020) Auf dem Trockenen – Der neue Kampf ums Wasser. Video documentation, 44:17. RBB Fernsehen, original broadcast 22nd September 2020. URL https://www.rbb-online.de/doku/a/auf-dem-trockenen.html – Last access in August 2021.

RBB24 (2021) Regen fehlt – Wasserpumpen aus Flüssen und Seen in Oberspreewald-Lausitz untersagt. RBB24 online news, 25 June 2021, 11:24. URL https://www.rbb24.de/studiocottbus/panorama/2021/06/oberspreewald-lausitz-wasserentnahme-verboten-allgemeinverfuegung.html – Last access in August 2021.

Reinermann, S., U. Gessner, S. Asam, C. Kuenzer, S. Dech (2019) The Effect of Droughts on Vegetation Condition in Germany: An Analysis Based on Two Decades of Satellite Earth Observation Time Series and Crop Yield Statistics. Remote Sensing 11 (15) 1783, 21 pp. doi:10.3390/rs11151783

RND (2020) Kreis Schaumburg: Wasserversorgung bricht wegen Hitze zusammen. Online news, Redaktionsnetzwerk Deutschland, 8th August 2020, 18:41. URL https://www.rnd.de/panorama/kreis-schaumburg-wasserversorgung-bricht-wegen-hitze-zusammen-2YYJXBUKR2O54LWJ4Q7NH7BOQE.html – Accessed in August 2021.

RP ONLINE (2018) Konzert: Emmerich bewertet Brandrisiko anders als Geldern. Online news, 19th August 2018, 12:36. URL https://rp-online.de/nrw/staedte/geldern/geldernsein-festival-2018-faellt-aus-rock-over-kiebitzsee-kann-stattfinden-trotz-waldbrandgefahr_aid-28256993 – Last accessed in September 2021.

Sächsische.de (2018) Mehr als 28 000 Badegäste. Online news, 5th September 2018, 20:23. URL https://www.saechsische.de/mehr-als-28000-badegaeste-4008087.html – Last accessed in August 2021.

Sächsische.de (2019a) Wälder nachts gesperrt. Online news, 25th April 2019, 15:59. URL https://www.saechsische.de/wald-nachts-gesperrt-5063603.html – Last accessed in August 2021.

Sächsische.de (2019b) Wälder nachts gesperrt. Online news, 25th July 2019, 19:05. URL https://www.saechsische.de/waelder-nachts-gesperrt-5099073.html – Last accessed in August 2021.

Sächsische.de (2020) Sachsens Fischer leiden unter Dürre. Online news, 10th August 2020, 09:54. URL https://www.saechsische.de/sachsens-fischer-leiden-unter-duerre-5248819.html – Last accessed in August 2021.

Scholz, [E.], [O.] Totsche (2021) Wasserwirtschaftlicher Jahresbericht der LMBV mbH für den Zeitraum 01.01.–31.12.2020. LMBV mbH, Senftenberg, 164 pp. URL https://www.lmbv.de/files/LMBV/Dokumente/Wassermanagement/Wasserjahresberichte/20210415%20Wawi_JB_2020_Endfassung%20mit%20Anlagen.pdf – Last accessed in August 2021.

Seintsch, B., H. Englert, M. Dieter (2020) Kalamitäten führen zu forstlichem "Rekordergebnis". Holz-Zentralblatt 146 (27) 506–507. URL https://literatur.thuenen.de/digbib_extern/dn062951.pdf – Last accessed in September 2021.

Simon, M., V. Bekele, B. Kulasová, C. Maul, R. Oppermann, P. Řehák (2005) Die Elbe und ihr Einzugsgebiet – Ein geographisch-hydrologischer und wasserwirtschaftlicher Überblick. Internationale Kommission zum Schutz der Elbe, Magdeburg, 258 pp. URL: https://www.ikse-mkol.org/fileadmin/media/user_upload/D/06_Publikationen/07_Verschiedenes/2005_IKSE-Elbe-und-ihr-Einzugsgebiet.pdf – last accessed in March 2021.

Simon, S., R. Schöpfer, D. Schumacher, C. Meyer (2019) Auswirkungen der Sommertrockenheit 2018 auf die öffentliche Wasserversorgung. Energie | Wasser-Praxis 19 (3) 14–19. URL https://www.dvgw.de/medien/dvgw/wasser/klimawandel/sommertrockenheit-wasserversorgung-energie-wasser-praxis-maerz-2019.pdf – Last accessed in August 2021.

SMEKUL (2020) Waldzustandsbericht 2020. Sächsisches Staatsministerium für Energie, Klimaschutz, Umwelt und Landwirtschaft (SMEKUL), Dresden, 64 pp. URL https://publikationen.sachsen.de/bdb/artikel/36806 – Last accessed in September 2021.

SMUL (2021) Aktuelle Borkenkäfersituation in Sachsen – Aktualisiert am 03. August 2021. Sächsisches Staatsministerium für Energie, Klimaschutz, Umwelt und Landwirtschaft, Dresden. Webpage archived on 19th August 2021, URL https://web.archive.org/web/20210819070920/https://www.wald.sachsen.de/aktuelle-situation-2020-8793.html

Spiegel (2018) Waldbrand in Brandenburg: Bundeswehr-Panzer sollen Schneisen schneiden. Online news, 25th August 2018, 16:46. URL https://www.spiegel.de/panorama/gesellschaft/waldbrand-in-brandenburg-bundeswehr-panzer-sollen-schneisen-schneiden-a-1224939.html – Last accessed in August 2021.

Spiegel (2019a) Feuer nahe Lübtheen breitet sich auf 600 Hektar aus - Bundeswehr unterstützt Löscharbeiten. Online news, 2nd July 2019, 11:54. URL https://www.spiegel.de/panorama/luebtheen-waldbrand-in-mecklenburg-vorpommern-auf-600-hektar-ausgeweitet-a-1275373.html – Last accessed in August 2021.

Spiegel (2019b) Zugausfälle bei der Bahn – Hitze setzt Klimaanlagen, Weichen und Lokomotiven zu. Online news. Spiegel, 27th July 2019, 18:44. URL https://www.spiegel.de/reise/aktuell/bahn-hitze-setzt-klimaanlagen-weichen-und-lokomotiven-zu-a-1279353.html – Last accessed in September 2021.

Staiger, H., K. Bucher, G. Jendritzky (1997) Gefühlte Temperatur. Die physiologisch gerechte Bewertung von Wärmebelastung und Kältestreß beim Aufenthalt im Freien in der Maßzahl Grad Celsius. Annalen der Meteorologie 33, 100–107. Deutscher Wetterdienst, Offenbach. ISSN 0072-4122, ISBN 3-88148-326-8. URN http://nbn-resolving.de/urn:nbn:de:101:1-201708172766 – Last accessed in September 2021.

Statistik BB (2016–2020) Erzeugung in Aquakulturbetrieben im Land Brandenburg. Statistischer Bericht C III 11 – j / 19. Amt für Statistik Berlin-Brandenburg, Potsdam. Periodical, annual releases. URL https://www.statistischebibliothek.de/mir/receive/BBHeft_mods_00042904 – Last accessed in September 2021.

Statistik BB (2016–2021) Gäste, Übernachtungen und Beherbergungskapazität im Land Brandenburg. Statistischer Bericht / G / IV / 1. Amt für Statistik Berlin-Brandenburg, Potsdam. Periodical, monthly releases. URL https://www.statistischebibliothek.de/mir/receive/BBSerie_mods_00000048 – Last accessed in September 2021.

Statistik BB (2021) Hitzebedingte Sterblichkeit in Berlin und Brandenburg, Heft 1/2021. URL https://download.statistik-berlin-brandenburg.de/4c241e5c83eedf6b/d9ec6a993297/hz_202101-06.pdf – Last accessed in September 2021.

Statistik SN (2020) Branchenreport Tourismus im Freistaat Sachsen 2019. Statistische Berichte / G / IV / 6. Statistisches Landesamt des Freistaates Sachsen, Kamenz, 161 pp. URL https://www.statistischebibliothek.de/mir/receive/SNHeft_mods_00022873 – Last accessed in September 2021.

Statistik ST (2020) Tourismus, Gastgewerbe – Gäste und Übernachtungen im Reiseverkehr, Beherbergungskapazität – Januar bis Dezember 2019, Endgülte [sic!] Ergebnisse, Korrekturausgabe. Statistisches Landesamt Sachsen-Anhalt, Halle (Saale), 51+28 pp. URL https://www.statistischebibliothek.de/mir/servlets/MCRFileNodeServlet/STHeft_derivate_00003759/6G401_12_19-A-Korrekturausgabe.pdf – Last accessed in September 2021.

Statistik ST (2021) Übersterblichkeit an Hitzetagen. Press release 260/2021. Statistisches Landesamt Sachsen-Anhalt, Halle (Saale). URL https://statistik.sachsen-anhalt.de/fileadmin/Bibliothek/Landesaemter/StaLa/startseite/Daten_und_Veroeffentlichungen/Pressemitteilungen/2021/h_August/260-Hitzesterblichkeit.pdf – Last accessed in September 2021.

Statistik TH (2016–2020) Gäste und Übernachtungen in Thüringen Dezember [Year] – Endgültige Ergebnisse. Periodical, monthly releases, final results in December issues. Thüringer Landesamt für Statistik, Erfurt. URL https://statistik.thueringen.de/webshop/webshop.asp?ansicht=frersch&ve=07401 – Last accessed in september 2021.

Statistische Ämter (2014) Bevölkerung – Ergebnisse des Zensus am 9. Mai 2011. CSV file (3 MB), Statistische Ämter des Bundes und der Länder. URL: https://www.zensus2011.de/SharedDocs/Downloads/DE/Pressemitteilung/DemografischeGrunddaten/csv_Bevoelkerung.zip – Last accessed in March 2021.

Statistische Ämter (2020) Erträge ausgewählter landwirtschaftlicher Feldfrüchte – Jahressumme – regionale Tiefe: Kreise und krfr. Städte. Regionalstatistische Datenbank [regional statistical data base], Table 41241-01-03-4. Statistische Ämter des Bundes und der Länder. URL https://www.regionalstatistik.de – Last accessed in August 2020.

Statistische Ämter (2021a) Bruttoinlandsprodukt, Bruttowertschöpfung in den Ländern der Bundesrepublik Deutschland. Excel file. Arbeitskreis »Volkswirtschaftliche Gesamtrechnungen der

Länder«, Statistische Ämter des Bundes und der Länder. URL: http://www.statistikportal.de/de/veroeffentlichungen/bruttoinlandsprodukt-bruttowertschoepfung – Last accessed in September 2021.

Statistische Ämter (2021b) Wassereinsatz der Wirtschaftszweige und privaten Haushalte 2016 nach Bundesländern. Excel file. Arbeitskreis »Umweltökonomische Gesamtrechnungen der Länder«, Statistische Ämter des Bundes und der Länder. URL: https://www.statistikportal.de/sites/default/files/2020-10/e_11.1.16.xlsx – Last accessed in August 2021.

Süddeutsche Zeitung (2019a) Wann Schüler Hitzefrei bekommen. Online news, 26th June 2019, 10:23. URL https://www.sueddeutsche.de/bildung/hitzefrei-schule-regelungen-1.4498963 – Last accessed in September 2021.

Süddeutsche Zeitung (2019b) Andauerende Trockenheit setzt Amphibien und Pflanzen zu. Online news, .27th July 2019, 08:34. URL https://www.sueddeutsche.de/wissen/natur-dresden-andauerende-trockenheit-setzt-amphibien-und-pflanzen-zu-dpa.urn-newsml-dpa-com-20090101-190727-99-230619 – Last accessed in September 2021.

Süddeutsche Zeitung (2019c) Niedrigwasser lässt Ausflugsschiffer umdenken. Online news, 1st September 2019, 10:12. URL https://www.sueddeutsche.de/wirtschaft/schifffahrt-lutherstadt-wittenberg-niedrigwasser-laesst-ausflugsschiffer-umdenken-dpa.urn-newsml-dpa-com-20090101-190901-99-692759 – Last accessed in September 2021.

SVZ (2020) Trockenheit: Frosch, Lurch und Molch fehlt Wasser. Online news, Schweriner Volkszeitung, 23rd May 2020, 05:00. URL https://www.svz.de/regionales/brandenburg/frosch-lurch-und-molch-fehlt-wasser-id28410542.html – Last accessed in September 2021.

T-Online (2018a) Bundeswehr-Soldaten lösen Waldbrand aus. Online news, »t-online.«, 28th June 2018, 16:55. URL https://www.t-online.de/-/84017740 – Last accessed in September 2021.

T-Online (2018b) Motorradrennen in Burg wegen Trockenheit abgesagt. Online news, »t-online.«, 26 July 2018, 11:45. URL https://www.t-online.de/-/84176528 – Last accessed in September 2021.

Tagesspiegel (2018) Feuergefahr wegen Hitze: Pyronale überraschend verschoben. Der Tagesspiegel online, 21st August 2018, 16:50. URL https://www.tagesspiegel.de/berlin/berlin-charlottenburg-feuergefahr-wegen-hitze-pyronale-ueberraschend-verschoben/22935984.html – Last accessed in September 2021.

Tagesspiegel (2019a) Wasserknappheit in Brandenburg – „Man muss ja nicht dreimal am Tag duschen oder den Pool neu füllen." Der Tagesspiegel online, 4th July 2019, 22:27. URL https://www.tagesspiegel.de/berlin/wasserknappheit-in-brandenburg-man-muss-ja-nicht-dreimal-am-tag-duschen-oder-den-pool-neu-fuellen-/24522050.html – Last accessed in August 2021.

Tagesspiegel (2019b) Weitere Osterfeuer am Samstag abgesagt. Der Tagesspiegel online, 20th April 2019, 15:23. URL https://www.tagesspiegel.de/berlin/waldbrandgefahr-in-berlin-brandenburg-weitere-osterfeuer-am-samstag-abgesagt/24239882.html – Last accessed in August 2021.

Tagesspiegel (2020) Umweltamt schließt drei Brandenburger Schleusen. Available at: https://www.tagesspiegel.de/berlin/wassermangel-in-der-spree-umweltamt-schliesst-drei-brandenburger-schleusen/26099692.html – Accessed in August 2021.

