

RESEARCH ARTICLE

Towards improved understanding of cascading and interconnected risks from concurrent weather extremes: Analysis of historical heat and drought extreme events

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Abstract

Weather extremes can affect many different assets, sectors and systems of the human environment, including human security, health and well-being. Weather extremes that compound, such as heat and drought, and their interconnected risks are complex, difficult to understand and thus a challenge for risk analysis and management, because (in intertwined systems) impacts can propagate through multiple sectors. In a warming climate, extreme concurrent heat and drought events are expected to increase in frequency, intensity and duration, posing growing risks to societies. To gain a better understanding of compound extremes and associated risks, we analyze eight historical heat and drought extreme events in Europe, Africa and Australia. We investigated and visualized the direct and indirect impact paths through different sectors and systems together with the impacts of response and adaptation measures. We found the most important cascading processes and interlinkages centered around the health, energy and agriculture and food production sectors. The key cascades result in impacts on the economy, the state and public services and ultimately also on society and culture. Our analysis shows that cascading impacts can propagate through numerous sectors with far reaching consequences, potentially being able to destabilize entire socio-economic systems. We emphasize that the future challenge in research on and adaptation to concurrent extreme events lies in the integration of assets, sectors and systems with strong interlinkages to other sectors and with a large potential for cascading impacts, but for which we cannot resort to historical experiences. Integrating approaches to deal with concurrent extreme events should furthermore consider the effects of possible response and adaptation mechanisms to increase system resilience.

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1. Introduction

Weather and climate extremes affect societies and the environment through direct impacts but also through impacts that cascade through natural and human systems [1–3]. Over the past couple of decades, the frequency and magnitude of concurrent climate extremes such as heat and drought events have increased and caused great damages [4–6]. Vulnerability to and potential consequences of heat and drought impacts are continuously increasing. In the United States, heat was the number one weather-related cause of death between 1990–2019 [7]. In Australia, heat waves have a greater negative impact on population health than any other natural hazard [8]. And for countries of Southern Europe heat-related mortality makes up >5% of warm-season deaths [9]. Drought-fire is the concurrent event with the highest occurrence in Europe, showing hotspots in parts of Ireland, the UK, Germany, France, Italy, and all of south-eastern Europe [10]. Significant increases in the severity of concurrent heat and drought extremes have been observed between 1951 and 2016 in North and South America, Europe, Africa, Asia and Australia [11]. Furthermore, there is evidence that concurrent heat and drought events will become more frequent in the future [12, 13]. The importance and severity of concurrent heat and drought extremes and their impacts has once more become evident in the recent events of summer 2021 in British Columbia in Canada and in southern Europe. Extreme heat in June 2021 led to hundreds of deaths and devastating fires caused destruction in B.C. Canada [14, 15]. Meanwhile in July 2021, the Mediterranean region was experiencing its worst heatwave in decades and fires spread from Turkey to Spain. The destruction of extensive forest areas in Greece caused important ecosystem losses and is expected to lead to even higher temperatures, desertification, greater exposure to natural hazards and loss of agricultural production affecting lives and livelihoods [16].

What is more compelling about correlated extremes is their knock-on effect on several interconnected systems and sectors. During the Northern Hemisphere prolonged hot and dry summer 2018, extreme low flow events meant that river navigation on major European river arteries had to be reduced with obvious consequences for the transport of critical goods. At the same time rail transport was also affected since trains tracks buckled and road melted because of prolonged heat [17, 18]. Ecosystems were also considerably affected which had consequences for agriculture productivity and urban ecology [17]. In general, more intense heat extremes affect labour productivity which in turn leads to a decrease in agricultural outputs already affected by prolonged dry periods. In the long run, this might contribute to spikes in food prices and result in food insecurity [19]. Along the same lines, Byers et al. 2018 developed a set of indicators covering land, water and energy sectors across different combination of climate and socio-economic scenarios and concluded that multi-risks for human population will be large and almost double as warming increase from 1.5°C to 2°C compared to pre-industrial levels [20]. These are some examples of the increasing complexity of our world and underpin the needs to understand impacts and risks well beyond sectorial approaches.

This need has been identified by both science and policy (e.g. [21–24]). There is a vast body of literature addressing the terms used to describe correlated extreme events, their interactions, their impacts and the propagation of these impacts through natural and socio-economic systems (cf. [3, 25–34]). Different methodologies, analysis and modelling tools have been proposed for dealing with concurrent events and for supporting decision making (e.g. [18, 28, 30, 35–37]).

The importance of integrated, up-to-date, scale-appropriate scientific knowledge (about process understanding, vulnerability of key social systems, process chains, etc.) for tailored management of extreme situations (e.g., [38]) has been clearly confirmed in the recent example of bush fires in Australia (e.g. [3, 39]). However, no study systematically analyzed the impacts

of past concurrent heat and drought events and their interconnectedness and cascading effects at the societal level in order to better inform future risk management and adaptation. In order to contribute to the understanding of concurrent extremes and associated risks, we here focus on concurrent heat and drought extreme events and analyze historical cases to shed light on the complexity of their cascading impacts and interconnectedness. We examine impact paths through different sectors, systems and assets to understand the most important interlinkages. Specifically, we elaborate, (1) what the particularly vulnerable systems and assets are, (2) how they have been affected and (3) what role adaptation can play, further interacting with impacts on systems and assets.

Terminology and methods

In this study, we focus on events that temporally and spatially coincide and refer to them as ‘concurrent’ events. We use the term ‘cascading’ for interconnected processes and impacts that are triggered by these events and potentially amplified by non-climatic factors, such as natural (e.g. ecological or geomorphological responses) or human (e.g. policy decisions) ones.

In order to understand the risks of concurrent heat and drought extremes we analyze past events characterized by high air temperatures anomalies and dry weather condition anomalies that led to widespread and severe impacts. We selected eight heat and drought extreme events from the past two decades. We chose the events based on their prominence in the literature and their complexity regarding the propagation of impacts through critical systems, but not based on specific climatological thresholds. The events analyzed in this study include the European summer heatwaves of 2003, 2015 and 2018, the Australian summer heatwaves of 2009, 2012/2013 and 2019/2020 paralleled by a multiyear drought period, the heat and drought event that took place in European Russia in 2010 as well as the multiyear drought in Cape Town from 2015 to 2018. We systematically analyzed those events regarding their meteorological extent (section 2), their direct, cascading and interacting impacts (section 3) and the response and adaptation actions they provoked (section 4). A schematic of this approach is shown in Fig 1.

To create the basis for a comparison of the impacts of different concurrent events, we defined categories of potentially affected critical systems, sectors and assets that play a key role for human society and well-being. Similar to the 5th Assessment Report of the IPCC and [40], we use the sectors ‘human health’, ‘water resources’, ‘agriculture and food production’, ‘energy’, ‘transport and mobility’, ‘infrastructure and buildings’, ‘economy and financial system’, ‘ecosystems’, and ‘culture and society’, ‘state and public service’ and ‘internet and communication’ for the identification of weather and climate related risks and impacts. These sectors can be impacted by climatic extremes (either concurrent or single) or by effects from other sectors, and they can impact other sectors (meaning that they are the cause for an effect). Heat waves and drought create the conditions for fire weather [10], but here wildfires are not counted as an impact category for itself, but they are rather seen as a possible secondary effect of heat and drought events.

A literature review was undertaken focusing primarily on scientific and secondarily on grey literature. Scopus and Web of Science were searched for key word combinations of ‘heat wave’, ‘drought’, ‘impact’, ‘compound’ and ‘concurrent’. The search was limited adding specific years (e.g. ‘2015’) or locations (e.g. ‘Europe’) to find publications on specific events and adding key words for different sectors like ‘transport’, ‘infrastructure’, ‘health’ etc. A detailed overview of the initial search and results can be found in the appendix (S1 Table). Starting from key papers for the different events found like this, we expanded the review list following references cited in those publications. Due to the large amount of potential key words to be

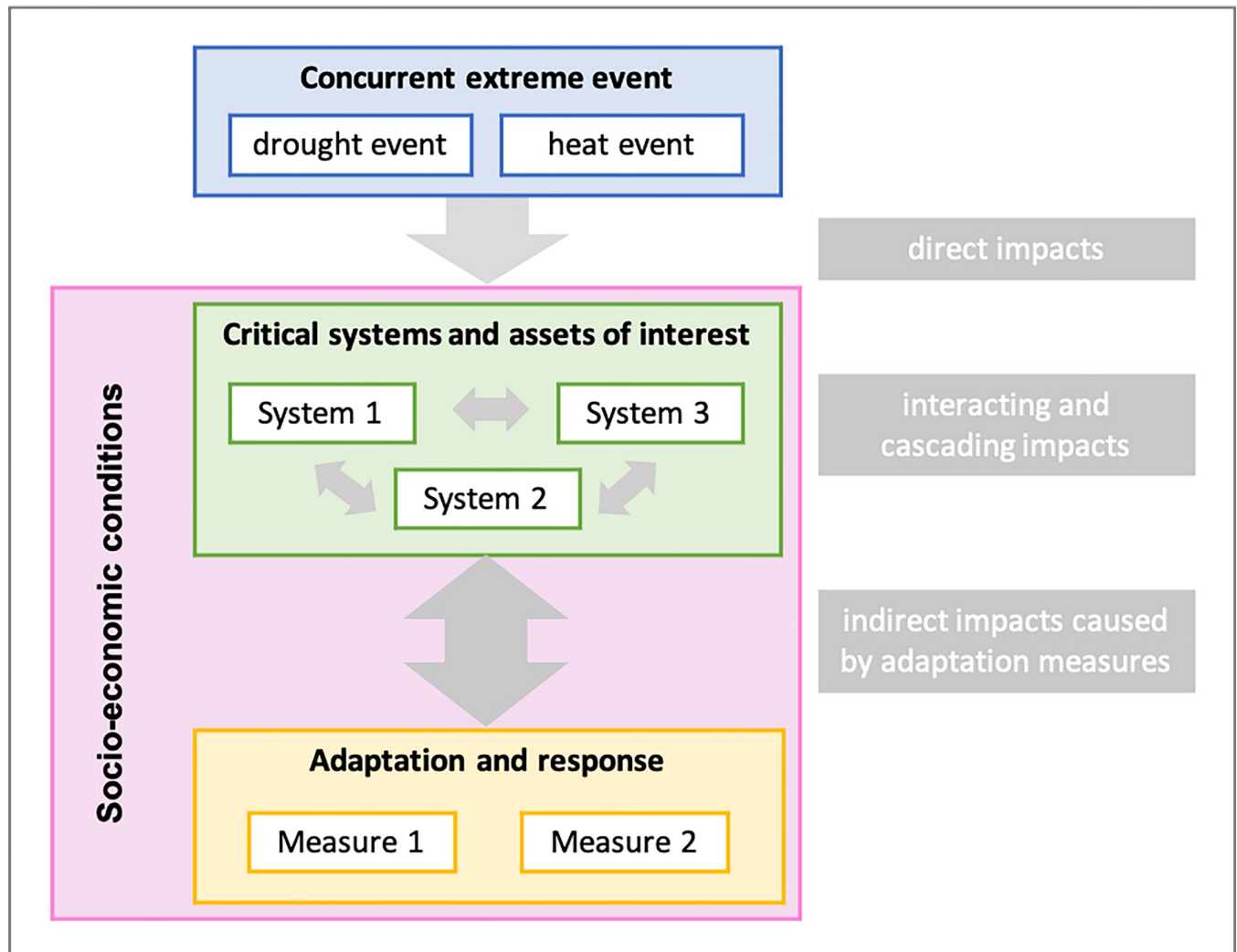


Fig 1. Schematic of the interconnectedness of the impacts, the critical systems and the adaptation and response measures in case of a heat and drought extreme event.

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used for the literature search and the extensive body of literature available in each respective field, a completely objective and exhaustive literature analysis was not feasible. Instead, we chose a limited set of key words to start the literature review and then specifically continued the search based on the information given in these key publications. We recognize that this approach adds a certain amount of subjectivity to the selection of relevant literature.

For assessing the level of impact between concurrent hazards and different sectors we analyzed the literature for 1) the number of mentions of the respective impact, and 2) indications of metrics that relate to the magnitude and/or frequency of the respective impact. Based on this analysis we visualized the impacts and interconnections between sectors and events (e.g. Fig 3). The information in all figures and tables are illustrative rather than exhaustive, as completeness would go beyond the possibilities of this study. Rather, we aim here for a compilation of examples that serve the purpose of visualizing impact interconnections.

It is important to mention that, if a sector is only rarely mentioned here, this does not necessarily mean that the sector is in reality not affected; rather it represents its (missing) presence

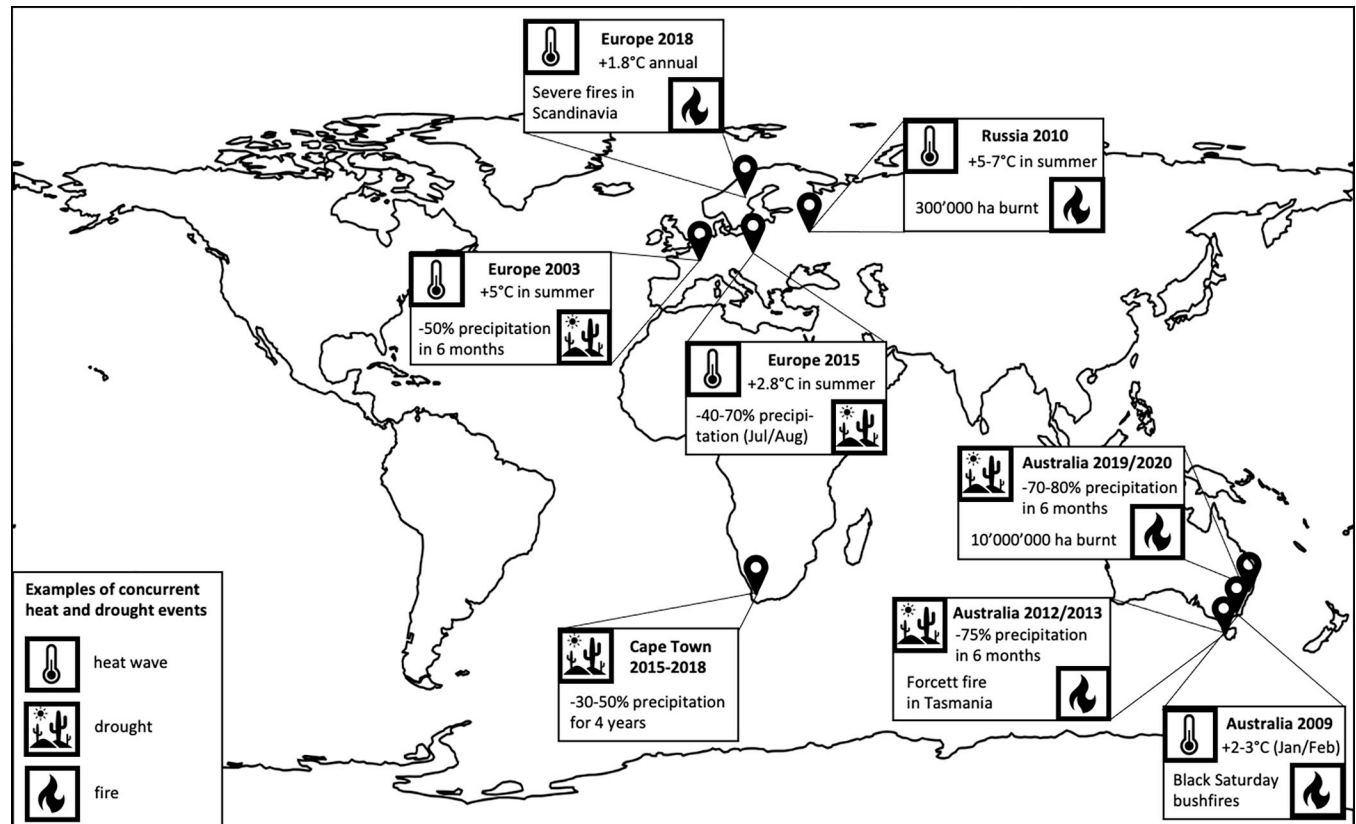


Fig 2. Illustrative selection of climatic information for different concurrent heat and drought events of the first two decades of the 21st century. The numbers on this figure are based on information provided in Table 1. This map was made with a base layer downloaded from Natural Earth (<https://www.naturalearthdata.com/downloads/110m-physical-vectors/>).

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in the academic literature we analyzed. Nevertheless, as this study concentrates on the main sectors and systems affected by heat and drought extremes, sectors that were not mentioned in the considered literature, were assumed to be negligible for the analysis. This, however, may not necessarily hold true for future heat and drought events.

2. Historical concurrent heat and drought extreme events

In Table 1, the heat and drought extreme events analyzed in this study are presented, including their climatic anomalies and an illustrative selection of climatic information. Fig 2 displays an overview of key numbers for each event and positions them in a geographical context.

In the following, key aspects of each event are outlined.

Europe 2003

In 2003, large sectors of Europe suffered from a persistent late winter and spring drought that was followed by the at the time clearly warmest summer in Europe since at least 1864 [77]. Very dry conditions prevailed during the entire summer of 2003, with drying of the soil exceeding the long-term average by far [41]. The largest positive anomalies in monthly mean temperatures were experienced in June and August [42]. Persistent heat stretched over a region from south-west Germany across Switzerland to the eastern and southern parts of

Table 1. Illustrative selection of climatic information for the different concurrent heat and drought extreme events.

Event	Temperature anomaly	Precipitation anomaly	Wildfire area	Sources
Europe 2003	Annual mean temperature: • Europe: +0.66°C Summer mean temperature: • Europe: +1.9°C • DE, CH, FR: +5°C	Annual precipitation: • Europe: -50% 6 months precipitation: • CH: -30-50% Monthly precipitation: • Europe: -50% (Feb/Mar)	GR, IT, FR, ES, PT: 739'000 ha	[41–44]
Australia 2009	Annual mean temperature: • Australia: +0.9°C Monthly mean temperature: • Victoria, NSW: +2–3°C (Jan/Feb)	Annual precipitation: • South Au, NSW: -10% • Victoria: -20% Monthly precipitation: • S AU, Victoria: -80% (Jan) • NSW: -67% (Jan)	Black Saturday bushfires: 450'000 ha	[45–48]
European Russia 2010	Annual mean temperature: Global: +0.96°C ¹ Summer mean temperature: • Eur. Russia: +5–7°C Monthly mean temperature: Eur. Russia: >+7°C (Aug) ³ • Moscow: +5.1–6°C (Aug)	Monthly precipitation: • Eur. Russia: -60% (Apr)	European Russia: 300'000 ha Thousands of fires (Jul/ Aug)	[49–54]
Australia 2012/2013	Annual mean temperature: • Australia: +1.2°C (2013) Summer mean temperature: • Australia: +1.6°C Monthly mean temperature: • Australia: +1.76 (Jan)	Annual precipitation: • Australia: -8% (2013) • S AU: -23% (2012) 6 months precipitation: • CE/S AU: up to -75% (2012)	NSW 2013: 768'000 Tasmanian Forcett fire: 25'000 ha	[55–58]
Europe 2015 (eastern and central Europe)	Annual mean temperature: • Global: +0.9 ¹ • FI: +1.9°C ⁴ • DE: +1.7°C ⁴ Summer mean temperature: • E/CE Europe: +2.8°C	Annual precipitation: • FR: -10% Monthly precipitation: E/CE Europe: -40% (Jul) ² • AT: -65% (Aug) CH: -50-70% (Jul) ⁴	AT, DE, FR, HR, PL, RO & RU: above average fire area	[59–63]
Cape Town 2015–2018	Annual mean temperature: • Global: 2015–2018 were the four warmest years on record with +0.2°C ⁶ • South Africa: +0.5°C (2018) ⁴	Annual precipitation: Cape Town: -30-50% (2015–2017) ⁵		[62, 64–66]
Europe 2018 (central and northern Europe)	Annual mean temperature: • Global: +0.8°C ¹ • Europe: +1.78°C ¹ 6M mean temperature: • N/CE Europe: +1°C ⁴ • CH, DE, AT: +3.3°C Summer mean temperature: • N/CE Europe: +1.3°C ⁴	6 months precipitation: N/CE Europe: -20% ⁴ CH: -30-40% ⁴	SE, NO, LV, FI, DE: >35'000 ha GR, HR, IT: > 225'000 ha	[17, 67–71]
Australia 2019/2020	Annual mean temperature: • Australia: +1.52°C (2019) • Australia: +1.15°C (2020) Summer mean temperature: • Australia: +1.88°C • NSW: +2.33°C Monthly mean temperature: • Australia: +3.21°C (Dec) • South AU: +4.1°C (Dec)	Annual precipitation: • Australia: -40% (2019) 6 months precipitation: • North NSW & South QLD: -70-80% (2019)	Australia: 10'000'000 ha	[39, 72–76]

Note: The numbers in this table are illustrative numbers to characterize the events. They are not exhaustive and more climatic data may be found in additional databases and literature sources. Reference periods: 1961–1990 if not stated any differently

¹ 20th century

² 1971–2000

³ 1980–2009

⁴ 1981–2010

⁵ 1998–2014

⁶ 2011–2015.