Templiner, A., L. Kynast, U. Pohrt (2021) Serie „Klimawandel und Bauunternehmen“, Teil 2/4: Zunehmende Hitzebelastung als Auswirkungen [sic!] des Klimawandels – Maßnahmen für Beschäftigte der Baubranche. Web page, BauPortal 2|2021. URL https://bauportal.bgbau.de/bauportal-22021/thema/branchenuebergreifend/serie-klimawandel-und-bauunternehmen/ – Last accessed in September 2021.

TI (2014) Dritte Bundeswaldinventur – Ergebnisdatenbank. Online resource. Johann Heinrich von Thünen-Institut, Braunschweig. URL: https://bwi.info – Accessed in August 2021.

TMIL (2020) Waldzustandsbericht 2020 – Forstliches Umweltmonitoring in Thüringen. Thüringer Ministerium für Infrastruktur und Landwirtschaft (TMIL), Erfurt, 30 pp. URL https://infrastruktur-landwirtschaft.thueringen.de/fileadmin/Forst_und_Jagd/Forstwirtschaft/20_11_20_WaldzustandsberichtWeb.pdf – Last accessed in September 2021

La Tribune (2019) Canicule et refroidissement des centrales nucléaires : le pire est à venir. Online news, 2nd July 2019, 10:31. URL https://www.latribune.fr/entreprises-finance/industrie/energie-environnement/canicule-et-refroidissement-des-centrales-nucleaires-le-pire-est-a-venir-822302.html

UBA (2020) Ozonsituation in Deutschland - Wissensstand, Forschungsbedarf und Empfehlungen. Dokumentation des Workshops „Was sind Gründe für die Ozonbelastung in Deutschland?“. Umweltbundesamt (UBA), Dessau-Roßlau. URL https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/dokumentation_02-2020_uba-iass_ozon-workshop_fin.pdf – Last accessed in September 2021.

UBA (2021) Aktuelle Luftdaten – Jahresbilanzen, Stand: 06.09.2021. Umweltbundesamt (UBA), Dessau-Roßlau. URL https://www.umweltbundesamt.de/daten/luft/luftdaten/jahresbilanzen/eJxrWpScv9B4UWXqEiMDIwMAML8Fsw== – Last accessed in September 2021.

VG1000 (2018) Verwaltungsgebiete 1:1 000 000 (Ebenen), Stand 01.01. Digital vector maps, 2018 edition. Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany. URL: https://daten.gdz.bkg.bund.de/produkte/vg/vg1000_ebenen_0101/2018/ – last accessed in August 2021.

VG250-EW (2021) Verwaltungsgebiete 1:250 000 mit Einwohnerzahlen (Ebenen), Stand 31.12. Digital vector maps. Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany. URL: https://gdz.bkg.bund.de/index.php/default/open-data/verwaltungsgebiete-1-250-000-mit-einwohnerzahlen-ebenen-stand-31-12-vg250-ew-ebenen-31-12.html – last accessed in April 2021.

Vicente-Serrano, S. M., S. Beguería, J. I. López-Moreno (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. Journal of Climate 23 (7) 1696–1718. doi:10.1175/2009JCLI2909.1

Vicente-Serrano, S. M., J. I López-Moreno, S. Beguería, J. Lorenzo-Lacruz, C. Azorin-Molina, E. Morán-Tejeda (2012) Accurate Computation of a Streamflow Drought Index. Journal of Hydrologic Engineering 17 (2) 318–332. doi:10.1061/(ASCE)HE.1943-5584.0000433

WELT (2018) Traktor- und Oldtimertag wegen Trockenheit abgesagt. Online news, 4th July 2018. URL https://www.welt.de/regionales/thueringen/article178756080/Traktor-und-Oldtimertag-wegen-Trockenheit-abgesagt.html – Last accessed in July 2021.

WELT (2019) Der Rhein war 2018 das wahre Problem für Deutschlands Chemieriesen. Online news, 26th February 2019. URL https://www.welt.de/wirtschaft/article189454417/BASF-Duerresommer-belastet-Konzern-mit-einer-Viertelmilliarde-Euro.html – Last accessed in September 2021.

WELT (2020) April zu trocken: Stress für Pflanzen und Amphibien. Online news, 18th April 2020. URL https://www.welt.de/regionales/thueringen/article207338895/April-zu-trocken-Stress-fuer-Pflanzen-und-Amphibien.html – Last accessed in July 2021.

Wetter, O., C. Pfister, J. P. Werner, E. Zorita, S. Wagner, S. I. Seneviratne, J. Herget, U. Grünewald, J. Luterbacher, M.-J. Alcoforado, M. Barriendos, U. Bieber, R. Brázdil, K. H. Burmeister, C. Camenisch, A. Contino, P. Dobrovolný, R. Glaser, I. Himmelsbach, A. Kiss, O. Kotyza, T. Labbé, D. Limanówka, L. Litzenburger, Ø. Nordl, K. Pribyl, D. Retsö, D. Riemann, C. Rohr, W. Siegfried, J. Söderberg, J.-L. Spring (2014) The year-long unprecedented European heat and drought of 1540 – a worst case. Climatic Change 125 (8) 349–363. doi:10.1007/s10584-014-1184-2 – Erratum: Climatic Change 125 (8) 365–367. doi:10.1007/s10584-014-1193-1

Wild, M. (2014) Global Dimming and Brightening. In: Freedman B. (ed.) Global Environmental Change. Handbook of Global Environmental Pollution, vol 1, pp. 39–47. Springer, Dordrecht. doi:10.1007/978-94-007-5784-4_2739–47

Wild, M., S. Wacker, S. Yang, A. Sanchez-Lorenzo (2021) Evidence for Clear-Sky Dimming and Brightening in Central Europe. Geophysical Research Letters 48 (6) e2020GL092216 (9 pp). doi:10.1029/2020GL092216

Wirth, C., R. A. Engelmann, N. Haack, H. Hartmann, R. Richter, F. Schnabel, M. Scholz, C. Seele-Dilbat (2021) Naturschutz und Klimawandel im Leipziger Auwald: Ein Biodiversitätshotspot an der Belastungsgrenze. Biologie in unserer Zeit 51 (1) 55–65. doi:10.11576/biuz-4107

WiWo (2019) Warum die Bahn ihre Schienen weiß anstreicht. Online news, Wirtschaftswoche, 25th July 2019. URL https://www.wiwo.de/technologie/umwelt/neue-farbe-warum-die-bahn-ihre-schienen-weiss-anstreicht/24699478.html – Last accessed in September 2021.

WMO (2012) World Meteorological Organization, 2012: Standardized Precipitation Index User Guide (M. Svoboda, M. Hayes and D. Wood). (WMO-No. 1090), Geneva. ISBN 978-92-63-11091-6. URL https://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf – last accessed in May 2021.

WMO & GWP (2016) World Meteorological Organization (WMO) and Global Water Partnership (GWP): Handbook of Drought Indicators and Indices (M. Svoboda and B.A. Fuchs). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva. ISBN 978-92-63-11173-9. URL https://public.wmo.int/en/resources/library/handbook-of-drought-indicators-and-indices – last accessed in May 2021.

ZDFheute (2021) Tesla in Brandenburg – Wasserverband: Fabrik verschärft Wassermangel. ZDFheute, online news of Zweites Deutsches Fernsehen, 16th March 2021, 18:05. URL

2. Boyne catchment

2.1 Assessing sectoral drought impacts

Given the lack of drought impacts formally collated at the catchment scale we employ newspaper archives and interviews with stakeholders to examine sectoral drought impacts. This dual approach fits well with understanding impacts from historical events (newspapers), helping us to identify commonly impacted sectors, the nature of impacts and any change over time, while interviews with stakeholder draw upon recent memories and experience of events.

2.1.1 Newspaper Records

Newspaper records have been used in analysis of historical droughts in Ireland, both to verify occurrence in meteorological records (Noone et al., 2017) and to gain insight into societal impacts (Noone et al., 2017; Murphy et al., 2017). Recently Jobbova et al. (2021) have systematically identified drought impact reports from the Irish Newspaper Archive; a collection containing hundreds of national and local newspapers from across the island. In this work the authors identified >6000 newspaper reports on drought impacts over the period 1733-2019. Each report was categorised according to the drought impact categories and subcategories used as part of the European Drought Impact Inventory (EDII) (Stahl et al., 2016). For the period post 1900 there is relative stability in the number of newspaper titles contained in the Irish Newspaper Archive and good coverage across the island. We therefore extract newspaper reports of drought impacts for counties contained in the Boyne catchment from the dataset compiled by Jobbova et al. (2021) for the period 1900-2019. We evaluate drought impacts for the impact categories described I the data; including; Agriculture and Livestock, Public Water Supplies; Waterborne Transportation; Human Health and Safety; Tourism and Recreation; Terrestrial Ecosystems; Freshwater Ecosystems; Freshwater Aquaculture and Fisheries, and; Energy and Industry.

2.1.2 Stakeholder engagement and interviews

To further understand drought impacts in key sectors we developed two semi-structured interview protocols for Boyne and national-level stakeholders that were tailored to interviewees to understand sectoral drought impacts in the catchment. All interviews were conducted remotely either via telephone, zoom or a similar virtual meeting platform. Interviews ranged from 30 to 100 minutes in duration. We approached target interviewees in January 2021 and conducted interviews between February and July 2021. We interviewed 39 individuals who can be broadly divided into three groups: individuals with a direct interest in drought from a livelihood perspective (n=6); individuals with a direct interest in drought from a recreational or general perspective (n=12); and those with an indirect professional interest (n=26) (Table 5).

Table 5: Type of interviewee.

No.	Organisation	Roles / Position	Interest			Scale		
			Livelihood	Recreation / general	Professional	Boyne	National	Non-Boyne Local / regional
1	Kells Anglers	Angler		☑		☑		
2	Newgrange Gold	Business/ landowner, Angler.	☑	☑		☑		
3	Inchamore house farm	Farmer, Vet, Business/ landowner, Angler.	☑	☑		☑		
4	Hotwell farm	Business/ landowner.	☑			☑		
5	Boyne Boats	Business owner, boater.	☑	☑		☑		
6	Sonairte	Charity volunteer, horticulturalist.		☑		☑		
7	Navan Anglers	Angler		☑		☑		
8	Birdwatch Ireland	Birder, conservationist.		☑		☑		
9	Waterways Ireland (Royal Canal)	Technical officer, engineer.			☑	☑		
10	Heritage Boat Association	Boater		☑		☑		
11	Baltrasna Boreen biodiversity group	Conservationist, citizen scientist.		☑		☑		
12	Ribbontail paddlers	Canoe club administrator		☑		☑		
13	Downing Group Water Scheme, Cork	Farmer, landowner, volunteer.	☑					☑
14	Lacka Group Water Scheme, Tipperary	Farmer, landowner, volunteer.	☑					☑
15	Coillte Tree Nursery (Carlow)	Nurseries manager			☑			☑
16	Waterways Ireland	Senior environmental officer.			☑		☑	
17	National Federation for Group Water Schemes	Senior Development Co-ordinator.			☑		☑	
18	An Foram Uisce	Research Lead			☑		☑	
19	Irish Council for Social Housing	Volunteer, Rep on An Foram Uisce.		☑	☑		☑	
20	Bord na Mona	Land / estate manager			☑		☑	
21	Bord na Mona	Ecology lead			☑		☑	
22	Teagasc	Agricultural researcher			☑		☑	

No.	Organisation	Roles / Position	Interest			Scale		
			Livelihood	Recreation / general	Professional	Boyne	National	Non-Boyne Local / regional
23	Local Authorities Water Programme (LAWPRO)	Catchment manager (East/Midlands)			☑		☑	
24	PTR Forests	Forestry consultant			☑		☑	
25	Climate Action Regional Office (East/Midlands)	Coordinator			☑		☑	
26	Forest Service	Inspector			☑		☑	
27	Dept of Housing	Principal Water Advisor			☑		☑	
28	Dublin City Council	Climate Action Coordinator			☑			☑
29	EPA Research	Scientific Officer (Hydro & Groundwater)			☑		☑	
30	Climate Change Advisory Council	Secretariat			☑		☑	
31	Dept. of Agriculture	Vet, Director (Animal Welfare)			☑		☑	
32	Dept. of Agriculture	Adaptation policy officer			☑		☑	
33	Dept. of Agriculture	Agricultural inspector, Scientist.			☑		☑	
34	Irish Farmers' Association	Dairy Executive, farmer.			☑		☑	
35	Geological Survey Ireland	Scientist			☑		☑	
36	Trinity College Ireland	Conservation scientist			☑		☑	
37	Dept. of Agriculture	Policymaker			☑		☑	
38	National Parks and Wildlife	Eco-hydrologist			☑		☑	
39	Atlantic Salmon Trust	Fisheries scientist/consultant		☑	☑		☑	
TOTAL			6	12	26	12	23	4

2.2 Linking drought impacts and metrics

Finally, we investigate the relationship between reported drought impacts from newspaper records and drought metrics in the catchment. We focus attention on using SPI and derive correlations between monthly SPI values for accumulation periods of 1 to 24 months and the annual number of drought impacts reported. Linking impacts and metrics in this way can help to inform drought monitoring strategies by identifying the SPI accumulation period and month most strongly correlated with societal impacts. We focus attention on the most reported impact categories, namely, Agriculture and Livestock and Public Water Supplies.

2.3 Sectoral Impacts

Given a lack of recording of impacts at the catchment scale we use two approaches to examine the sectoral impacts of drought in the Boyne catchment. First, we use newspaper archives to examine impacts according to the sectoral impacts identified in the European Drought Impact Inventory database. Second, we employ interviews with stakeholders in the catchment to understand the impact of recent drought events on their activities and livelihoods. The following sections detail results from each approach.

2.3.1 Newspaper archives

Using the comprehensive newspaper impact database developed by Jobbova et al. (2021) we selected drought impact reports from counties and locations contained in the Boyne catchment for the years 1900-2019. In total we identified 700 individual drought impact reports over this time period (see Figure 11). On an annual basis the largest number of drought impact reports are returned for 1949 (53), 1934 (36), 1921 (33), 1984 (32) and 1989 (22). Notably the recent drought of 2018 only ranks as the 19th most impactful event according to newspaper reports covers almost 120 years. While 1949 ranks as the year with the highest number of impacts reported, the severity of droughts in 1949 generally do not rank in the top ten most severe droughts as defined by SPI over the same period. This also applies to droughts in 1984 and 1989. Therefore, for these years, while droughts were not extreme they did result in significant impacts in the catchment. This highlights the challenge of linking drought events and impacts, with the latter largely defined by socioeconomic activities and vulnerabilities. Extreme drought events are recorded in 1934 and 1921, with both generally ranking withing the top ten events by severity over the past 120 years.

Looking at sectoral impacts, the largest number of drought reports are returned for the agriculture and livestock sector. These predominantly relate to problems with grass growth and food production. In total more than 50 percent of all drought impact reports are associated with agriculture and livestock, consistent with the predominance of this sector in the catchment. The largest number of reports are associated with droughts of 1949, 1984 and 1989. From Figure 14 there has also been an overall decreasing trend in the number of agriculture and livestock impact reports with time. While difficult to disentangle exactly why, it is likely that a reduction in drought frequency post the 1970 period, together with the modernisation of Irish agriculture in the 1960s have contributed to this decline.

The second most commonly impacted sector in the newspaper database is public water supply with 133 impact reports identified for the catchment over the period of analysis. Numerous droughts over the past 120 years, including in 2018 have given rise to water shortages for major towns in the catchment. Unlike agricultural impacts, which tend to be associated with drought conditions in the spring and summer months, public water supply impacts are often associated with longer drought accumulation periods, with some instances of water shortages associated with drought during winter. For example, Figure 15 highlights water shortage concerns for Kells Town as a result of lack of winter precipitation to recharge groundwater and lakes. For other impact categories/sectors the number of impact reports reduces considerably. However, the importance of impacts to Freshwater Ecosystem and Freshwater Fisheries should be noted, given the importance of fishing and tourism in the catchment.

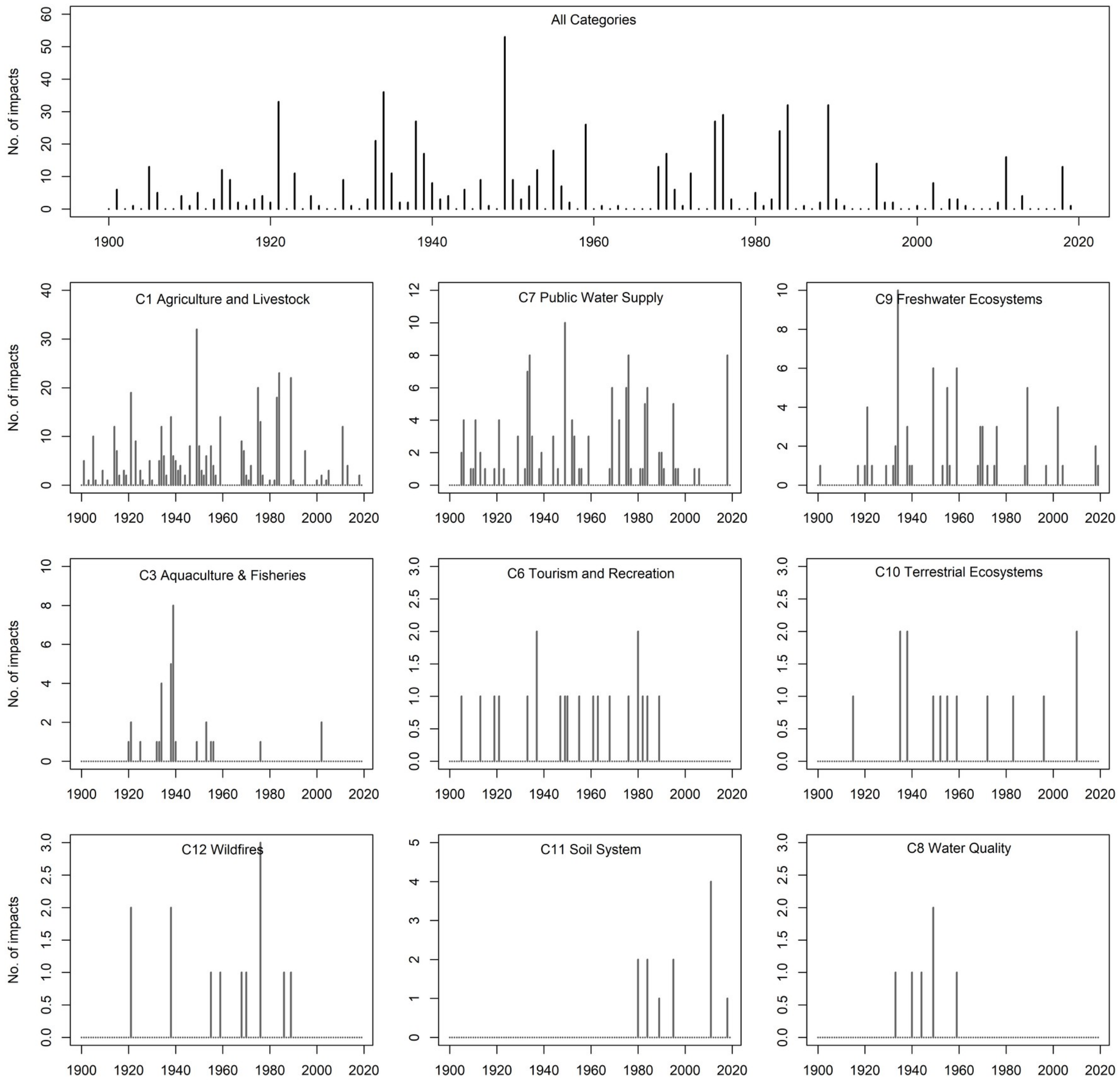

Figure 14: Drought impact reports from newspaper archives for the Boyne catchment for the period 1900-2019. The top panel shows all impact reports returned for the period, while sub panels show the reports for different impact categories/sectors as defined by the European Drought Impact Inventory.

Kells Water Supply Suffering Due To Low Rainfall Winter

CLAIMS that the main source of Kells water supply, Lough Bane, is being excessively drained, to the detriment of anglers and farmers, were challenged this week by Area Administrator, Mr. Bill Sweeney. The particularly dry winter until mid-January had put pressure on the Lough, and an extensive supply audit was currently underway, he said.

A petition from 25 landowners was submitted to the Co. Council last week, citing their fears of damage by draining. Boundary fences no longer reached the water edge, it stated, causing problems with roaming livestock. Animals could no longer drink in safety at the lakeside as the shore shelved very quickly into deep water. Its underlying marl was very soft, making the likelihood of a trapped animal almost inevitable. That shore area had already been designated an area of special scientific interest with unique flora, fauna and wildlife. But this was in jeopardy, with reed beds exposed, fewer nest sites, and frost damaging its rare water mosses and plants.

The 150 strong Lough Bane angling club had also claimed that there had been a dramatic fall in water levels, making their investment completely useless owing to the loss of natural spawning this season. The whole food chain of the lake was suffering with the lowered levels, aggravated by the drought conditions of autumn and early winter.

The landowners claimed that the present rate of water extraction would do irreversible damage. The concerns about water levels, cited 22 years ago when the original ministerial order was made, were stronger than ever. They called on the Co. Council to set out extraction rates, replenishment levels through rainfall and groundwater, and future projections of demand on Lough Bane.

Their concerns were strongly supported this week by Colr. Michael Lynch of Oldcastle. He had worked long and hard to secure the Regional Water Supply scheme for Kells and Oldcastle, he said. But the concern now was that there was considerable water wastage, even after extensive Council efforts to locate the leaks. He supported calls for water conservation, and noted that recent heavy rainfall will have eased matters in the short term. But the long term picture was "not good". He feared the water supply situation could fall back to the unsatisfactory situation of the 1970s, and was concerned that there may be excessive water demand on the supply which the Council had provided for some Cavan households.

The Area Administrator said yesterday (Tuesday) that there had been difficulties with the lengthy dry period, the night frosts of mid-January (which resulted in pipe bursts and high wastage as some households left taps running to avoid bursts) and normal wear and tear. The Council had been renewing piping and urging the public to conserve supplies. A number of households in Cavan had been provided with a supply, and this was being monitored. He noted that Cavan Co. Council provided some Meath households with their water supply also.

Mr. Sweeney said that the Environmental Protection Agency (EPA) had carried out a study on Lough Bane and nearby lakes recently. This had examined the concerns of landowners and anglers about water levels. The EPA findings suggested that continuing land drainage works were adversely affecting the levels of replenishing groundwater entering the lakes. Repairs on the system were continuing, but he rejected suggestions that up to half of the current supply was being lost through wastage. The abnormal drought conditions had also badly affected Lough Bane. The water audit now underway would establish whether water levels there had been permanently altered.

Figure 15: Newspaper impact report on public water supply issues associated with low winter rainfall.

2.3.2 Stakeholder Interviews

Interviews with stakeholders representing a range of sectors in the catchment indicate that drought impacts in the Boyne (and Ireland more broadly) are understood and experienced from diverse perspectives. The following sections summaries key insights from key sectors. Insights are largely drawn from memories and experiences of recent drought events in the catchment, including the drought of summer 2018 and spring 2020.

2.3.2.1 Impacts on public water supplies

Despite not being able to meet anyone from Irish Water, the national water utility, we interviewed other national-level stakeholders from the Dept of Housing and others with recent experiences and knowledge of how public water supplies were impacted during the 2018 and 2020 events. Interviews suggest that, while there has been broad agreement for a long time of systemic problems with Ireland's supply network, experiencing two drought events so close together highlighted vulnerabilities and focused minds within the Department of Housing. Dublin and the eastern region of Ireland is considered particularly at risk due to the lack of storage capacity and increasing demand for water resources. According to a water advisor at the Dept. of Housing, Dublin is currently "operating on a 2 to 3% headroom [while] international practice would be nearer to 15 or 20%." (Dept of Housing). Several stakeholders highlighted how supplies relying on flashy catchments in the West can also be vulnerable even during short dry spells. In Spring 2020, run of the river supplies on the Cork-Kerry border were so low that Irish Water had to impose hosepipe bans, pressure reductions and rationing. Some sections of river needed to be sandbagged to abstract water and water tankers were also needed in some places. Several stakeholders also highlighted the serious risk posed by multi-year events as some reservoirs and aquifers need time to recharge. In terms of the Boyne catchment, public water supplies don't seem to be an immediate concern, but development of the Dublin-Belfast economic corridor could bring pressures in the long-term.

2.3.2.2 Impacts on group / private water supplies

While we did not report direct impacts on water supplies, the 2018 event alerted landowners and farmers in the Boyne to the potential vulnerability of private wells to drought. Interviewees recalled wells going dry in the 1970s/80s due to dry weather and arterial drainage. We found some farmers were also concerned about future restrictions on river abstraction during dry periods and the affect that could have on their farm costs and product quality.

2.3.2.3 Impact on watercourses and waterways

Waterways Ireland (the governmental agency responsible for management of the Royal Canal) and boaters and businesses on the Boyne were concerned about the impact of low flows on not only navigation but also the structural integrity of canal embankments and bridges as they dry out and crack. The Royal Canal, which runs across the Boyne catchment, is fed by Lough Owel which also supplies the town of Mullingar. During dry periods, Waterways Ireland supplement this supply by pumping water from the upper Boyne catchment into the Royal Canal. Other stakeholders were concerned about low flows increasing water temperatures and adversely effecting quality as water becomes more concentrated and the watercourse’s ability to assimilate wastewater diminishes. Some reported that often, when there’s heavy rainfall after a dry spell, recently applied agricultural fertilizer and wastewater solids that build up in pipes are flushed into river systems. Low flows and reductions in water quality encourage weed growth and adversely impact fisheries, freshwater ecosystems, and their cultural and recreational value to society. For most stakeholders, drought is mainly understood as something that exacerbates existing catchment pressures from agriculture, water management and historical drainage policies.

2.3.2.4 Impacts on dairy / livestock farming

It’s clear from interviews with farmers, Teagasc, IFA and DAFM staff that dairy production is particularly at risk from drought in the Boyne and nationwide. For dairy and livestock farmers, drought is synonymous with shortages of grass and other crops for fodder and bedding. In fact, according to a member of the IFA dairy executive dairy farmers would drought define as “when your 21-day rotation doesn’t replenish you with grass.” All stakeholders reported that grass growth dropped dramatically in 2018, particularly in Munster and Leinster. They talked of "unfamiliar territory" and "a sector unprepared for such a long drought" as silage and straw prices "went through the roof". Similar conditions across Europe led to the EU and Irish government organising extra imports of feed. However, according to a Teagasc scientist, this safety valve may not be possible in the future given that the EU green deal policies are looking to stop our dependence on the global supply chain of feed, as it is contributing to the destruction of tropical rainforests and carbon emissions. During the 2018 event, interviewees were encouraged to see farmers in the less effected northwest use social media to help move silage and straw around the country. According to several stakeholders, Teagasc’s recommendation to farmers to spread fertilizer on crops during this time caused massive nitrate leaching when the rainfall finally arrived in August. It should be said, while there were clear financial and mental health impacts on farms, animal welfare, breeding and milk production was largely unaffected. There was widespread concern from interviewees about the general vulnerability of intensive dairy operations particularly those with high cow density. According to an animal welfare expert at DAFM, some dairy farms are operating at such a limit that the weather almost needs to stay perfect for them to survive.

There was also some concern from the dairy sector that drought could bring serious water shortages in the future particularly if intensification continues. Peak milk production and therefore water demand coincides with the summer. During this period, dairy cows require up to 70 litres a day and additional water is required for the milk production process and all the cleaning of the equipment and buildings. In term of impacts, shortages can lead to increased cow aggression and dominance issues. While a lot of farms have access to mains water, many of the larger more intense operations find it more cost-effective to privately manage water supplies. As a result, in 2018 some farms with intensive dairy herds ran out of water and had to abstract from nearby rivers. While this might not have been as widespread an issue as the fodder shortage, this was obviously a very stressful situation for the most vulnerable farms.

2.3.2.5 Impacts on tillage systems

In terms of tillage farming, 2018 and 2020 droughts impacted quality and yields on some farms.

The wet autumn of 2017 and late, cold spring not only contributed to the 2018 fodder crisis but also meant that sowing windows for a lot of spring crops were missed. According to DAFM staff, irrigation is becoming more necessary in recent years particularly for potato farmers in the southeast. Some farmers are already starting to adapt to drier summer by moving to minimum soil disturbance systems to retain moisture in dry conditions. In the future, DAFM expects to see grass and field beans in the southeast being replaced by deep rooted crop varieties or even crops like maize, soya or peas that are more tolerant to drought and associated pests.