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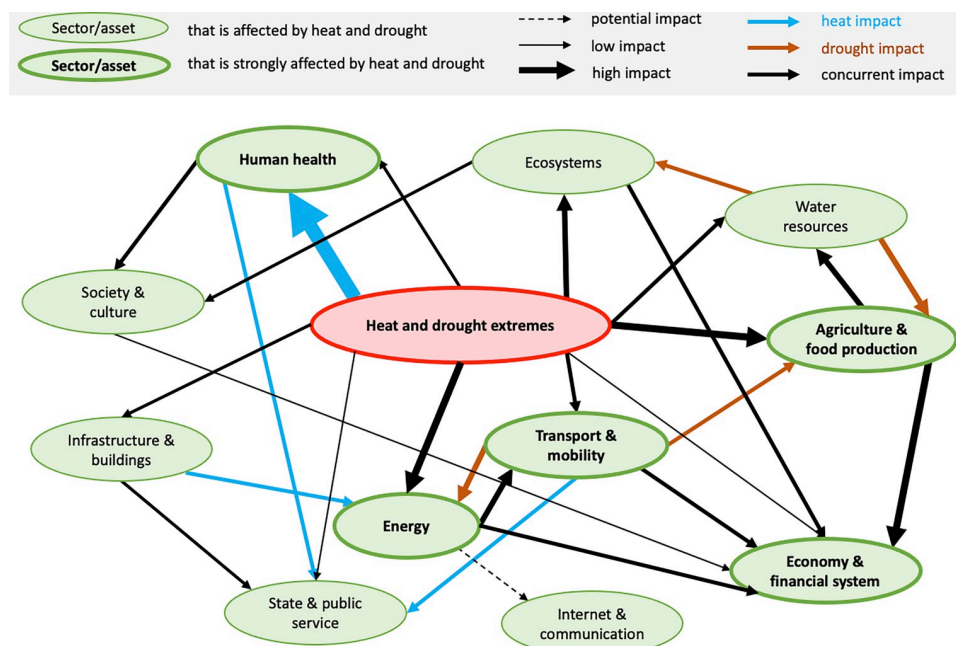


Fig 3. Scheme of cascading impacts and interconnectedness of systems, sectors and assets affected by heat and drought extreme events. The arrows point from the event or sector that affects another sector or asset to the sector or asset that is affected. The colors of the arrows identify the main driver of the impact and the width of the arrows is representative for the importance of the impact. It reflects the number of associated interconnections or mentions found in the literature.

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France and an exceptional heatwave lasting from 1 to 13 of August beat temperature records in much of Europe [42]. The extreme heat and drought conditions led to summer fires in Greece, Italy, France, Spain and Portugal [41].

Australia 2009

South-eastern Australia was hit by an exceptional heatwave during late January and early February 2009. Records were set for maximum day and nighttime temperatures as well as for the duration of extreme heat in Tasmania, the state of Victoria, part of New South Wales and southern South Australia [78]. The hottest periods of the heatwaves were between the 27 and the 30 January 2009, and the 6 and 8 of February 2009 [45]. Very low humidity and high winds in Victoria were observed during the Black Saturday bushfires on 7 of February 2009 that devastated vast areas of Melbourne's peri-urban region [45, 78].

Russia 2010

In 2010, European Russia experienced a strong summer heat wave that lasted from June until mid-August [50] with two peaks—one of 6 days in late June and one of 44 days between 6 July and 18 August [79]. At the same time 25% of the territory of European Russia experienced a large-scale drought and below normal soil moisture in the area further amplified the heat wave [49]. The parched soil and extremely dry conditions contributed to more than 550 wildfires in the affected areas [80] and the prolonged heat wave in Moscow triggered numerous wildfires in forests and peat bogs near the city [79].

Australia 2012/2013

Summer 2012/2013 was the hottest summer in Australia since records began in 1910. Most of Australia experienced extreme heat between late December 2012 and the first weeks of January 2013 with the most extreme and persistent high temperatures in the central and southern interior of the continent. The event affected a much larger area and lasted for longer than previous extreme events like the 2009 event [56]. Much of Australia had been drier than normal since mid-2012 [56]. The heat and drought event caused major bushfires in Tasmania, New South Wales and Victoria with up to 40 fires in Tasmania on January 4th [55].

Europe 2015

Eastern and central Europe was hit by four heat wave episodes in 2015, with the summer 2015 being the second hottest and climatologically driest summer between 1950 and 2015 over an area stretching from the eastern Czech Republic to Ukraine [60]. Temperature records were hit in major cities across Europe (e.g. London, Paris, Berlin) [81]. High evapotranspiration rates and lack of precipitation caused one of the worst and long duration drought recorded in Europe [60] with very dry conditions in Slovakia, Czech Republic and Poland [82] and extremely low water levels in central Europe and France [82].

Cape Town 2015–2018

In 2015, South Africa had its driest year since 112 years, with Cape Town starting to suffer from the awaiting multi-year drought between 2015 and 2018 [83]. Precipitation was extremely limited over three consecutive years [84] and during its worst drought in living memory, the city's water reservoir lake level was at its lowest in 19 years as of December 2017 [85], eventually threatening the city's drinking water provision and pointing to a day zero, when enforced rationing would be put in place [86].

Europe 2018

In 2018, Europe was struck by a heatwave that was especially severe in the countries of the North, such as Finland, Sweden, Denmark, Norway, the Netherlands and Belgium [87]. This heatwave was exacerbated by a severe drought caused by a persisting circulation anomaly [88]. Negative drought impacts appeared to affect an area 1.5 times larger and to be significantly stronger in July 2018 compared to August 2003 [89]. Devastating fires destroyed vast amounts of forests in Scandinavia [17], and in Sweden the fires were considered to be the most serious in the country's modern history [69]. Strong fires were also experienced close to Athens at the Attica coast on 23 July [90, 91].

Australia 2019/2020

Up to 2020, every year since 2013 had been amongst the ten hottest years on record for Australia [72]. 2019 was the warmest and driest year on record for Australia as a whole and December 2019 had the highest area-averaged maximum, minimum and mean temperatures on record for Australia [73]. Below average rainfall had been observed across Australia over the year 2019 building upon longer-term rainfall deficiencies in eastern Australia since the beginning of 2017, as 2018–2019 had been southeast Australia's driest two-year period on record [72]. Extreme fire danger ratings were experienced at locations and times of the year never before recorded. For the first time ever catastrophic fire conditions were forecast for Greater Sydney [72]. The bushfire season was the worst on record for Australia since the European settlement, with bushfires unprecedented in scale and harm [72, 92].

Table 2. Main systems and sectors affected (x) for the analyzed historical heat and drought extreme events.

System	Human health	Water resources	Agriculture and food production	Energy	Transport and mobility	Internet and communication	Infrastructure and buildings	State and public service	Economy and financial system	Ecosystems	Culture and society
Event											
Europe 2003	x	x	x	x			x	x	x	x	x
Switzerland 2003	x			x							x
Australia 2009	x	x		x	x		x	x	x		
Russia 2010	x		x						x		
Australia 2012–13	x						x			x	
Europe 2015	x	x	x	x	x			x	x	x	x
Switzerland 2015	x	x	x	x	x					x	x
Cape Town 2016–18		x	x								
Europe 2018	x		x	x	x		x		x	x	
Switzerland 2018	x	x	x	x	x				x	x	
Australia 2019–20	x		x	x	x		x	x	x	x	x
Mentions	91%	55%	73%	73%	55%	0%	45%	36%	64%	64%	45%

Note: “Mentions” gives the percentage of assessed extreme events for which a strategic system or sector has been affected. Switzerland is listed individually for the European events of 2003, 2015 and 2018, as it is not part of the European Union, but was in the center of several extreme events and it is documented by a rich amount of publications and reports.

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3. Impacts of heat and drought extreme events

In this section we analyze the most recurring impacts and effects on critical systems and inter-linked sectors to understand how these impacts propagate within the system and which sectors and subsystems are most vulnerable to compound heat and drought extremes.

3.1 Sectors and assets

Table 2 shows the sectors mainly affected (according to the literature) for each of the extreme events assessed. Table 3 contains illustrative examples of impacts reported in the different sectors, that served as a basis for the analysis in this chapter and for the elaboration of Fig 3. This table is not intended to be exhaustive, but it mainly offers key examples for the purpose of understanding the connections and interdependencies between sectors.

Human health. Excess mortality increased during all of the mentioned extreme heat and drought events, except for the case of Cape Town, for which no excess deaths were reported specifically in relation to the extreme drought years. For Europe most of the excess mortality was caused by extreme heat. In 2003 Europe counted more than 80’000 excess deaths [93]. Garcia-Herrera *et al.* (2010) argue that increased mortality in Europe in summer 2003 was caused by a combination of extreme temperatures and poor air quality. During the heat wave in Moscow in 2010 more than one fifth of the 10’000 excess deaths can be attributed to interactions between high temperature and air pollution from wildfires [79]. In 2009, around 500 excess deaths were recorded in southeastern Australia [94]. However, we did not find complete and publicly available excess mortality data for most years in Australia and [95] suggest

Table 3. Illustrative examples of impacts caused by concurrent heat and drought extremes in different sectors.

Human health	Sources
<p>Commonly reported impacts: Deterioration of air quality due to smoke Increased risks of suicide during hot weather</p> <p>Examples of health threats:</p> <ul style="list-style-type: none"> • Europe 2003: Increased stress for pollen allergic population in CH • Australia 2009: 690 people treated for heat related illness in Adelaide • Europe 2018: Increased stress for pollen allergic population in CH Increased appearance of ticks and tiger mosquitos in CH Increased appearance of bloodsucking horseflies in UK • General: Deterioration of air quality due to smoke Increased risks of suicide during hot weather <p>Examples of heat related excess mortality:</p> <ul style="list-style-type: none"> • Europe 2003: Summer: +7% in Europe, between +14.3% (LU) and +2.2% (NL) in LU, ES, FR, IT, PT, CH, HR, SI, BE, DE, NL (ref. 1998–2002) August: +17% in Europe, between 36.9% (FR) and 4.9% (EAW) in FR, PT, LU, ES, IT, DE, SI, CH, HR, BE, NL, EAW (ref. 1998–2002) • Australia 2009: January: +32.4% in Adelaide (ref. 1993–2004) • Europe 2015: Summer: +5.4% in CH (ref. 2005–2015), +5.8% in DE (ref. 1971–2000), +14% in SK (ref. 1996–2015) • Europe 2018: August: +3.4% in CH (ref. 2009–2017) <p>Examples of heat related excess deaths:</p> <ul style="list-style-type: none"> • Europe 2003: Summer: >80'000 during all summer in 12 countries August: 45'000 of which >15'000 in FR, ~9700 in IT, ~7300 in DE, >6400 in ES • Australia 2009: 424–500 in South-eastern Australia 173 due to wildfires • Russia 2010: >10'000 in Moscow, >55'000 in Russia • Europe 2015: 804 in CH, 539 in SK • Europe 2018: 91 heat strokes in GR, 9 heat strokes in ES 102 in GR due to wildfires • Australia 2019/2020: 34 due to wildfires 417 due to smoke exposure 	<p>[8, 17, 39, 43, 52, 67, 79, 93, 94, 111–117]</p>
Water resources	Sources
<p>Commonly reported impacts: Increased water consumption Low water levels in precipitation driven streams and partly higher water levels in glacier melt driven streams High water temperatures, low oxygen levels and water quality, pressure on water treatment facilities Low water availability with consequences for ecosystems, agriculture, energy production, waterway transport, leisure activities etc.</p> <p>Examples of low water levels in streams and lakes:</p> <ul style="list-style-type: none"> • Europe 2003: Danube, Rhine • Europe 2015: Danube, Rhine, Elbe, Oder, Weser, Vistula, Odra and Don rivers • Cape Town 2015–2018: Water level in the city's reservoir dropped to less than 20% • Europe 2018: Thur, Limmat, Reuss and Rhine rivers, lake Constance and lake Walen <p>Examples of water provision issues:</p> <ul style="list-style-type: none"> • Europe 2003: Threats to water supply systems • Australia 2009: Water treatment plants affected by evaporation, algal blooms and the breakdown of pumps and other equipment • Cape Town 2015–2018: Extreme limitation of water use (down to daily 50l p.p.) • Europe 2015: Water scarcity in agriculture and alpine farming context Water transfers in DE Restriction of water abstraction for non-priority uses in FR, NL, CZ, SK, DE • Europe 2018: Drinking water scarcity in karst areas in CH Restriction of water extraction for agriculture in CH Increasing demand for water redistribution, transfers and transport <p>Examples of water quality issues:</p> <ul style="list-style-type: none"> • Europe 2003: Bathing water impairment in DE and CH Drinking water quality problems in PT, ES and BG • Europe 2015: Insufficient waste water dilution in streams of several cantons in CH Blue-green algae bloom and botulism Deterioration of water quality in RO, NL • Europe 2018: Extremely high water temperatures 	<p>[41, 42, 59, 60, 67, 82, 86, 98, 99, 118, 119]</p>
Agriculture and food production	Sources

(Continued)

Table 3. (Continued)

Human health	Sources
<p>Commonly reported impacts: Agriculture and livestock production losses</p> <p>Price increase for agricultural and livestock products</p> <p>Examples of decrease in agriculture crop yield:</p> <ul style="list-style-type: none"> Europe 2003: Large crop losses in large parts of Europe e.g. harvest decrease in arable crops (-20%) in CH (ref. 1991–1999) Reduction in primary productivity (-20%) (ref. 1960–1990) Australia 2009: Harvest decrease for wine grapes (-7%) (ref. 2008) Production decrease for irrigated rice (-99%) and cotton (-80%) in southeast Australia (Murray-Darling Basin) (ref. 2000) Russia 2010: Harvest decrease for grains (-30%) (ref. projected harvest) Destruction of 17% of sown area in Russia Europe 2015: Harvest decrease for sugar beet and potatoes (-50%) in CZ, DE and PL for hay (-50%) in CZ (ref. NA), and for pasture (-12%) and grain maize (-18%) in CH (ref. 2000–2014) Cape Town 2015–2018: Severe crop losses Europe 2018: Crop losses in DE, CH and UK Harvest decrease for wheat and spelt (-9.5%), maize (-6–10%), sugar beet (-16.5%) and potatoes (-16.4%) (ref. 2017) <p>Examples of decrease in production in the livestock sector:</p> <ul style="list-style-type: none"> Europe 2003: Increased mortality in livestock and poultry sector ~4 M broilers died in FR, reduction of poultry flock in ES (-20%) (ref. 2002) Europe 2015: Decrease in milk production in CH, SK and RO <p>Examples of shortages, market impacts and interruption of food supplies:</p> <ul style="list-style-type: none"> Europe 2003: Shortage in green fodder supply in DE, AT and ES (-30%), IT (-40%) and FR (-60%) (ref. 2002) Russia 2010: Rise in grain prices and in dairy product prices Europe 2018: >50% fodder import in CH (\$ 35 million) (ref. 2010–2017) Rise in wheat prices (+10%, ref. 2017) Australia 2019/2020: Strong negative impact on agriculture 	<p>[17, 41, 42, 44, 52, 59, 67, 80, 82, 89, 100–103, 120, 121]</p>
Energy	Sources
<p>Commonly reported impacts: Vulnerability of electricity transmission and distribution components</p> <p>Loss of efficiency, difficulty of machine cooling, expansion of power lines leading to power flow reduction</p> <p>Output reduction due to lacking water (for power generation or cooling purposes)</p> <p>Increasing power demand for cooling purposes</p> <p>Examples of Increase in electricity demand and price:</p> <ul style="list-style-type: none"> Europe 2003: Increased power demand in FR Rise in energy prices Australia 2009: Increased power demand due to AC <p>Examples of change in electricity production:</p> <ul style="list-style-type: none"> Europe 2003: Power reduction from hydropower and thermoelectric power plants Power reduction from nuclear power plant in DE Australia 2009: Power reduction due to outages (transformer explosion) and heat-related shutdowns of powerlines Europe 2015: Reduced power production in DE, CZ, PL and RU Reduced production from nuclear power plants in CH Reduced production from hydropower plants in FR and CZ and river power stations in CH Europe 2018: Shutdown of 4 nuclear plants in FR Power reduction from nuclear power stations in CH Power reduction from 3 coal-fired power plants in DE Power reduction from natural gas plants in UK Power reduction from and shutdown of hydropower stations in CH <p>Examples of outages and restricted power supply:</p> <ul style="list-style-type: none"> Europe 2003: Regional power outages and restrictions in Italy Power export restrictions in France due to domestic demand Australia 2009: Power outages in Melbourne with 0.1 million residents without power Europe 2015: Power shortages in PL Australia 2019/2020: Interruptions of power and fuel supply 	<p>[1, 17, 42, 45, 52, 59, 67, 82, 88, 99, 105]</p>
Transport and mobility	Sources

(Continued)

Table 3. (Continued)