2.3.2.6 Impacts on the forestry sector

Interviews with the forest sector indicate that drought can have significant impacts on newly planted forests. I interviewed someone from the forest service who went to sites in the Boyne during summer 2018 and reported severe stress and 100% failure on some sites for the first time in his career. It was so bad that DAFM had to set up a financial support scheme so that landowners and foresters could replant young trees that had failed. Young broadleaf forests planted in free draining mineral soil (e.g. in the southeast) were particularly susceptible. According to a consultant from PTR forest, survival seemed to be related to the ground preparation technique used when planting.

2.3.2.7 Impacts on wetlands and peatlands

Ecologists and conservationists in Ireland were concerned that more extreme drought will further destabilize and degrade wetlands and peatlands ecosystems that already have limited resilience. In 2018, wetlands dried up that had never previously been known to dry. According to one peatland ecologist, bog vegetation was like parchment paper peeling away from the peat underneath and in some places, because there was no moss or algae layer the surface easily cracked and crumbled. In terms of wildlife, interviewees highlighted how drought events and resulting fires can also have short-term effects on insect and bird populations. Bord na Mona (the semi-state company historically responsible for harvesting peat) would have welcomed drought as it increased productivity. However, as they are moving towards a policy of wetland restoration or rehabilitation, they are going to need to carefully manage water levels which could be challenging as demand for water resources increases and drought become more frequent and intense.

2.3.2.8 Second-order risks

Drought also brings secondary risks. Ecologists and foresters were concerned about fires starting on drained, harvested peatlands and forests during periods of prolonged dry weather. There were fires in the Boyne in 2018 and there is a long history of wildfires in Ireland causing damage to resources, wildlife, property, and infrastructure. Droughts are also likely to create conditions for bog slides in Ireland. In June 2020, an otherwise intact bog in Co. Leitrim slipped into a river. According to an ecologist interviewed, this was caused by the dry weather in spring followed by intense rainfall in June. These events not only destroy peatlands, but the floods can also impact water quality, fish, biodiversity, farmland and infrastructure downstream. During previous dry summers, dust particles from peat harvesting and fires could also impact local air quality.

2.4 Linking drought impacts and accumulation periods

Using the derived newspaper impact reports and precipitation record we correlate impacts with SPI of accumulation period ranging from 1 to 24 months to identify the timing and accumulation period most strongly correlated with impacts. Our analysis is undertaken for the period of concurrent records 1900-2019. Such information can help in informing development of drought monitoring strategies in the catchments and refining future research examining drought impacts. Results are presented in Figure 13. Taking all reported drought impacts it is evident that strongest correlations between drought impacts and metrics are apparent during the later summer and early autumn for accumulation periods of 4 to 7 months. For agriculturally based impacts similar results are evident, given their dominance in the impact dataset, with strongest correlations evident for SPI-4 in July and SPI-5 in August and September. These results indicate the importance of drought during the spring and summer period in impacting agriculture which is based primarily on grass growth. For water based impacts the strongest correlations with impacts are evident later in the year and for higher accumulation periods, indicating the importance of prolonged drought conditions for impacting water supply. For instance, the strongest correlations are evident for SPI-7 in August and September, indicating the importance of deficits over the period late winter through to late summer/early autumn.

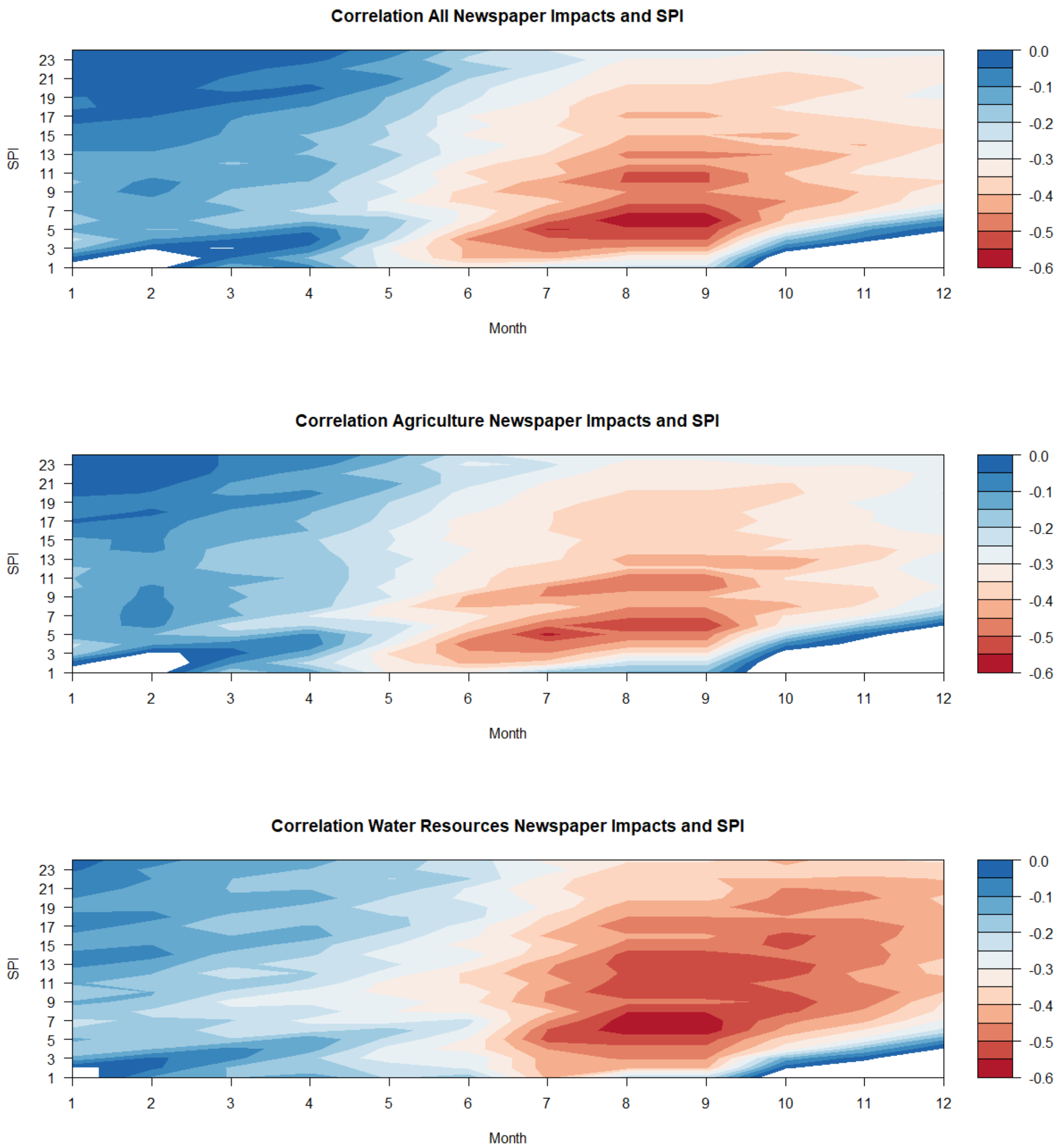

Figure 16: Correlations between drought impacts (all impacts: top; agricultural impacts: middle; water resources impacts: bottom) and SPI for accumulation periods ranging from 1 to 24 months in the Boyne catchment for the period 1900-2019.

2.5 Conclusions

This research has extended available precipitation records for the Boyne catchment to cover the period 1850-2019, providing a detailed view of drought conditions over nearly 170 years in the catchment. We have also employed hydrological models to evaluate the impacts of arterial drainage on drought metrics in the catchment and to extend river flow records to a period concurrent with precipitation observations. Our historical analysis indicates the frequent occurrence of drought in the Boyne catchment and provides a catalogue of drought events derived from the standardised precipitation index and the standardised runoff index.

We find limited evidence that arterial drainage impacted drought in the Boyne. We also find evidence for trends in SPI series and drought events themselves, dominated by increasing trends in SPI in winter and decreasing trends for SPI-3 in summer (ie. more drought in summer) over the period of record. We also find an increasing trend in accumulated deficits of SPI-3 droughts, indicating decreasing severity. While formal data on drought impacts across sectors is missing in Ireland, we have leveraged newspaper archives and stakeholder interviews to better understand drought impacts in the catchment. Newspaper sources provide detailed insight into drought impacts over a long period of time. They highlight the predominance of agriculture and livestock impacts in the catchment, followed by public water supply impacts. It is not the case that the most severe droughts result in the most severe impacts, with some of the most impactful droughts being ranked outside the most severe events according to SPI. This highlights the challenge of tracking drought impacts, even at the catchment scale. Vulnerability to drought is also dynamic and there is evidence that modernisation of Irish agriculture in the 1960s has reduced susceptibility to drought in the catchment. However, interviews indicate that there is increasing concern about how the intensification of dairy farming is leading to increased vulnerability to water shortages. Despite the considerable impacts felt by stakeholders during the drought of 2018, the event itself does not stand out as remarkable in our long-term reconstructions.

2.6 References

Bailey, A. D. and Bree, T. (1981) Effect of improved land drainage on river flow, in: Flood Studies Report – five Years on, Thomas Telford, London, 131–142.

Barker, L.J., Hannaford, J., Chiverton, A. and Svensson, C. (2016) From meteorological to hydrological drought using standardised indicators. *Hydrology and Earth System Sciences*, *20*(6), pp.2483-2505.

Bree, T. and Cunnane, C. (1979) Evaluating the effects of arterial drainage on river flood discharges, Annexe 1, Office of the Public Works, Dublin, Ireland.

Burdon, D. J. (1986) Hydrogeological Aspects of Agricultural Drainage in Ireland, Environ. Geol. Water S., 9, 41–65.

Casty, C., Raible, C., Stocker, T.F., Wanner, H. and Luterbacher, J. (2007) A European pattern climatology 1766–2000. *Climate Dynamics*, 29, 791–805.

Coron, L., Thirel, G., Delaigue, O., Perrin, C. and Andréassian, V. (2017) The suite of lumped GR hydrological models in an R package. *Environmental Modelling & Software*, 94, 166–171.

Harrigan, S., Murphy, C., Hall, J., Wilby, R.L. and Sweeney, J. (2014) Attribution of detected changes in streamflow using multiple working hypotheses. *Hydrology and Earth System Sciences*, *18*(5), pp.1935-1952.

Hawkins, E., Burt, S., McCarthy, M., Murphy, C., Ross, C., Baldock, M., Brazier, J., Hersee, G., Huntly, J., Meats, R., O'Grady, J., Scrimgeour, I., Silk, T. (2021) Millions of historical monthly rainfall observations taken in the UK and Ireland rescued by citizen scientists. Geoscience Data Journal. Under Review.

Jobbova, E., Crampsie, A., Horvath, C., Ludlow, F., Mcleman, R., Murphy, C. (2021) A database of Irish drought impacts derived from newspaper archives 1733-2019. Geoscience Data Journal (Under Submission).

McKee, T.B., Doesken, N.J. and Kleist, J. (1993) January. The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on Applied Climatology*, Vol. 17, No. 22, pp. 179-183.

Mouelhi, S., Michel, C., Perrin, C. and Andréassian, V. (2006) Stepwise development of a two-parameter monthly water balance model. *Journal of Hydrology*, 318(1–4), 200–214.

Murphy, C., Noone, S., Duffy, C., Broderick, C., Matthews, T. and Wilby, R.L., (2017) Irish droughts in newspaper archives: rediscovering forgotten hazards?. *Weather*, *72*(6), pp.151-155.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R.L. and Murphy, C. (2017) A 250-year drought catalogue for the Island of Ireland (1765–2015). *International Journal of Climatology*, *37*, pp.239-254.

Noone, S., Murphy, C., Coll, J., Matthews, T., Mullan, D., Wilby, R.L. and Walsh, S. (2016) Homogenization and analysis of an expanded long-term monthly rainfall network for the Island of Ireland (1850–2010). *International Journal of Climatology*, *36*(8), pp.2837-2853.

O'Connor, P., Murphy, C., Matthews, T. and Wilby, R.L. (2021) Reconstructed monthly river flows for Irish catchments 1766–2016. *Geoscience Data Journal*, *8*(1), pp.34-54.

O'Kelly, J. J. (1955) The employment of Unit Hydrographs to determine the flows of Irish arterial drainage channels, Proc. Inst. Civil Eng., 4, 365–412.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F. et al. (2005) Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2-Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *Journal of Hydrology*, 303(1–4), 290–306.

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., De Stefano, L., Acácio, V., Dias, S., Stagge, J.H., Tallaksen, L.M., Kampragou, E. and Van Loon, A.F. (2016). Impacts of European drought events: insights from an international database of text-based reports. *Natural Hazards and Earth System Sciences*, *16*(3), pp.801-819.

Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), pp.1696-1718.

Vicente-Serrano, S.M., Domínguez-Castro, F., Murphy, C., Hannaford, J., Reig, F., Peña-Angulo, D., Tramblay, Y., Trigo, R.M., Mac Donald, N., Luna, M.Y. and Mc Carthy, M. (2021) Long-term variability and trends in meteorological droughts in Western Europe (1851–2018). *International journal of climatology*, *41*, pp.E690-E717.

Yue, S. and Wang, C. (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water resources management*, *18*(3), pp.201-218.

3. Aragon basin

3.1 Crop yield data:

Crop yield data for the dry lands of the upper Aragón basin were obtained from the Spanish Ministry of Agriculture (https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/) for the period 2001-2019. Annual yield data (Kg/ha) were provided for the two major cultivated crops: winter barley and wheat. This information is based on annual crop field surveys (Peña-Gallardo et al., 2019). In addition, we obtained crop yields in the irrigated area of Bardenas for barley, wheat and corn from 2003 to 2015; dry land crop yields were also available for barley and wheat in the municipalities that include these irrigated lands, so this information was used for comparative purposes.

3.2 Drought impacts on crop yields

The response of rainfed barley and wheat crop yields to variability of climatic drought seems to be minimal (Figure 17) Results indicate that there is no crop failure in the upper Aragón basin, even during years with extreme climatic droughts. Thus, wheat and barley crop yields are characterized by a certain interannual variability but in general high yields are recorded during all years. The crop yields recorded in the upper Aragón basin show a similar magnitude to the irrigated lands of Bardenas (Figure 18). These results together suggest that drought is not a key driver of barley and wheat yields in the rainfed crops of the upper Aragón basin.