Human health	Sources
<p>Commonly reported impacts: Delay and failure of railway service due to track buckling and power loss Road transport interruptions due to heat related melting, or wildfires Restriction of waterway transport due to low water levels</p> <p>Examples of railway transport interruptions:</p> <ul style="list-style-type: none"> • Australia 2009: Reduced rail service in Melbourne (-24%) and Adelaide (-7%) for four days due to rail track buckling and power loss Failure of traffic signals and AC • Europe 2015: Rail track buckling in UK and CH • Europe 2018: Rail track buckling in UK, CH and NL <p>Examples of road transport interruptions:</p> <ul style="list-style-type: none"> • Australia 2009: Road traffic affected by melting roads • Europe 2018: Road traffic affected by melting roads in NL and UK • Australia 2019/2020: Far reaching transport interruptions, isolation of some communities <p>Examples of waterway transport interruptions:</p> <ul style="list-style-type: none"> • Europe 2015: Freight load reduction on the Rhine, Danube, Elbe, Oder, Weser and Don Cost increase for lock operations for boats in NL • Europe 2018: Massive transport reduction and partial suspension on the Rhine between CH and DE 	[17, 52, 67, 72, 82, 94, 107, 122]
Infrastructure and buildings	Sources
<p>Commonly reported impacts: Building materials affected by extreme heat and drought Damage and destruction of buildings and infrastructure caused by fires</p> <p>Examples of building and infrastructure damage:</p> <ul style="list-style-type: none"> • Australia 2012/2013: 200 properties and 21 businesses destroyed by fires • Europe 2018: Melting of the roof of a building in UK Stability issues in dike system in NL ~3000 buildings destroyed in GR by fires Damage in electricity distribution networks in GR due to fires • Australia 2019/2020: ~5900 buildings destroyed by fires 	[17, 52, 88, 90, 91, 108]
State and public service	Sources
<p>Commonly reported impacts: Increased demand for public services Limitations and restrictions of public services</p> <p>Examples of demand for public services:</p> <ul style="list-style-type: none"> • Europe 2003: Increased demand for health care Increased demand for emergency services (e.g. ambulances) • Australia 2009: Increased demand for emergency ambulance service in Victoria • Europe 2015: Increased demand for fire fighter interventions in CZ Increased demand for ambulance interventions in PL <p>Examples of limitations and restriction of public services:</p> <ul style="list-style-type: none"> • Australia 2009: Failure of water treatment plants due to breakdown of pumps and other equipment • Australia 2019/2020: Closure of schools in Sydney Cancellation of play and sports activities in schools Closure of the airport in Canberra Public servants were instructed to stay home Difficulty of evacuation and rescue due to fast spreading of fires 	[8, 41, 52, 72, 82, 94, 98, 99]
Economy and financial system	Sources
<p>Commonly reported impacts: Increased costs and economic losses in agriculture, energy production, transport services, tourism, due to property destruction, health implications, decrease in labour productivity etc.</p> <p>Examples of increased costs and economic loss*:</p> <ul style="list-style-type: none"> • Europe 2003: € 17.4 B (0.17% GDP) agriculture and forestry losses in FR, IT, DE (€ 2.1 B; 0.072% GDP), ES, PT (€ 1.3 B; 0.68% GDP), AT, HU, EE, SK and CH (€ 305–440 M, i.e. CHF 370–530 M; 0.072–0.1% GDP) • Australia 2009: US\$ 669 M (A\$ 1.023 B; 0.08% GDP) losses due to power outages, transport disruptions and response costs • Russia 2010: US\$ 1.7 B (R 81.7 B; 0.176% GDP) agriculture losses • Australia 2013: US\$ 6.2 B (0.33–0.47% GDP) economic loss due to work absenteeism and reductions in work performance • Europe 2015: € 22.6 M (€ 17.86 M; 0.0009% GDP) due to public transport delays in EN € 0.54–1.078 B (0.012–0.023% GDP) agriculture losses in CZ 50% transport losses due to waterway freight load reduction 1600 of the biggest companies in PL suffered from power restrictions • Cape Town 2015–2018: Commercialization and valuation of water • Europe 2018: 305 burnt vehicles due to fires in GR 3% net agriculture income decrease in CH (ref. 2017) • Australia 2019/2020: US\$ 80.6 B (A\$ 113 B; 5.71% GDP) total cost due to fires US\$ 1.36 B (A\$ 1.95 B; 0.098% GDP) insurance claims after fire destruction US\$ 8.4–36.6 M (A\$ 12.3–51.4 M; 0.62–2.6% GDP) daily losses due to transport interruptions and smoke around Sydney 3.141 B US\$ (A\$ 4.629 B; 0.23% GDP) tourism losses <p>* All costs and economic losses are transformed to currencies of the year 2021. The percentages of the GDP are given for the year of the respective extreme event.</p>	[39, 41–43, 67, 72, 80, 82, 86, 90, 94, 100, 107, 109, 123, 124]

(Continued)

Table 3. (Continued)

Human health	Sources
Ecosystems	Sources
<p>Commonly reported impacts: Heat and drought stress and increased mortality of vegetation and animal species</p> <ul style="list-style-type: none"> Proliferation of pests and diseases Fire damage to ecosystems <p>Examples of heat and drought stress to vegetation and animal species:</p> <ul style="list-style-type: none"> • Europe 2003: Shortening of pollen season <ul style="list-style-type: none"> Negative impact on vegetation health • Europe 2015: Dehydration of birds and decreased survival chances of young birds in CH <ul style="list-style-type: none"> Loss of spawning habitat in water bodies in CH 25% loss of water ecosystem plants in CZ Early colouring of forests in CH Reduction of spruce growth below 1500 m a.s.l. in CH Reduction in flower and insect abundance in CH • Europe 2018: Death of aquatic animal and plant species in CH (3t of dead fish in the Rhine) <ul style="list-style-type: none"> Garden birds threatened in UK Early defoliation and drying out of trees in CH <p>Examples of proliferation of pests and diseases:</p> <ul style="list-style-type: none"> • Europe 2003: Increased bark beetle and woodborer infestations in DE, AT, CH, FR and CZ • Europe 2015: Increased bark beetle infestations (and similar species) in CH • Europe 2018: Increased bark beetle infestations and forced wood harvests in CH and DE <ul style="list-style-type: none"> Proliferation of algae in CH <p>Examples of wildfire damage to ecosystems:</p> <ul style="list-style-type: none"> • Europe 2003: 5% of national territory burnt in PT <ul style="list-style-type: none"> Loss of forest cover and wildlife in FR • Australia 2012/2013: 25'000 ha burnt in Tasmania and 768'000 ha in NSW • Europe 2018: 5-fold increase of erosion rates after fires in GR <ul style="list-style-type: none"> Threat to plants, birds and mammals from toxic ashes in GR • Australia 2019/2020: 21% of Australian temperate broadleaf and mixed forests burnt, <ul style="list-style-type: none"> 81% of the Blue Mountains World Heritage Area burnt, 54% of the Gondwana Rainforests burnt 1.5 billion animals killed 	<p>[17, 41, 52, 55–57, 59, 67, 68, 72, 82, 89, 108, 114, 125–127]</p>
Society and culture	Sources
<p>Commonly reported impacts: Restrictions of tourism and leisure activities</p> <ul style="list-style-type: none"> Increased risk of violence and suicide Increase in aggressive crimes (e.g. rioting and civil unrest, street violence, attacks and homicide), road rage, and domestic violence. <p>Examples of restrictions of leisure activities:</p> <ul style="list-style-type: none"> • Europe 2003: Increased level of ice and rock falls leading to closure of climbing routes • Europe 2015: Restriction of recreational activities in water bodies <ul style="list-style-type: none"> Restriction of access to forests due to fire risk • Australia 2019/2020: Australian Open matches delayed or abandoned <ul style="list-style-type: none"> Closure of shopping areas State of Emergency declarations for NSW and the Capital Territory 	<p>[8, 42, 52, 82, 122]</p>

Note: Two-letter country codes are used according to ISO 3166–1.

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substantial under-reporting of heat-related mortality for Australia. The fatalities associated with wildfires in Australia are substantially higher than in Europe with dozens of deaths in 2009 and 2019/2020 directly due to the fires and hundreds of deaths as well as thousands of hospitalizations due to hazardous air quality resulting from the wildfires [45, 52, 96].

Water resources. Water availability in Europe was temporally low in all three years 2003, 2015 and 2018, but drinking water supply shortfalls have so far been locally bounded [41, 59]. The millenium drought 2000–2009 in Australia led to a substantial decrease in water resources and caused a sense of water crises latest by 2009 [97]. Water provision issues exacerbated when water treatment plants were affected by evaporation, algae, power outages and the breakdown of pumps during the extreme heatwave of 2009 [98]. The extreme drought in Cape Town

between 2015 and 2018 caused severe water scarcity and anxiety due to the possibility of a city-wide water crisis [86].

Agriculture and food production. Agricultural losses were experienced in most of the analyzed events in the last two decades. Large losses in crop yield were observed in large parts of Europe in 2003 [42] as well as in 2015 [99] and in 2018 [88]. The concurrent heat and drought events affected grain crops and other arable crops like potatoes and sugar beet, as well as pasture harvests for animal fodder [17, 59, 89, 100, 101]. In 2003, the fodder deficit in Europe varied from 30% to 60% in Germany, Austria, Spain and France [41]. In 2010, the affected regions of Russia experienced crop losses of 1/3 of the cultivated area [80]. Australia registered large losses in their wine grape harvest [102], and the irrigated cotton and rice production dropped to 20% and to virtually 0% in the catchment of the country's largest river system in 2009 [103]. While drought often causes yield losses in agriculture, livestock are vulnerable to heat stress affecting their production levels as well as their health [104]. In 2003 a decrease in milk production, as well as an increase in the mortality in the livestock and poultry stocks were recorded in several European countries [41, 42, 59].

Energy. The energy system during heat and drought extreme events is influenced by an altered energy supply and demand. Increased air-conditioning beside others led to a substantial rise in electricity demand in Melbourne in 2009 as well as for example in France in 2003 [1, 45]. On the other hand power production was lower in concurrent heat and drought situations, due to low water levels in hydropower plants and a lack of cooling water in nuclear power plants [59, 67, 82, 105, 106]. The electricity sector is generally found vulnerable to heat, due to a loss of efficiency, difficulty of machine cooling, expansion of power lines and their sagging below minimum height beside others [45]. Shutdowns in Europe as well as in Australia led to restrictions, shortages and regional power outages [42, 45, 82, 90, 99].

Transport and mobility. The sector of transport and mobility was affected by both, heat and drought. Extreme heat led to the buckling of rail tracks in the public train transport system and it caused damage in road transport through bitumen sticking to tyres, both observed in Australia as well as in Europe [17, 45, 67, 107]. Drought on the other hand mainly affected waterway transport. In Europe this was strongly experienced in waterway cargo transportation that had to be reduced and up to suspended in several occasions in the past two decades [59, 67, 82, 88]. Lastly, wildfires led to road closure and transportation blockages [52]. Said transport and mobility interruptions caused far-reaching delays in Europe [107] and in occasions led to the isolation of communities that were then only accessible by water or air in Australia [52].

Internet and communication. For this sector no impacts were reported in our literature selection. (cf. Tab. 2; 0% mentions). Therefore, we did not assess it in an own category.

Infrastructure and buildings. Buildings and infrastructure were most often damaged by wildfires. In Australia, close to 200 properties and 21 businesses were destroyed in the summer 2012/2013 [108] and about 5900 buildings were destroyed and another 1021 homes and thousands of facilities and outbuildings damaged in the summer 2019/2020 [52, 72]. In Greece, the 2018 fires close to Athens led to the total or partial destruction of approximately 3000 buildings [91]. In the UK, the extreme heat in 2018 led to the melting of a roof of a building [17]. And in the same year the Netherlands experienced stability issues in their dike systems due to a lack of freshwater [88].

State and public service. In all of the analysed cases the need for statal intervention and public services increased. The demand for health care, emergency services, fire fighter interventions and evacuations due to excess heat and fire impacts was reported in Europe and Australia [8, 41, 52, 82, 94, 99]. At the same time public services were often restricted, and schools, airports and other public institutions and infrastructures closed [72].

Economy and financial system. In Australia in 2009 financial losses arose mainly as a consequence of wildfire destruction, power outages, transport service disruptions and response costs [94]. The wildfires of 2019/2020 in Australia caused an economic loss of around US\$ 80.6 billion (i.e., 5.71% GDP) until January 2020 [109]. In Portugal the wildfires of 2003 caused losses of more than € 1.3 billion (i.e., 0.68% GDP) [41]. And in the fires around Athens in 2018, 305 vehicles were burnt and lost [90]. Apart from these exceptional fires, in Europe, losses were mostly documented for the agricultural and forestry sectors and for mobility and transport disruptions as well as power restrictions [82]. In 2003 damage in agriculture and forestry exceeded € 17.4 billion (i.e., 0.17% GDP) in Europe [41, 42]. Crop and fodder imports in order to compensate for harvest losses, caused additional costs [67]. In 2010, Russia's agricultural sector suffered losses of US\$ 1.7 billion (i.e., 0.18% GDP) which pushed a steep increase in grain prices and widespread market speculation [80].

Ecosystems. Extreme heat and drought events caused losses and damage in the natural environment especially affecting forests and aquatic ecosystems, but also birds and insects [17, 59]. Hot temperature records in many water bodies in 2003, 2015 and 2018 threatened fish and water ecosystem plants in Europe [41, 59, 67, 82]. At the same time many European countries reported significant increases in woodborer infected wood [41, 59, 67] and high tree mortality [89]. The natural environment of Australia suffered most from wildfires. Although in many ecosystems of Australia and other dry regions, forest fires are part of the natural ecological cycle [110], climate change has likely increased the fire risk and contributed to the recent large Australian bushfires [52], which also affected ecosystems not adapted to natural fires, such as rainforests. Thousands to millions of hectares of bushland and forests burnt down in wildfires in 2009, 2012/2013 and 2019/2020 leading to the direct death of more than 1 billion animals [72, 108]. Fires in Europe burnt particularly large and critical areas in Portugal, Spain, France and Greece [41, 42, 91].

Culture and society. Culture and society experienced manifold consequences arising from heat and drought extreme events. In several European countries tourism and recreation in water bodies were limited due to low water levels, and access to recreation areas like forests was restricted during high fire risk [82]. Hiking and climbing routes were closed due to an increased level of ice and rock falls in the Alps [42]. And in 2019/2020 due to the fires in Australia, some Australian Open tennis matches were delayed or abandoned and other sports events were cancelled [72].

3.2 Impact interaction and cascading effects

Heat and drought extreme events can impact single sectors as well as multiple sectors, and some sectors can be affected by several extreme events. At the same time, impacts in one sector can also propagate and affect other sectors, putting strain not only on one sector but on the whole system. Fig 3 is a simplified visualization of the interconnectedness of the different sectors and impacts based on the assessed historical heat and drought extreme events. For a more detailed version of the scheme consult the appendix (S1 Fig). The most reported direct impacts of heat and drought extreme events affect human health and the agricultural and food production sector. However, almost all the assessed sectors have been affected indirectly through cascading impacts emerging from other sectors, the most affected ones being the sectors of energy, transport and mobility as well as the economy and financial system. Sectors that have been given less importance to but have themselves strong potential to affect other sectors are water resources, ecosystems as well as critical infrastructure and buildings. Eventually all impacts propagating through the system can be expected in one way or another to end up compromising the economy, the state and public services and thus society and culture. The

only sector that was not reported to have experienced important failures and losses is ‘*internet and communication*’. However, the internet and communication sector strongly depends on the availability of electricity which was found to be affected by concurrent heat and drought events. With increasing frequency and magnitude of concurrent heat and drought events, the internet and communication sector can thus be expected to become increasingly affected too.

Heat and drought extremes are documented to have a high impact on health. For instance in the second week of August during the heat wave of 2003, the excess mortality ratio reached values between 21% (Belgium) and >96% (France) in most central and western European countries [93]. These excess deaths are especially important as they happened only within one week putting strain on the health system. For example, it was found for Australia as well as for Europe, that the demand for emergency health services such as ambulance interventions and presentation to emergency departments increases during hot weather [8, 41] and wildfires [96]. In the Australian summer 2009 the dispatch of ambulance service increased by 3326% compared to the same time in the previous year [94]. Apart from the heat and wildfire related excess mortality, [79] also found excess risks for other common causes of death—not directly linked to heat—including cancer and diseases of the digestive system during the heat wave in Moscow in 2010. They hypothesize that this is related to poor conditions in hospitals and other treatment facilities, such as lack of air conditioning [79]. Similar impacts are reported from the COVID pandemic, which also brought the health system in most countries to its very limits, delaying treatment of people with other severe diseases like cancer. Heat waves in combination with other types of ‘extreme events’ can thus even heavily affect and put life in danger of people with severe diseases.

The energy sector suffers concurrent impacts from heat and drought extremes which are cascading through the infrastructure and building as well as the transport sectors. The need for climatization in the short-term and for climate-proving of buildings and infrastructure in the long-term is ever increasing [98] and has implication for the energy sector as well as for the economy on broader terms. The increased electricity demand during hot extremes potentially causes a gap between demand and supply. Especially as the energy sector is already strongly affected by heat and drought extremes, suffering from efficiency loss and reduction in both the generation as well as the distribution of power. Lower supply and higher demand can lead to a rise in energy prices [42, 98], trading restrictions and market contorsions with social consequences (such as fuel poverty [98]) and international consequences as seen in France that cut power exports by more than half due to the unprecedented demand on its domestic energy infrastructure in 2003 [1].

While the electricity system is strongly connected to all relevant sectors of society, its importance has shown especially evident in its interaction with the transport and mobility sector. As seen in Europe as well as in Australia, disruption in the rail and electrical transport system may be significant. Power outages have led to the failure of traffic signals and air conditioning in trains [45] and have the potential to cause major mobility disruptions when relying on electrical transportation. At the same time the energy sector in landlocked countries like Switzerland is found to be strongly dependent on a functioning transport system for import of fossil fuel. In Switzerland, vulnerability arises from the high importance of waterway transportation for the energy supply. Most affected are the reserves of motor and combustible fuel, since 25% of the petroleum used in Switzerland is imported through the Rhine river [67].

While the disruption of road and railway transport caused by power outages, rail buckling and the melting of roads causes problems in the public transport system and creates losses and repair costs, low water levels limit waterway traffic and lead to increased shipping prices and costs for the associated industries and economy. Similar to the import of fossil fuels, waterway transport plays an essential role in the transportation of feeding stuff and comestible goods. In

Switzerland a significant portion of animal feeding stuff and comestible goods are imported through the Rhine river [67], affecting the livestock and agriculture sector and eventually impacting food production. This has particularly severe consequences when the agricultural sector already suffers great losses in extreme heat and drought periods and relies even more on import. Extreme heat increases evapotranspiration and the crop's need for water and drought causes the necessity for crop irrigation potentially depleting natural water resources. Heat stress and insufficient irrigation lead to harvest losses and fodder shortages causing production losses in both the agriculture and livestock sector, again having strong consequences for commodity prices and exporting as well as importing economies. In 2010, Russia's agricultural sector suffered losses of US\$ 1.7 billion which pushed a steep increase in grain prices and widespread market speculation [80]. Hoarding and panic buying led to shortages of buckwheat and higher prices for bread and grain products, as well as for dairy products due to higher feed prices. And as Russia is a significant grain exporter, losses in agriculture also caused losses in exportation and had global-scale impacts on food security [116]. At the same time one of the reasons agricultural losses were so high during 2010, is market-driven changes in crop rotation practices that resulted in a decline in drought resistance in cultivated crops [116].

The increased water use in agriculture stands in direct conflict with environmental needs and the domestic water demand. In 2003 several European regions suffered threats to their water supply systems [41] and during the multiannual extreme drought in South Africa water transfers from the agricultural sector to the urban supply system caused severe financial consequences for farmers [120].

Incompliance with ecological minimum flow standards [82] compromise ecosystems and biodiversity already suffering from the extreme heat and drought. And beside heat-related eutrophication, algae bloom and botulism [82, 119], insufficient dilution of waste water in streams can further degrade the water quality [59]. While this in turn can put more strain on water treatment and affect the public water service [98], it also has severe consequences for the environment. Aquatic organisms lose their habitat and most ecosystems suffer from heat and drought stress weakening flora and fauna. Weak organisms are more vulnerable to pest infestation or extreme weather events and associated impacts as storms and wildfires. Not only leads this to extreme soil erosion and biodiversity loss, it also has cascading impacts on economy and society. Forced wood harvesting and water oxygenation, as well as widespread fish death cause elevated costs and losses in forestry and aquaculture. The increased drying of vegetation makes it easier for wildfires to rapidly spread and not only consume ecosystems and biodiversity, but also cause destruction in urban regions entailing high monetary losses and putting increased strain on insurance companies. Especially in an urban context wildfires can pose a serious threat to human life and health.

The protection of human health in wildfire situations as well as generally in heat and drought extreme events increases the need for public services and often demands for restrictions in cultural and societal opportunities and leisure possibilities. Due to wildfires in the Czech Republic, there were twice as many fire fighter interventions in 2015 than on average [82]. And in Sydney and Canberra the air contamination in summer 2019/2020 was so severe that schools were forced to close, and play and sports activities were cancelled in the former, and public servants were instructed to stay home and the airport of Canberra was closed on two occasions [72]. While wildfires are a recurring and well visible hazard related to extreme heat and drought events, other problems arise for nature and people. Hazardous high water levels in streams with glacier contribution related to extreme heat, drought related stability issues of dike systems or heat and drought related dying of forests can lead to the necessity of closing off certain sectors. Not only has this restriction of access to water bodies, forests and mountains in order to protect human or environmental health affect society and culture.

Together with the destruction of the natural environment and the contamination of urban centres it can lead to a potential loss of image and landscape value and to reductions of consumption and tourism yields [72].