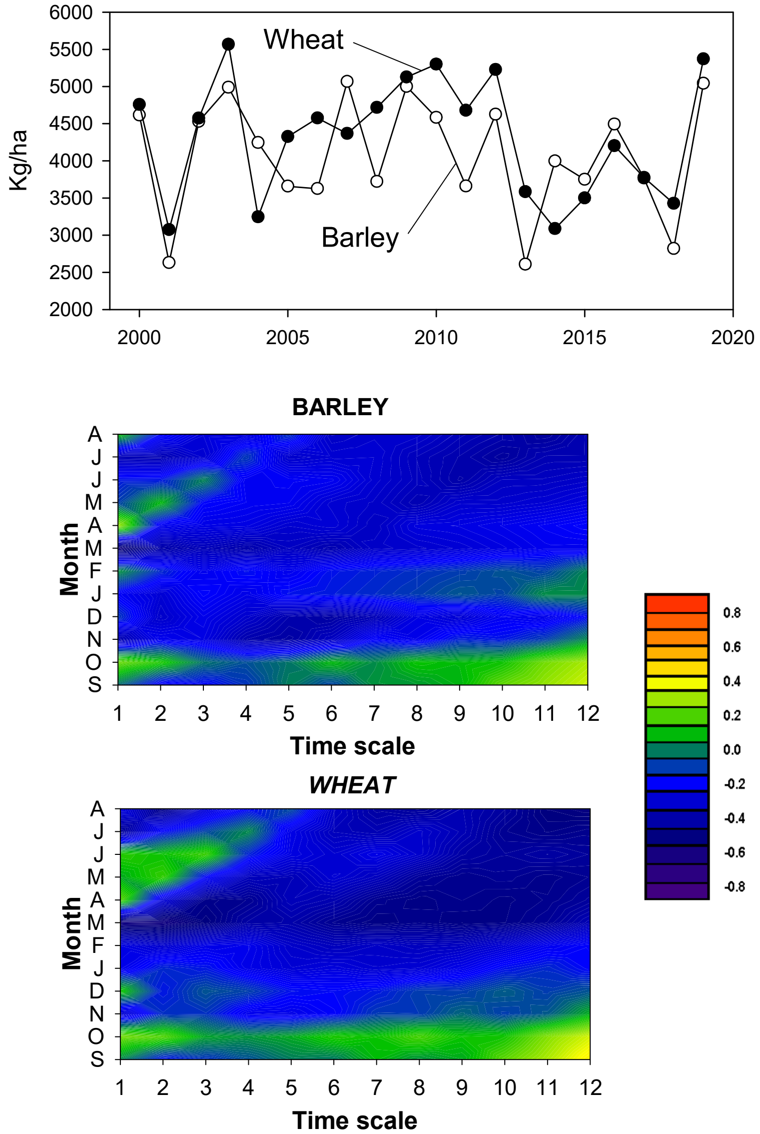

Figure 17: Evolution of the Aragón basin annual yield of wheat and barley (upper panel), and their monthly correlations with SPEI at 1- to 12-month timescales (central and lower panels).

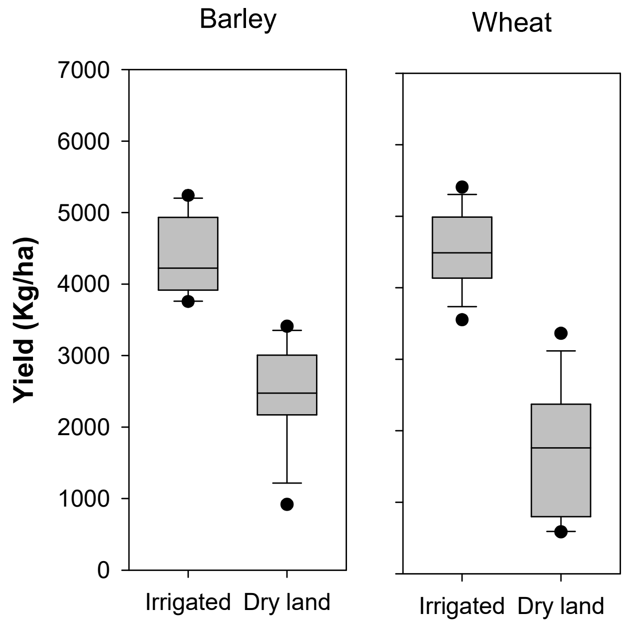

Figure 18: Box-plots showing the annual crop yields of barley and wheat in both the irrigated and dry lands. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes. Upper and lower black dots refer to the 95th and 5th percentiles.

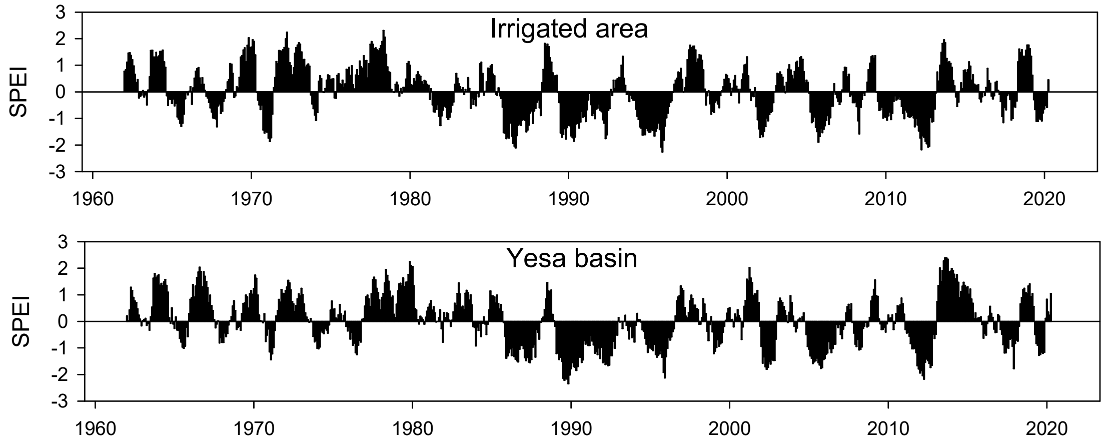

Figure 19: Temporal evolution of the SPEI 12-month timescale in the irrigated lands and the Yesa basin between 1961 and 2020.

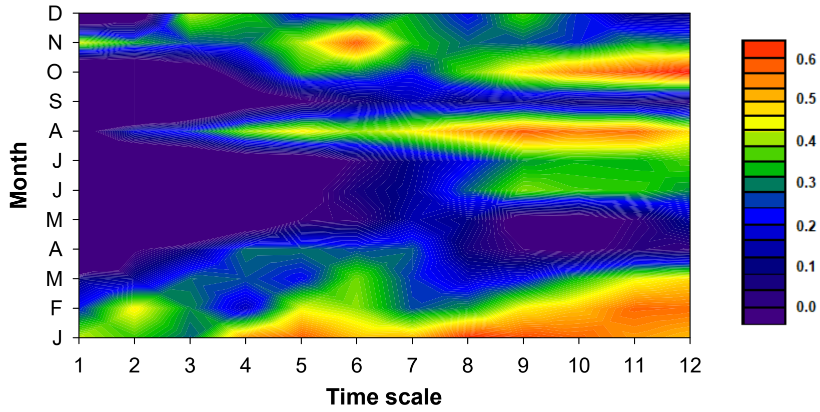

Figure 20: Pearson's correlations between the SPEI at 1- to 12-month timescales and those of the SSI in the Bardenas channel.

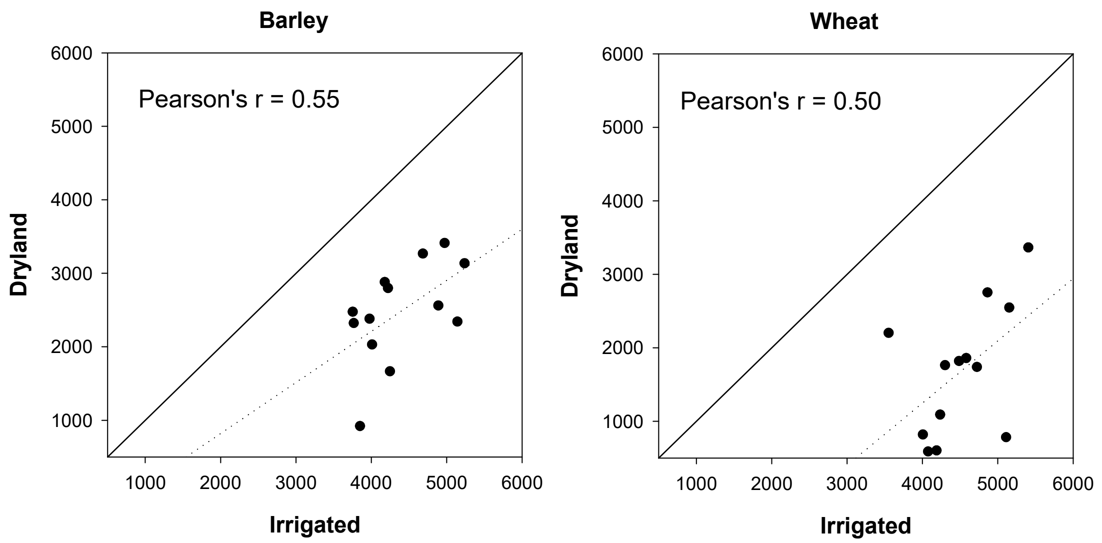

Figure 21: Relationships between the annual barley and wheat yields in the irrigated and dry lands. The dotted line indicates the best fitted regression line.

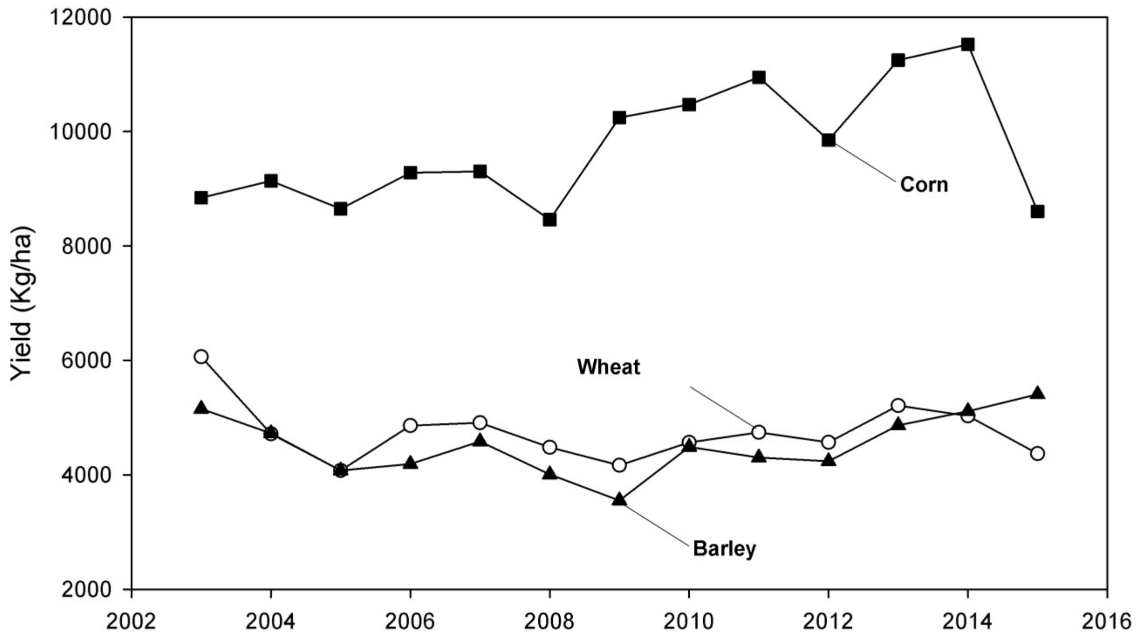

Figure 22: Evolution of the annual yields of corn, wheat, and barley in the irrigated lands.

3.3 Drought impacts downstream the upper Aragón basin

Figure 19 demonstrates that the temporal variability of climatic drought shows a similar pattern in both the upper Aragón basin and the irrigated lands of Bardenas, with Pearson's r equal 0.85. However, although consistent drought episodes can be determined for both areas, the flows of the Bardenas channel from the upper Aragón basin to the Bardenas irrigated area are less correlated with climatic drought in the Bardenas irrigated fields (Figure

20). The yield of irrigated crops was found higher than crops located in the dry lands of the Bardenas area (Figure 18), which may suggest that the channel flows can be seen as an independent signal in relation to climatic drought in the basin. Figure 21 confirms this finding, as the correlation between the interannual variability of irrigated wheat and barley yields and those of dry land yields was low, explaining only 25% of the total variability. Barley and wheat yields in the irrigated lands showed low temporal variability and accordingly more stable yields. For corn, the yields were higher, with an increasing trend from 2003 onwards (Figure 22). Although the average vegetation activity in the Bardenas areas, obtained from EVI, witnessed an increase from 2000 to 2020 (Figure 23.a), the correlation between vegetation activity and climatic drought (i.e. SPEI) was generally low (Figure 23.b), mainly during summer climatic stress conditions. Accordingly, the monthly correlations between vegetation activity, as derived from EVI, and hydrological droughts in the Bardenas channel were much higher than those with local climatic drought (Figure 23.c). This dependency on hydrological drought is mostly seen during summer months, in which corn cultivation is determined largely by the availability of irrigated water. The wheat and barley yields in the irrigated and dry land cultivations of the Bardenas area showed clear differences in their response to climatic drought between 2003 and 2015 (Figure 24). Specifically, in the irrigated lands, the higher correlations were found between February and April considering long time scales. On the other hand, the correlations for the crops in the dry areas were higher in the period from February to April, but considering shorter SPEI timescales (i.e. 3- to 5-month). For hydrological droughts, the correlation between the yields of wheat and barley in the irrigated lands and monthly SSI in the Bardenas channel was low during the period of crop development. Nevertheless, this correlation was high during summer in the case of the corn. Conversely, the dependency between corn yield and climatic drought in the Bardenas area was less significant.