4. Response and adaptation in the face of heat and drought extreme events

The impacts of heat and drought extreme events have led to manifold responses and a call for adaptation in different sectors and systems. In this chapter we analyze the immediate responses in different sectors as well as implemented and suggested adaptation measures following the historical heat and drought extreme events.

4.1 Sectors and assets

Response and policy are analyzed for the sectors with most adaptation actions mentioned in the assessed literature. Most response measures and adaptation policy were taken in the sectors of human health, water resources, agriculture and food production and transport and mobility. The analyzed literature did not mention specific adaptation measures to heat and drought events for the internet and communication sector, and only few specific measures for the energy sector. The sectors of infrastructure and buildings, and energy are assessed together with the other sectors due to their connections. The economy and financial system are discussed in chapter 4.2, as they are strongly interlinked with any adaptation measures taken in the other sectors. Fig 4 is a simplified visualization of the different types of responses and adaptation policies for the most important sectors and assets.

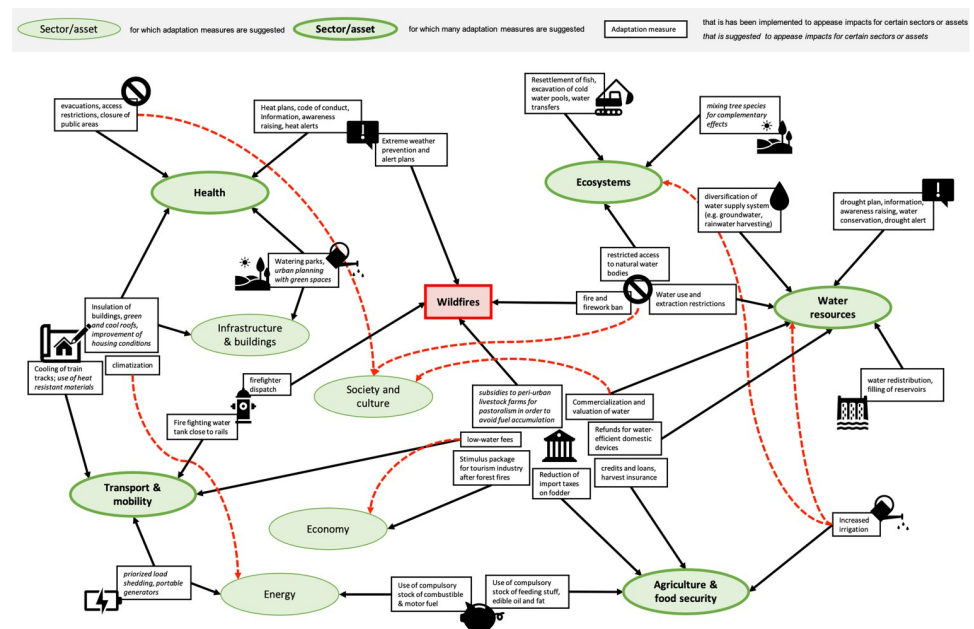


Fig 4. Scheme of implemented and suggested response measures and adaptation policy in the face of heat and drought extreme events. The arrows point from the adaptation measure to the sectors or assets (green boxes) for which they are aiming at adaptation. “Wildfires” (red box) is treated as an additional sector here, as it is an event strongly connected to heat and drought extremes and like some of the other sectors causes a lot of need for response and adaptation measures. The black symbols give an indication of the type of measure that is implemented or suggested (e.g. communication, restriction, planning etc.). The red arrows indicate when responses or adaptation in one sector may have adverse effects in another sector.

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Human health. Similarly to the findings of [98], the adaptation measures against the health risk of heat and drought extreme events we found in the assessed literature were mainly based on technological mechanisms (such as air-conditioning in private and public spaces), as well as institutional mechanisms (like monitoring and alerting actions or restrictions if needed). In order to respond to the health threat of heat waves, countries developed extreme-temperature prevention and alert plans that act as heat health warning systems, based on heat wave forecasts and aiming at vulnerable population groups [8, 41]. The European heat wave in 2003 pushed an improvement of alert systems specifically aimed at the elderly population, the improvement of housing conditions and better social and health care [41]. Some cantonal heat action plans in Switzerland initiated contacting of vulnerable people such as residents aged more than 75 years living in single households [59, 67]. Central and regional institutions generally distributed relevant information and launched awareness raising campaigns. In Switzerland the federal health office and the media informed on correct behavior in heat waves and on the current ozone pollution [59] and all cantons started recommending the tick vaccination [67]. Monitoring campaigns were put in place to inform about the spread of vector diseases [128]. In order to protect people from emerging threats like contaminated waters, falling trees and branches and rock falls, the access to potentially dangerous areas got restricted by local authorities [42, 67, 82].

Adaptation in the infrastructure and buildings sector as well as urban planning aiming at a reduction of the urban heat island effect in densely populated areas, ultimately addresses human health as well. While climatization relieves immediate heat stress [129] but puts strain on the energy system, the insulation of buildings in order for them to require minimum energy for heating and cooling is suggested as a longer-term adaptation measure [8, 67, 122, 130]. Zuo *et al.* (2015) states that building design especially in residential areas as an adaptation measure was largely overlooked and that it should be given more focus, considering the amount of time residents stay at home. Studies state that green and cool roofs could reduce urban heat island effects by several degrees at daytime [131]. Their implementation could potentially offset heat-related excess mortality in urban centers [132]. Green roofs that allow the reuse of wastewater could at the same time reduce the exploitation of regional freshwater resources [133]. Urban planning with trees and green spaces is seen as an important adaptation in the long run [134]. Green spaces may, however, increase the water demand in drought events. In 2015, in several German, Dutch, Slovak and Romanian cities, additional water was required for watering parks to avoid further development of the urban heat island [82].

Water resources. The estimated irrigation water use in France increased by 1–1.7 billion million m³ from 2002 to 2003 [135]. In the same year 2003, the Swiss army carried out water transports by helicopter to meet the water needs in remote and alpine areas in the country [100]. And in the Czech Republic, in Poland, Slovakia and southern Germany tank trucks were ordered to fill reservoirs in municipalities with water supply deficiencies [82]. Following the extreme drought years in Cape Town, the city developed a platform to educate and raise awareness about water scarcity among residents [85]. Advertisements on television and in newspapers on how to use water sustainably and the distribution of educational materials to schools and colleges aimed at the reduction of water use [136]. When the drought in Cape Town became an imminent threat to the region's water supply system, the town announced the coming of a "Day Zero"—an actual date for when the city could no longer supply residential water—to encourage conservation and voluntary reductions in water consumption. A similar effect was observed in Australia during the Millennium Drought (2000–2009), when a sense of water crisis led to household water conservation in Brisbane and Melbourne [97], that resulted in a reduction of Melbourne's household water demand by 50% during and after the extreme drought period [137]. To push these tendencies Cape Town offered refunds for using

more water-efficient washing machines and dishwashers [86, 120, 136]. Similarly, in Europe, Barcelona subsidized the improvement of water distribution networks, water re-use and external supply options [138]. Also in Switzerland, municipalities publicly appealed for water saving before establishing binding restrictions of water use [59]. However, during the drought spell in July and August 2015, Switzerland issued significant restrictions of water use for agriculture [59]. And in 2018 again, the country restricted the water extraction from surface water bodies and groundwater in many regions, with several cantons implementing emergency supply measures. The restriction of water abstraction from streams led farmers to using water from the drinking water system for irrigation or getting water loads by trucks, putting more strain on the drinking water supply system [67]. In 2015, France issued water abstraction restrictions and a ban for non-priority uses, including irrigation bans in 70 departments [82]. With the extreme drought proceeding, Cape Town introduced fines for using water for car washing or daytime lawn watering [136]. The city eventually withdrew the universal water provision of the first six kilograms of free basic water and commercialized and valuated water with new water tariffs. Water use was restricted to 87 liters first and later on to 50 liters per person during 8 months having far reaching consequences for the city's population [86]. Beside the adaptation of water demand, redistribution and diversification of water supply is also mentioned in the literature. In Switzerland, redistributing water from one to another supply group was necessary in several occasions to guarantee the sustainability of the local water supply system. Contracts with neighboring supply groups were set in place to help to cover the water drawing in exceptional situations [67]. In 2018, Switzerland started pushing the opening up of new groundwater access [67]. As a result of the Australian Millennium Drought (2000–2009), Victoria constructed a desalination plant to supply water to Melbourne's supply network [139]. And also in Brisbane, the State government reacted by constructing major infrastructure works such as a desalination plant, recycled water plants and pipelines interconnecting major cities and towns [137]. In Cape Town, rainwater harvesting was considered as an alternative water resource. And in Melbourne, Australia, nearly 30% of houses have installed rainwater tanks, and plans to increase the use of stormwater have been published [139].

Agriculture and food production. The cases have shown that policy in the agriculture and food sector focused on irrigation practices on one hand and on reserves or import and export regulations on the other hand. Van der Velde et al. (2010) found that maize losses as in 2003 in France could be compensated by more than 40% with weekly irrigation [135]. In 2010, also Russia suggested an increase of the area of agricultural land that is irrigated [80]. In 2015, crop irrigation to relieve heat and drought stress was practiced where possible in European agriculture [82]. Where water for irrigation was not available, crop yields suffered losses. While the Swiss state granted loans for hardship cases in 2003 and 2015 for example [59, 100], literature suggested insurance of harvest loss in drought situations for bigger producers as in North America [67]. As a reaction to the decline in fodder production in 2003, Switzerland reduced the import taxes on hay, silage maize, grass and feed grain [100]. Similar actions were taken in 2015 and in 2018 [59, 67]. Russia on the other hand banned grain exports from summer 2010 to summer 2011 and released several million tons of grain from its reserves [80]. In order to avoid similar shortages from happening, Russia discussed plans to bring unused land into use in order to increase grain and feed grain production [80]. Due to higher shipping prices and lower waterway import capacities in 2018, Switzerland started tapping compulsory stocks of edible oil and fat as well as animal feed [67].