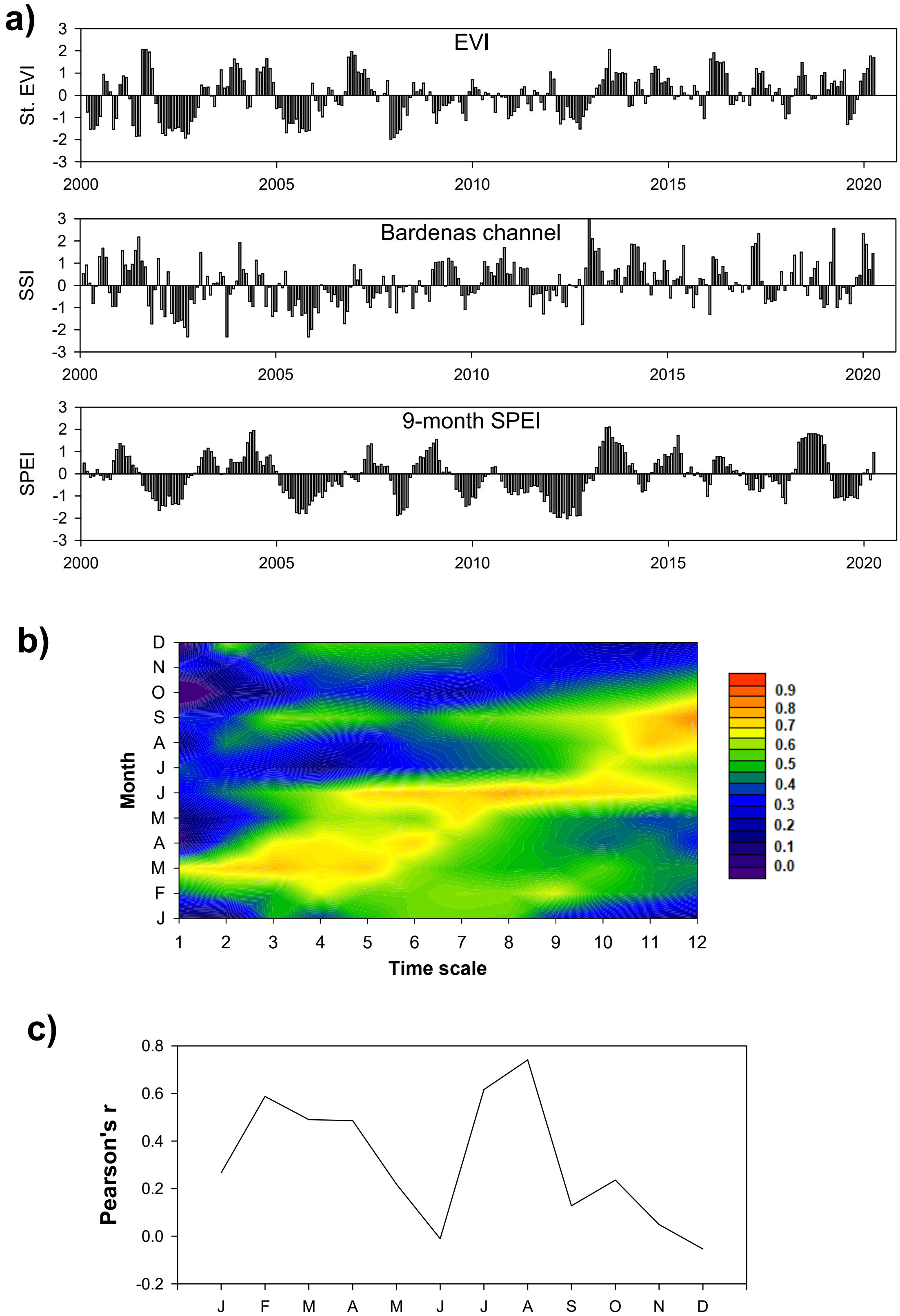

Figure 23: a) Evolution of the mean standardized EVI and SSI from the Bardenas channel flows, as compared to the SPEI 9-month timescale in the irrigated lands, b) monthly correlations between the EVI in the irrigated lands and SPEI 1- to 12-month timescales, and c) the monthly correlations between the EVI and the Bardenas channel flows.

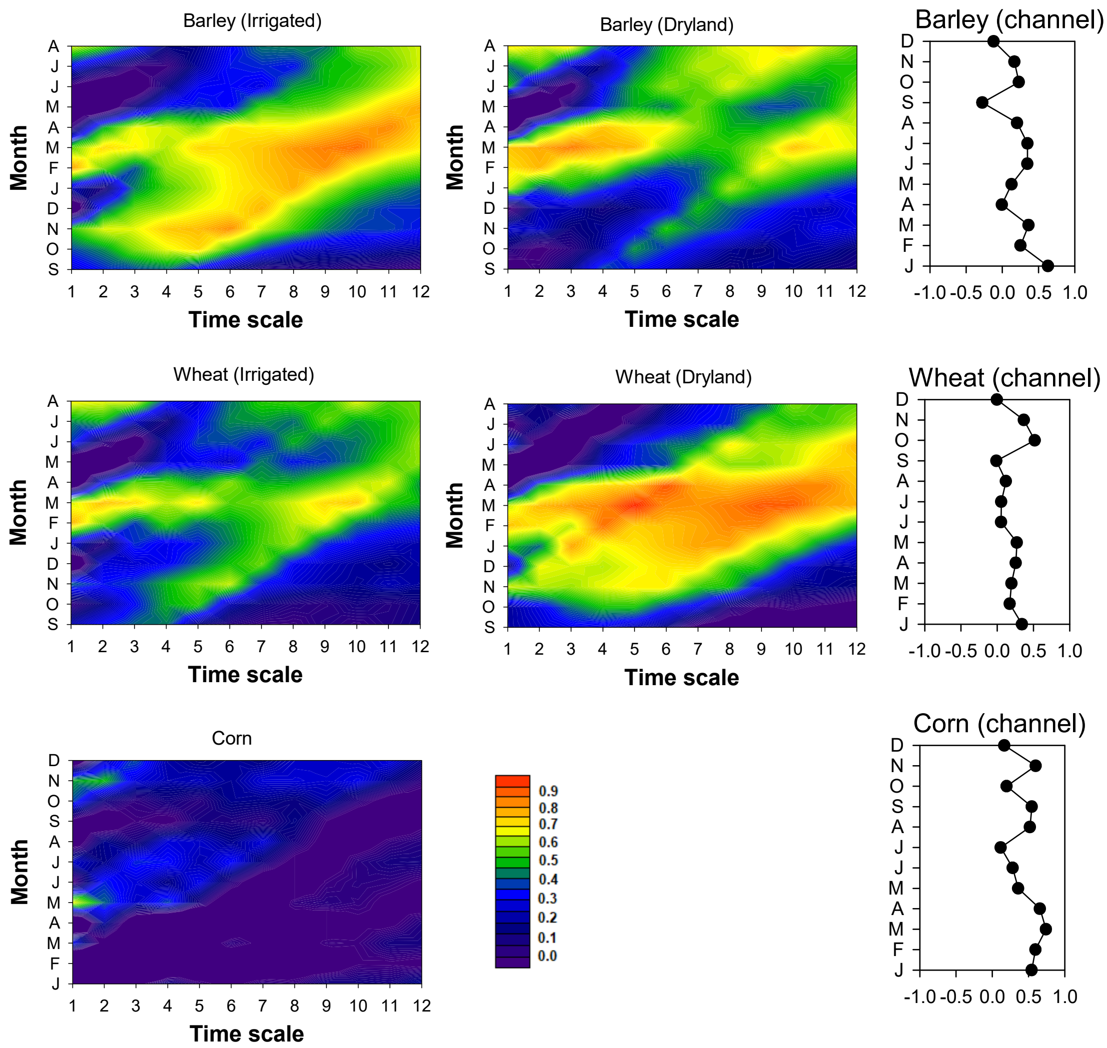

Figure 24: Pearson's r correlations between the monthly SPEI 1- to 12-month timescales and the annual crop yields in the irrigated and dry lands for barley and wheat. The corn is only cultivated in irrigated lands. The right plots show the Pearson's r correlations between the annual crop yields and the Bardenas channel flows.

3.4 Impacts of climatic droughts on crop yield

Among the different drought impacts in the upper Aragón basin, we have found that the interannual variability of winter cereals (i.e. rainfed barley and wheat) yields in the basin over the past two decades does not exhibit a significant dependency on the variability of climatic drought. This finding sounds interesting in the context that previous studies in the Iberian Peninsula indicated a general high dependency of winter cereal yields on drought variability (e.g. Páscoa et al., 2017; Peña-Gallardo et al., 2019; Vicente-Serrano et al., 2006). However, we must consider the particular climatic characteristics of the study basin, in which precipitation amounts, even in the driest years of the available record, are generally sufficient to guarantee the yield of these two crops. Observed climate records between 2001 and 2020 reveal that, -even in the lowest elevated areas of the basin where winter cereals are mainly distributed, annual rainfall totals were above 600 mm in all years. This amount exceeds water requirements for cereal crops in the region (Vicente-Serrano et al., 2006). This would explain why there was no year affected by crop failure or by a noticeable decrease in the crop yield over the investigated period. Thus, crop yields in the upper Aragón basin are mostly similar to those recorded in the irrigated lands of the central Ebro basin, and even higher than those of the dry lands in the same region (Vicente-Serrano et al., 2006).

We indicated that the interannual variability of the EVI2 in the crop areas of the upper Aragón basin is correlated with climatic drought during summertime, which could suggest a possible role of drought on crop development. Nevertheless, our results on the relationship between the integral of the growing season obtained from the phenological analysis and drought variability is largely consistent with the correlations found between crop yield and drought variability. The integral of the growing season could be a better metric of total net primary production, compared to vegetation activity, in specific months. Thus, the EVI2 of any particular month could sometimes be less representative of the total crop yield or more sensitive to the growth of some natural herbaceous cover after crop harvesting. Overall, our results reveal that – with the availability of crop water requirements- cereal crop yield seems to be less sensitive to drought variability in the upper Aragón basin. Rather, thermal conditions (e.g. changes in degree days, late frost, early heat) could have more impact on crop yield, as suggested in similar cold and humid regions (e.g. Cammarano et al., 2019).

Finally, although crop yields were not noticeably affected by drought variability in the upper Aragón basin, climate droughts showed a remarkable influence on crop yield in the irrigated lands of Bardenas. A water manager's priority is to maintain the Bardenas channel flows against the water releases to the Aragón basin. This issue is not critical during the cold season, in which the channel flows did not respond to the drought variability of the upper Aragón basin. The good correlation between the EVI2 and flows of the Bardenas channel can be seen as an indicator of the role of water availability in the development of winter cereals. Thus, under irrigated conditions, the correlation of wheat and barley crops, with local droughts did not show clear patterns. In contrast, crops of dry areas showed significant responses to drought, especially with the high climatic variability during wintertime and early spring, which could influence soil moisture recharge (Austin et al., 1998), and thus determine crop yields (Vicente-Serrano et al., 2006). Nevertheless, the impacts of water availability in the Bardenas channel on crop yields are much more evident during summer months. In this dry season, water deficits could drastically affect both vegetation activity and corn yield, especially with the strong impacts of climatic droughts on water releases to the Bardenas channel. There has been a notable increase in the flows of the Bardenas channel, which has secured water requirements for corn yields. We have seen that although climatic droughts occurred during the last decade in the upper Aragón basin (e.g. in 2013), the decision of the water managers was to increase the severity of hydrological drought in the downstream reaches of the Aragón River to maintain the normal releases to the Bardenas channel.

3.5 References

A. Changnon, S., E. Easterling, W., Changnon, S.A., Easterling, W.E., 2007. Measuring Drought Impacts: The Illinois Case. JAWRA J. Am. Water Resour. Assoc. 25, 27–42. https://doi.org/10.1111/j.1752-1688.1989.tb05663.x

Allen, C.D., Breshears, D.D., McDowell, N.G., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6. https://doi.org/10.1890/ES15-00203.1

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (T. ., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259, 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Anderegg, W.R.L., Klein, T., Bartlett, M., Sack, L., Pellegrini, A.F.A., Choat, B., Jansen, S., 2016. Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. Proc. Natl. Acad. Sci. U. S. A. 113, 5024–5029. https://doi.org/10.1073/pnas.1525678113

Anderegg, W.R.L., Konings, A.G., Trugman, A.T., Yu, K., Bowling, D.R., Gabbitas, R., Karp, D.S., Pacala, S., Sperry, J.S., Sulman, B.N., Zenes, N., 2018. Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature 561, 538–541. https://doi.org/10.1038/s41586-018-0539-7

Anderegg, W.R.L., Trugman, A.T., Bowling, D.R., Salvucci, G., Tuttle, S.E., 2019. Plant functional traits and climate influence drought intensification and land–atmosphere feedbacks. Proc. Natl. Acad. Sci. U. S. A. 116, 14071–14076. https://doi.org/10.1073/pnas.1904747116

Arzac, A., García-Cervigón, A.I., Vicente-Serrano, S.M., Loidi, J., Olano, J.M., 2016. Phenological shifts in climatic response of secondary growth allow Juniperus sabina L. to cope with altitudinal and temporal climate variability. Agric. For. Meteorol. 217. https://doi.org/10.1016/j.agrformet.2015.11.011

Austin, R.B., Cantero-Martínez, C., Arrúe, J.L., Playán, E., Cano-Marcellán, P., 1998. Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. Eur. J. Agron. 8, 239–248. https://doi.org/10.1016/S1161-0301(97)00063-4

Babst, F., Bouriaud, O., Alexander, R., Trouet, V., Frank, D., 2014a. Toward consistent measurements of carbon accumulation: A multi-site assessment of biomass and basal area increment across Europe. Dendrochronologia 32, 153–161. https://doi.org/10.1016/j.dendro.2014.01.002

Babst, F., Bouriaud, O., Papale, D., Gielen, B., Janssens, I.A., Nikinmaa, E., Ibrom, A., Wu, J., Bernhofer, C., Köstner, B., Grünwald, T., Seufert, G., Ciais, P., Frank, D., 2014b. Above-ground woody carbon sequestration measured from tree rings is coherent with net ecosystem productivity at five eddy-covariance sites. New Phytol. 201, 1289–1303. https://doi.org/10.1111/nph.12589

Bachmair, S., Kohn, I., Stahl, K., 2015. Exploring the link between drought indicators and impacts. Nat. Hazards Earth Syst. Sci. 15, 1381–1397. https://doi.org/10.5194/nhess-15-1381-2015

Bachmair, S., Svensson, C., Hannaford, J., Barker, L.J., Stahl, K., 2016. A quantitative analysis to objectively appraise drought indicators and model drought impacts. Hydrol. Earth Syst. Sci. 20, 2589–2609. https://doi.org/10.5194/hess-20-2589-2016

Bachmair, S., Tanguy, M., Hannaford, J., Stahl, K., 2018. How well do meteorological indicators represent agricultural and forest drought across Europe? Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaafda

Barker, L.J., Hannaford, J., Chiverton, A., Svensson, C., 2016. From meteorological to hydrological drought using standardised indicators. Hydrol. Earth Syst. Sci. 20, 2483–2505. https://doi.org/10.5194/hess-20-2483-2016

Beguería, S., López-Moreno, J.I., Lorente, A., Seeger, M., García-Ruiz, J.M., 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32, 283–286. https://doi.org/10.1579/0044-7447-32.4.283

Bloomfield, J.P., Marchant, B.P., 2013. Analysis of groundwater drought building on the standardised precipitation index approach. Hydrol. Earth Syst. Sci. 17, 4769–4787. https://doi.org/10.5194/hess-17-4769-2013

Bloomfield, J.P., Marchant, B.P., Bricker, S.H., Morgan, R.B., 2015. Regional analysis of groundwater droughts using hydrograph classification. Hydrol. Earth Syst. Sci. 19, 4327–4344. https://doi.org/10.5194/hess-19-4327-2015

Camarero, J.J., Bigler, C., Linares, J.C., Gil-Pelegrín, E., 2011. Synergistic effects of past historical logging and drought on the decline of Pyrenean silver fir forests. For. Ecol. Manage. 262, 759–769. https://doi.org/10.1016/j.foreco.2011.05.009

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., Vicente-Serrano, S.M., 2015. To die or not to die: Early warnings of tree dieback in response to a severe drought. J. Ecol. 103. https://doi.org/10.1111/1365-2745.12295

Cammarano, D., Hawes, C., Squire, G., Holland, J., Rivington, M., Murgia, T., Roggero, P.P., Fontana, F., Casa, R., Ronga, D., 2019. Rainfall and temperature impacts on barley (Hordeum vulgare L.) yield and malting quality in Scotland. F. Crop. Res. 241, 107559. https://doi.org/https://doi.org/10.1016/j.fcr.2019.107559

Carlson, T.N., Ripley, D.A., 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote Sens. Environ. 62, 241–252. https://doi.org/10.1016/S0034-4257(97)00104-1

Chaves, M.M., Maroco, J.P., Pereira, J.S., 2003. Understanding plant responses to drought - From genes to the whole plant. Funct. Plant Biol. 30, 239–264. https://doi.org/10.1071/FP02076

Cihlar, J., St.-Laurent, L., Dyer, J.A., 1991. Relation between the normalized difference vegetation index and ecological variables. Remote Sens. Environ. 35, 279–298. https://doi.org/10.1016/0034-4257(91)90018-2

Dalla Costa, L., Gianquinto, G., 2002. Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: Lysimeter studies. Aust. J. Agric. Res. 53, 201–210. https://doi.org/10.1071/AR00133

Domínguez-Castro, F., Vicente-Serrano, S.M., Tomás-Burguera, M., Peña-Gallardo, M., Beguería, S., El Kenawy, A., Luna, Y., Morata, A., 2019. High spatial resolution climatology of drought events for Spain: 1961–2014. Int. J. Climatol.

Folland, C.K., Hannaford, J., Bloomfield, J.P., Kendon, M., Svensson, C., Marchant, B.P., Prior, J., Wallace, E., 2015. Multi-annual droughts in the English Lowlands: A review of their characteristics and climate drivers in the winter half-year. Hydrol. Earth Syst. Sci. 19, 2353–2375. https://doi.org/10.5194/hess-19-2353-2015

Fritts, H.C., 1976. No Title. Tree Rings Clim.

García-Ruiz, J.M., López-Moreno, J.I., Lasanta, T., Vicente-Serrano, S.M., González-Sampériz, P., Valero-Garcés, B.L., Sanjuán, Y., Beguería, S., Nadal-Romero, E., Lana-Renault, N., Gómez-Villar, A., 2015. Geo-ecological effects of global change in the Central Spanish Pyrenees: A review at different spatial and temporal scales [Los efectos geoecológicos del cambio global en el pirineo central español: Una revisión a distintas escalas espaciales y temporales. Pirineos 170. https://doi.org/10.3989/Pirineos.2015.170005

Gazol, A., Camarero, J.J., Anderegg, W.R.L., Vicente-Serrano, S.M., 2017. Impacts of droughts on the growth resilience of Northern Hemisphere forests. Glob. Ecol. Biogeogr. 26. https://doi.org/10.1111/geb.12526

Gazol, A., Camarero, J.J., Vicente-Serrano, S.M., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., Sangüesa-Barreda, G., Novak, K., Rozas, V., Tíscar, P.A., Linares, J.C., Martín-Hernández, N., Martínez del Castillo, E., Ribas, M., García-González, I., Silla, F., Camisón, A., Génova, M., Olano, J.M., Longares, L.A., Hevia, A., Tomás-Burguera, M., Galván, J.D., 2018. Forest resilience to drought varies across biomes. Glob. Chang. Biol. 24. https://doi.org/10.1111/gcb.14082

Giner, C., Martínez, B., Gilabert, M.A., Alcaraz-Segura, D., 2012. Trends in vegetation greenness and gross primary production in Spain (2000-2009) | Tendencias en el verdor de la vegetación y en la producción primaria bruta de las áreas forestales en la España peninsular (2000-2009). Rev. Teledetec. 51–64.

Heim, R.R., 2002. A Review of Twentieth-Century Drought Indices Used in the United States. Bull. Am. Meteorol. Soc. 83, 1149–1165. https://doi.org/10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Kim, W., Iizumi, T., Nishimori, M., 2019. Global Patterns of Crop Production Losses Associated with Droughts from 1983 to 2009. J. Appl. Meteorol. Climatol. 58, 1233–1244. https://doi.org/10.1175/JAMC-D-18-0174.1

Lasanta-Martínez, T., Vicente-Serrano, S.M., Cuadrat-Prats, J.M., 2005. Mountain Mediterranean landscape evolution caused by the abandonment of traditional primary activities: A study of the Spanish Central Pyrenees. Appl. Geogr. 25. https://doi.org/10.1016/j.apgeog.2004.11.001

Lasanta, T., Vicente-Serrano, S.M., 2007. Cambios en la cubierta vegetal en el pirineo aragonés en los últimos 50 años. Pirineos.

Liu, W.T., Kogan, F.N., 1996. Monitoring regional drought using the vegetation condition index. Int. J. Remote Sens. 17, 2761–2782. https://doi.org/10.1080/01431169608949106

Lloyd-Hughes, B., 2014. The impracticality of a universal drought definition. Theor. Appl. Climatol. 117, 607–611. https://doi.org/10.1007/s00704-013-1025-7

López-Moreno, J.I., Beguería, S., García-Ruiz, J.M., 2004. The management of a large

Mediterranean reservoir: Storage regimens of the Yesa Reservoir, Upper Aragon River basin, Central Spanish Pyrenees. Environ. Manage. 34, 508–515. https://doi.org/10.1007/s00267-003-0249-1

López-Moreno, J.I., García-Ruiz, J.M., 2004. Influence of snow accumulation and snowmelt on streamflow in the central Spanish Pyrenees | Influence de l'accumulation et de la fonte de la neige sur les écoulements dans les Pyrénées centrales espagnoles. Hydrol. Sci. J. 49, 787–802.

López-Moreno, J.I., Soubeyroux, J.M., Gascoin, S., Alonso-Gonzalez, E., Durán-Gómez, N., Lafaysse, M., Vernay, M., Carmagnola, C., Morin, S., 2020. Long-term trends (1958–2017) in snow cover duration and depth in the Pyrenees. Int. J. Climatol. n/a. https://doi.org/10.1002/joc.6571

López-Moreno, J.I., Vicente-Serrano, S.M., Begueria, S., Garcia-Ruiz, J.M., Portela, M.M., Almeida, A.B., 2009. Dam effects on droughts magnitude and duration in a transboundary basin: The lower river tagus, pain and Portugal. Water Resour. Res. 45. https://doi.org/10.1029/2008WR007198

López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M., 2011. Impact of climate evolution and land use changes on water yield in the ebro basin. Hydrol. Earth Syst. Sci. 15. https://doi.org/10.5194/hess-15-311-2011

López-Moreno, J.I., Vicente-Serrano, S.M., Zabalza, J., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., Morán-Tejeda, E., 2013. Hydrological response to climate variability at different time scales: A study in the Ebro basin. J. Hydrol. 477, 175–188. https://doi.org/10.1016/j.jhydrol.2012.11.028

Lorenzo-Lacruz, J., Garcia, C., Morán-Tejeda, E., 2017. Groundwater level responses to precipitation variability in Mediterranean insular aquifers. J. Hydrol. 552, 516–531. https://doi.org/10.1016/J.JHYDROL.2017.07.011

Lorenzo-Lacruz, J., Vicente-Serrano, S.M., González-Hidalgo, J.C., López-Moreno, J.I., Cortesi, N., 2013. Hydrological drought response to meteorological drought in the Iberian Peninsula. Clim. Res. 58. https://doi.org/10.3354/cr01177

Marchant, B.P., Bloomfield, J.P., 2018. Spatio-temporal modelling of the status of groundwater droughts. J. Hydrol. 564, 397–413. https://doi.org/10.1016/j.jhydrol.2018.07.009

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Eighth Conf. Appl. Climatol. 179–184.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Morán-Tejeda, E., Lorenzo-Lacruz, J., López-Moreno, J.I., Ceballos-Barbancho, A., Zabalza, J., Vicente-Serrano, S.M., 2012. Reservoir Management in the Duero Basin (Spain): Impact on River Regimes and the Response to Environmental Change. Water Resour. Manag. 26. https://doi.org/10.1007/s11269-012-0004-6

Mukherjee, S., Mishra, A., Trenberth, K.E., 2018. Climate Change and Drought: a Perspective on Drought Indices. Curr. Clim. Chang. Reports 4, 145–163. https://doi.org/10.1007/s40641-018-0098-x

Nakayama, T., Shankman, D., 2013. Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Glob. Planet. Change 100, 38–50. https://doi.org/10.1016/j.gloplacha.2012.10.004

Nicholson, S.E., Davenport, M.L., Malo, A.R., 1990. A comparison of the vegetation response to rainfall in the Sahel and East Africa, using normalized difference vegetation index from NOAA AVHRR. Clim. Change 17, 209–241. https://doi.org/10.1007/BF00138369

Noguera, I., Domínguez-Castro, F., Vicente-Serrano, S.M., 2020. Characteristics and trends of flash droughts in Spain, 1961-2018. Ann. N. Y. Acad. Sci. https://doi.org/10.1111/nyas.14365

Ortigosa, L.M., Garcia-Ruiz, J.M., Gil-Pelegrin, E., 1990. Land reclamation by reforestation in the Central Pyrenees. Mt. Res. & Dev. 10, 281–288. https://doi.org/10.2307/3673607

Páscoa, P., Gouveia, C.M., Russo, A., Trigo, R.M., 2017. The role of drought on wheat yield interannual variability in the Iberian Peninsula from 1929 to 2012. Int. J. Biometeorol. 61, 439–451. https://doi.org/10.1007/s00484-016-1224-x

Pasho, E., Camarero, J.J., de Luis, M., Vicente-Serrano, S.M., 2011. Impacts of drought at different time scales on forest growth across a wide climatic gradient in north-eastern Spain. Agric. For. Meteorol. 151. https://doi.org/10.1016/j.agrformet.2011.07.018

Peguero-Pina, J.J., Camarero, J.J., Abadía, A., Martín, E., González-Cascón, R., Morales, F., Gil-Pelegrín, E., 2007. Physiological performance of silver-fir (Abies alba Mill.) populations under contrasting climates near the south-western distribution limit of the species. Flora Morphol. Distrib. Funct. Ecol. Plants 202, 226–236. https://doi.org/10.1016/j.flora.2006.06.004

Peguero-Pina, J.J., Sancho-Knapik, D., Cochard, H., Barredo, G., Villarroya, D., Gil-Pelegrin, E., 2011. Hydraulic traits are associated with the distribution range of two closely related Mediterranean firs, Abies alba Mill. and Abies pinsapo Boiss. Tree Physiol. 31, 1067–1075. https://doi.org/10.1093/treephys/tpr092

Peña-Gallardo, M, SM, V.-S., Domínguez-Castro, F., Quiring, S., Svoboda, M., Beguería, S., Hannaford, J., 2018. Effectiveness of drought indices in identifying impacts on major crops across the USA . Clim. Res. 75, 221–240.

Peña-Gallardo, Marina, Vicente-Serrano, S.M., Camarero, J.J., Gazol, A., Sánchez-Salguero, R., Domínguez-Castro, F., El Kenawy, A., Beguería-Portugés, S., Gutiérrez, E., de Luis, M., Sangüesa-Barreda, G., Novak, K., Rozas, V., Tíscar, P.A., Linares, J.C., del Castillo, E., Ribas Matamoros, M., García-González, I., Silla, F., Camisón, Á., Génova, M., Olano, J.M., Longares, L.A., Hevia, A., Galván, J.D., 2018. Drought Sensitiveness on Forest Growth in Peninsular Spain and the Balearic Islands. Forests 9.

Peña-Gallardo, M, Vicente-Serrano, S.M., Dom\'\inguez-Castro, F., Beguer\'\ia, S., 2019. The impact of drought on the productivity of two rainfed crops in Spain. Nat. Hazards Earth Syst. Sci. 19, 1215–1234. https://doi.org/10.5194/nhess-19-1215-2019

Peña-Gallardo, M., Vicente-Serrano, S.M., Hannaford, J., Lorenzo-Lacruz, J., Svoboda, M., Domínguez-Castro, F., Maneta, M., Tomas-Burguera, M., Kenawy, A.E., 2019. Complex influences of meteorological drought time-scales on hydrological droughts in natural basins of the contiguous Unites States. J. Hydrol. 568.

https://doi.org/10.1016/j.jhydrol.2018.11.026

Peng, D., Wu, C., Li, C., Zhang, X., Liu, Z., Ye, H., Luo, S., Liu, X., Hu, Y., Fang, B., 2017. Spring green-up phenology products derived from MODIS NDVI and EVI: Intercomparison, interpretation and validation using National Phenology Network and AmeriFlux observations. Ecol. Indic. 77, 323–336. https://doi.org/10.1016/j.ecolind.2017.02.024

Rangecroft, S., Van Loon, A.F., Coxon, G., Breña-Naranjo, J.A., Van Ogtrop, F., Van Lanen, H.A.J., 2018. Using paired catchments to quantify the human influence on hydrological droughts. Hydrol. Earth Syst. Sci. Discuss. 1–23. https://doi.org/10.5194/hess-2018-215

Restaino, C.M., Peterson, D.L., Littell, J., 2016. Increased water deficit decreases Douglas fir growth throughout western US forests. Proc. Natl. Acad. Sci. U. S. A. 113, 9557–9562. https://doi.org/10.1073/pnas.1602384113

Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., Zabalza, J., Arguedas, G., Vicente-Serrano, S.M., 2014. Mapping the annual evolution of snow depth in a small catchment in the Pyrenees using the long-range terrestrial laser scanning. J. Maps 10. https://doi.org/10.1080/17445647.2013.869268

Reynolds, J.F., Virginia, R.A., Kemp, P.R., De Soyza, A.G., Tremmel, D.C., 1999. Impact of drought on desert shrubs: Effects of seasonality and degree of resource island development. Ecol. Monogr.

Richardson, A.D., Carbone, M.S., Keenan, T.F., Czimczik, C.I., Hollinger, D.Y., Murakami, P., Schaberg, P.G., Xu, X., 2013. Seasonal dynamics and age of stemwood nonstructural carbohydrates in temperate forest trees. New Phytol. 197, 850–861. https://doi.org/10.1111/nph.12042

Sah, R.P., Chakraborty, M., Prasad, K., Pandit, M., Tudu, V.K., Chakravarty, M.K., Narayan, S.C., Rana, M., Moharana, D., 2020. Impact of water deficit stress in maize: Phenology and yield components. Sci. Rep.

Sánchez-Salguero, R., Camarero, J.J., Dobbertin, M., Fernández-Cancio, T., Vilà-Cabrera, A., Manzanedo, R.D., Zavala, M.A., Navarro-Cerrillo, R.M., 2013. Contrasting vulnerability and resilience to drought-induced decline of densely planted vs. natural rear-edge Pinus nigra forests. For. Ecol. Manage. 310, 956–967. https://doi.org/10.1016/j.foreco.2013.09.050

Scaini, A., Sánchez, N., Vicente-Serrano, S.M., Martínez-Fernández, J., 2015. SMOS-derived soil moisture anomalies and drought indices: A comparative analysis using in situ measurements. Hydrol. Process. 29. https://doi.org/10.1002/hyp.10150

Sena, A., Barcellos, C., Freitas, C., Corvalan, C., 2014. Managing the health impacts of drought in Brazil. Int. J. Environ. Res. Public Health 11, 10737–10751. https://doi.org/10.3390/ijerph111010737

Skomarkova, M.V., Vaganov, E.A., Mund, M., Knohl, A., Linke, P., Boerner, A., Schulze, E.-D., 2006. Inter-annual and seasonal variability of radial growth, wood density and carbon isotope ratios in tree rings of beech (Fagus sylvatica) growing in Germany and Italy. Trees - Struct. Funct. 20, 571–586. https://doi.org/10.1007/s00468-006-0072-4

Slette, I.J., Post, A.K., Awad, M., Even, T., Punzalan, A., Williams, S., Smith, M.D., Knapp, A.K., 2019. How ecologists define drought, and why we should do better. Glob. Chang. Biol.

25, 3193–3200. https://doi.org/10.1111/gcb.14747

Slette, I.J., Smith, M.D., Knapp, A.K., Vicente-Serrano, S.M., Camarero, J.J., Beguería, S., 2020. Standardized metrics are key for assessing drought severity. Glob. Chang. Biol. 26, e1–e3. https://doi.org/10.1111/gcb.14899

Sperry, J.S., Love, D.M., 2015. What plant hydraulics can tell us about responses to climate-change droughts. New Phytol. 207, 14–27. https://doi.org/10.1111/nph.13354

Stanke, C., Kerac, M., Prudhomme, C., Medlock, J., Murray, V., 2013. Health effects of drought: a systematic review of the evidence. PLoS Curr. 5. https://doi.org/10.1371/currents.dis.7a2cee9e980f91ad7697b570bcc4b004

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D., Stephens, S., 2002. The drought monitor. Bull. Am. Meteorol. Soc. 83, 1181–1190. https://doi.org/10.1175/1520-0477(2002)083<1181:TDM>2.3.CO;2

Tan, B., Gao, F., Tan, B., Gao, F., Wolfe, R.E., Pedelty, J.A., Nightingale, J., Morisette, J.T., Ederer, G.A., Nightingale, J., 2011. An Enhanced TIMESAT Algorithm for Estimating Vegetation Phenology Metrics From MODIS Data. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 4, 361–371. https://doi.org/10.1109/JSTARS.2010.2075916

Tijdeman, E., Bachmair, S., Stahl, K., 2016. Controls on hydrologic drought duration in near-natural streamflow in Europe and the USA. Hydrol. Earth Syst. Sci. 20, 4043–4059. https://doi.org/10.5194/hess-20-4043-2016

Tijdeman, E., Hannaford, J., Stahl, K., 2018. Human influences on streamflow drought characteristics in England and Wales. Hydrol. Earth Syst. Sci. 22, 1051–1064. https://doi.org/10.5194/hess-22-1051-2018

Tomas-Burguera, M., M Vicente-Serrano, S., Beguería, S., Reig, F., Latorre, B., 2019. Reference crop evapotranspiration database in Spain (1961-2014). Earth Syst. Sci. Data 11, 1917–1930. https://doi.org/10.5194/essd-11-1917-2019

Trnka, M., Dubrovský, M., Svoboda, M., Semerádová, D., Hayes, M., Žalud, Z., Wilhite, D., 2009. Developing a regional drought climatology for the Czech Republic. Int. J. Climatol.

Trnka, M., Hlavinka, P., Možný, M., Semerádová, D., Štěpánek, P., Balek, J., Bartošová, L., Zahradníček, P., Bláhová, M., Skalák, P., Farda, A., Hayes, M., Svoboda, M., Wagner, W., Eitzinger, J., Fischer, M., Žalud, Z., 2020. Czech Drought Monitor System for monitoring and forecasting agricultural drought and drought impacts. Int. J. Climatol. n/a. https://doi.org/10.1002/joc.6557

Tucker, C.J., Sellers, P.J., 1986. Satellite remote sensing of primary production. Int. J. Remote Sens. 7, 1395–1416. https://doi.org/10.1080/01431168608948944

Van Lanen, H.A.J., Wanders, N., Tallaksen, L.M., Van Loon, A.F., 2013. Hydrological drought across the world: Impact of climate and physical catchment structure. Hydrol. Earth Syst. Sci. 17, 1715–1732. https://doi.org/10.5194/hess-17-1715-2013

Van Loon, A.F., 2015. Hydrological drought explained. Wiley Interdiscip. Rev. Water 2, 359–392. https://doi.org/10.1002/wat2.1085

Vicente-Serrano, S., Cuadrat-Prats, J.M., Romo, A., 2006. Early prediction of crop production using drought indices at different time-scales and remote sensing data: Application in the Ebro Valley (north-east Spain). Int. J. Remote Sens. 27. https://doi.org/10.1080/01431160500296032

Vicente-Serrano, S.M., 2016. Foreword: Drought complexity and assessment under climate change conditions. Cuad. Investig. Geogr. 42. https://doi.org/10.18172/cig.2961

Vicente-Serrano, S.M., Beguería, S., Lasanta, T., 2006. Spatial diversity of vegetal activity in abandoned fields of the central Spanish Pyrenees: Analysis of the processes of succession by means of Landsat imagery (1984-2001). Pirineos.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. J. Clim. 23. https://doi.org/10.1175/2009JCLI2909.1

Vicente-Serrano, S.M., Camarero, J.J., Azorin-Molina, C., 2014. Diverse responses of forest growth to drought time-scales in the Northern Hemisphere. Glob. Ecol. Biogeogr. 23. https://doi.org/10.1111/geb.12183

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J.I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2013. Response of vegetation to drought time-scales across global land biomes. Proc. Natl. Acad. Sci. U. S. A. 110, 52–7. https://doi.org/10.1073/pnas.1207068110

Vicente-Serrano, S.M., López-Moreno, J.I., 2005. Hydrological response to different time scales of climatological drought: An evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. Hydrol. Earth Syst. Sci. 9. https://doi.org/10.5194/hess-9-523-2005

Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., Morán-Tejeda, E., 2012. Accurate Computation of a Streamflow Drought Index. J. Hydrol. Eng. 17. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000433

Vicente-Serrano, S M, Martín-Hernández, N., Reig, F., Azorin-Molina, C., Zabalza, J., Beguería, S., Domínguez-Castro, F., El Kenawy, A., Peña-Gallardo, M., Noguera, I., García, M., 2020. Vegetation greening in Spain detected from long term data (1981–2015). Int. J. Remote Sens. 41, 1709–1740. https://doi.org/10.1080/01431161.2019.1674460

Vicente-Serrano, S.M., Quiring, S., Peña-Gallardo, M., Domínguez-castro, F., Yuan, S., 2020. A review of environmental droughts: Increased risk under global warming? Earth Sci. Rev.

Vicente-Serrano, S M, Zabalza-Martínez, J., Borràs, G., López-Moreno, J.I., Pla, E., Pascual, D., Savé, R., Biel, C., Funes, I., Azorin-Molina, C., Sanchez-Lorenzo, A., Martín-Hernández, N., Peña-Gallardo, M., Alonso-González, E., Tomas-Burguera, M., El Kenawy, A., 2017. Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain. J. Hydrol. Reg. Stud. 12, 13–32. https://doi.org/10.1016/j.ejrh.2017.01.004

Vicente-Serrano, S.M., Zabalza-Martínez, J., Borràs, G., López-Moreno, J.I., Pla, E., Pascual, D., Savé, R., Biel, C., Funes, I., Martín-Hernández, N., Peña-Gallardo, M., Beguería, S., Tomas-Burguera, M., 2017. Effect of reservoirs on streamflow and river regimes in a heavily regulated river basin of Northeast Spain. Catena 149. https://doi.org/10.1016/j.catena.2016.03.042

Vose, J.M., Miniat, C.F., Luce, C.H., Asbjornsen, H., Caldwell, P.V., Campbell, J.L., Grant, G.E., Isaak, D.J., Loheide, S.P., Sun, G., 2016. Ecohydrological implications of drought for forests in the United States. For. Ecol. Manage. 380, 335–345. https://doi.org/10.1016/j.foreco.2016.03.025

Wang, H., Vicente-serrano, S.M., Tao, F., Zhang, X., Wang, P., Zhang, C., Chen, Y., Zhu, D., Kenawy, A.E., 2016. Monitoring winter wheat drought threat in Northern China using multiple climate-based drought indices and soil moisture during 2000–2013. Agric. For. Meteorol. 228–229. https://doi.org/10.1016/j.agrformet.2016.06.004

Wang, J., Yang, D., Detto, M., Nelson, B.W., Chen, M., Guan, K., Wu, S., Yan, Z., Wu, J., 2020. Multi-scale integration of satellite remote sensing improves characterization of dry-season green-up in an Amazon tropical evergreen forest. Remote Sens. Environ.

Webber, H., Ewert, F., Olesen, J.E., Müller, C., Fronzek, S., Ruane, A.C., Bourgault, M., Martre, P., Ababaei, B., Bindi, M., Ferrise, R., Finger, R., Fodor, N., Gabaldón-Leal, C., Gaiser, T., Jabloun, M., Kersebaum, K.-C., Lizaso, J.I., Lorite, I.J., Manceau, L., Moriondo, M., Nendel, C., Rodríguez, A., Ruiz-Ramos, M., Semenov, M.A., Siebert, S., Stella, T., Stratonovitch, P., Trombi, G., Wallach, D., 2018. Diverging importance of drought stress for maize and winter wheat in Europe. Nat. Commun. 9, 4249. https://doi.org/10.1038/s41467-018-06525-2

Wilhite, D.A., 2009. Drought Monitoring as a Component of Drought Preparedness Planning, in: Iglesias, A., Cancelliere, A., Wilhite, D.A., Garrote, L., Cubillo, F. (Eds.), Coping with Drought Risk in Agriculture and Water Supply Systems: Drought Management and Policy Development in the Mediterranean. Springer Netherlands, Dordrecht, pp. 3–19. https://doi.org/10.1007/978-1-4020-9045-5_1

Wilhite, D.A., 2005. Drought. Encycl. Earth Sci. Ser. 338–341. https://doi.org/10.1007/1-4020-3266-8_70

Wilhite, D.A., 2002. Combating drought through preparedness. Nat. Resour. Forum 26, 275–285. https://doi.org/10.1111/1477-8947.00030

Wilhite, D.A., Pulwarty, R.S., 2017. Drought as Hazard: Understanding the Natural and Social Context, in: Drought and Water Crises: Integrating Science, Management, and Policy. pp. 3–22.

Wilhite, D.A., Svoboda, M.D., Hayes, M.J., 2007. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. Water Resour. Manag. 21, 763–774. https://doi.org/10.1007/s11269-006-9076-5

Xu, Y., Zhang, X., Wang, X., Hao, Z., Singh, V.P., Hao, F., 2019. Propagation from meteorological drought to hydrological drought under the impact of human activities: A case study in northern China. J. Hydrol. 579. https://doi.org/10.1016/j.jhydrol.2019.124147

Zhang, L., Xiao, J., Zhou, Y., Zheng, Y., Li, J., Xiao, H., 2016. Drought events and their effects on vegetation productivity in China. Ecosphere 7. https://doi.org/10.1002/ecs2.1591

Zhang, R., Chen, X., Zhang, Z., Shi, P., 2014. Evolution of hydrological drought under the regulation of two reservoirs in the headwater basin of the Huaihe River, China. Stoch. Environ. Res. Risk Assess. 29, 487–499. https://doi.org/10.1007/s00477-014-0987-z

Zhang, X., Zhang, L., Zhao, J., Rustomji, P., Hairsine, P., 2009. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resour. Res. 45. https://doi.org/10.1029/2007WR006711