Transport and mobility. For the same reason as above Switzerland tapped the stocks of diesel and petrol and later on of liquid motor and combustible fuel reducing the compulsory reserves of the country [67]. While in the past two decades low-water fees for transport were imposed on the Rhine, in 2015, some canals in north-eastern France were even completely

closed to transportation for several months [67, 82]. To respond to electrical faults experienced in 2009 in the public transport system in Australia, several solutions were suggested in the literature. While trains with higher heat tolerance, automatic closing doors and a higher temperature level inside trains could help avoid air conditioning failure, prioritized load shedding as well as standby and portable generators to restore power could be used to keep transportation and signaling functional [45]. During the heat wave in Australia in 2009, train tracks were cooled by pouring water over them to avoid buckling, and extra maintenance expenses were provided for repairing buckled rails overnight [45]. Previous to the 2018 heat and drought event in Europe, several rail track sectors of the Swiss railway network were covered in white paint. This was found to decrease the rail track temperature by several degrees and to slightly reduce the risk of buckling [67]. Apart from monitoring of high-risk locations and cooling tracks, the replacement of tracks by heat resistant materials was suggested in Australia [45].

Ecosystems. In the environmental sector, we found that adaptation policy mainly focuses on relieving stress in aquatic ecosystems and avoiding wildfires. In 2015, record water transfers were implemented in Germany from the Danube to the Main rivers for flow augmentation [82]. Switzerland elaborated emergency concepts for fishing waters in several cantons. In the river Rhine in the canton of Basel those concepts included a swimming ban in areas used by fish to seek protection from the heat [67]. In some river outlets, pools were excavated to collect colder water [67]. Fish were resettled in Germany, the Czech Republic and Slovakia as well as in Switzerland [59, 82]. However, insights into the effectiveness of resettling fish are lacking [67]. For terrestrial ecosystems, some of the contemporary strategies found in the literature for fighting tree mortality in future are mixing appropriate species to increase the likelihood of complementary effects, the introduction of non-native, more heat resistant species [68], and the conversion of coniferous to broadleaf forests [140]. However, the introduction of non-native species bares risks as it is uncertain if newly introduced species could provide the same ecological functions of the present day European forest species [68].

Wildfires. Wildfire prevention was found to be high on the agenda in Australia as well as in European countries with frequent heat and drought extreme events, as wildfires have the potential to affect the majority of the mentioned sectors and assets (e. g. health, ecosystems, agriculture and food production, energy, transport and mobility, infrastructure and buildings etc.). To prevent them, fire restrictions in and close to forests were issued in Switzerland in 2015 and 2018, and fireworks were banned on the National day 2018 [59, 67]. In Greece a review of the local agricultural policy was planned in order to design peri-urban agricultural zones aiming at the controlling of the growth of artificial areas and the preventing of direct contact between woodland and urban land [127]. In order to avoid fuel accumulation for wildfires, it was suggested to foster pastoralism through subsidies to peri-urban livestock farms [141]. Similarly, the extreme drought and wildfires in 2010 drove major changes in the forest management structure in Russia [116]. In consideration of possible wildfires in the Leventina in Switzerland, a firewater basin was installed where wildfires could draw near railway lines [67]. Another important adaptation method to wildfires was found to be early warning and communication. Fire alert systems were generally based on the estimation of fire danger indices [142]. In Australia for example, threat level information was provided via radio, television, social media and via signs on all major rural roads [52]. The fire danger index (FDI) used in Australia [73] was found to be under state and local level jurisdiction, and after the fires in 2009 a nationally standardized wildfire early warning system was strongly suggested in Australia [52]. In summer 2012/2013 hundreds of people were evacuated from the Tasman Peninsula [108]. And in summer 2019/2020 several State of Emergency declarations were made for New South Wales and the Capital Territory in Australia and evacuation orders went out for the south coast prior to New Year's Eve [52]. In that bushfire season volunteer fire fighters saved countless lives and significantly

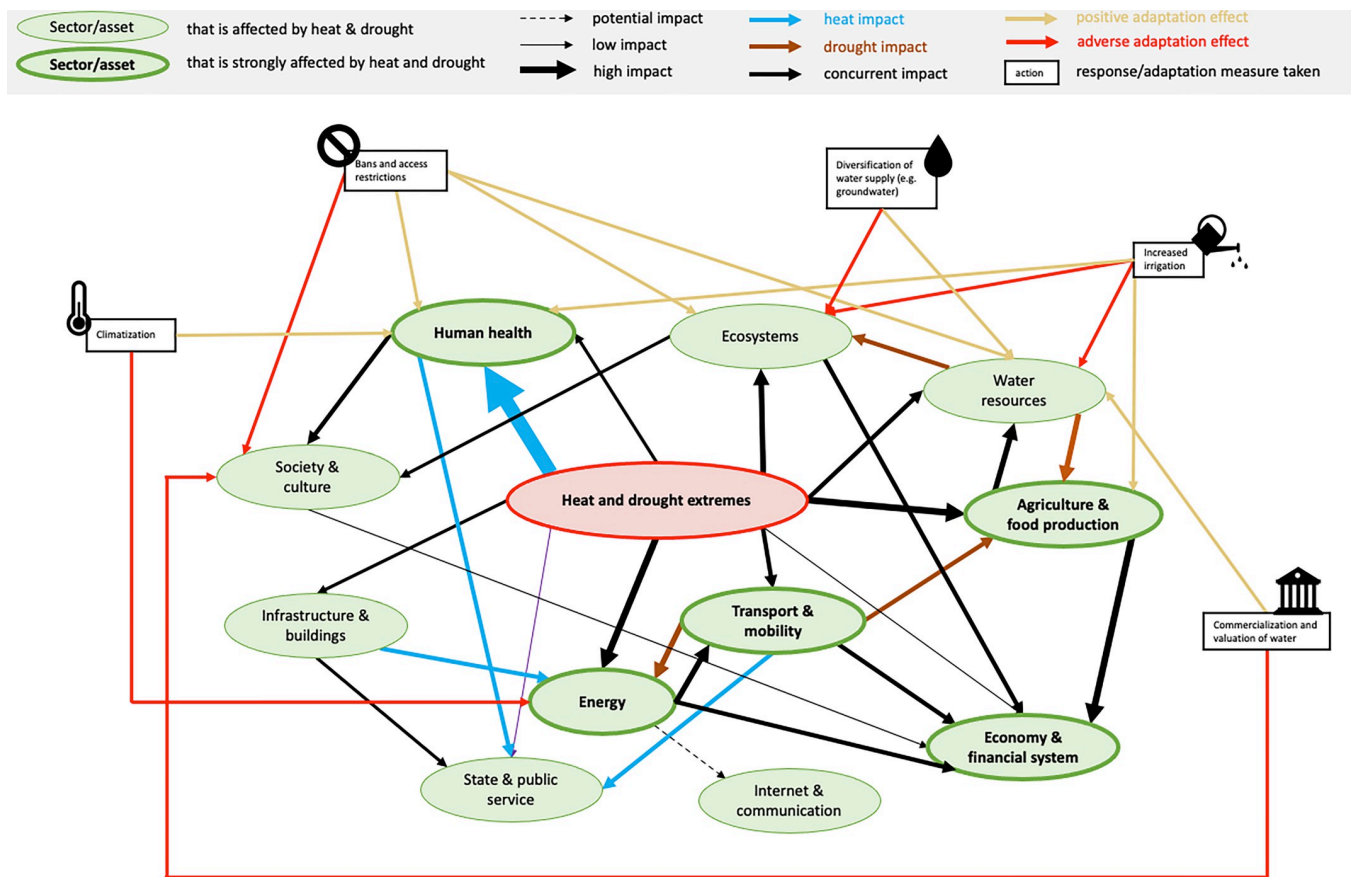


Fig 5. Combined scheme of cascading impacts and interconnectedness of systems, sectors and assets affected by heat and drought extreme events as well as by adverse effects of adaptation actions taken to relieve heat and drought impacts. The arrows point from the affecting event (red circle), adaptation action (white boxes) or sector (green circles) to the sector or asset that is affected. The colors of the arrows identify the main driver of the impact and indicate the effect of adaptation measures. The width of the impact arrows is representative for the importance of the impact. It reflects the number of associated interconnections or mentions found in the literature. The width of the arrows used to show response and adaptation effects is uniform and does not represent their importance.

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reduced impacts on life, infrastructure and buildings [52]. To assist different sectors after the catastrophic wildfires of 2019/2020, the Australian Government announced more than US\$ 50 million in both mental health funding as well as for the tourism sector [52, 72].

4.2 Implications, interactions and cascading impacts

Based on evidence we found, heat and drought extremes can stress the state and the public service system due to impacts in different sectors that demand reaction and remedy. They generally increased the need for state action and public service and had wide ranging effects on national and regional systems. In this chapter we discuss the implications and interactions of immediate responses and designed adaptation policy on the different systems and assets. Fig 5 is a visualization of the interaction of the cascading effects of compound heat and drought extreme events on all the analyzed sectors and assets, and the impacts of adaptation measures taken in some of the sectors.

The cases have shown that threats to human life and health caused by extreme heat and drought events have mainly been met with monitoring and alert systems focused on vulnerable population groups, based on information, communication and sensitization about health risks and appropriate behavior. Immediate responses to wildfires, transport system failures, water

scarcity, yield losses and many others have been necessary in the past two decades in Europe, Australia and South Africa. An increasing demand for fire fighter and emergency service dispatches, water transports, the use of national energy and food stuff reserves and actions to keep essential ecosystems functioning was found to put strain on state and public service demanding great financial and organizational efforts. While immediate actions were asked for in some sectors, they were found to have impacts on other sectors. In compound heat and drought extreme situations, the demand for both water and energy increased, at the same time as its supply decreased (e.g. [98, 143]). To avoid massive losses in the agricultural sector, irrigation was found to be indispensable [82, 135]. And the watering of green spaces in urban areas was often applied to limit the urban heat island effect and with it, health issues for the urban population [82]. Water was also used for cooling purposes in transport infrastructures as well as in the energy sector [45, 144]. The analyzed cases have shown that in compound heat and drought extreme events, the increased water need to relieve heat stress stands in direct conflict with the lower water supply caused by extreme drought (e.g. [143]). Water extraction for cooling and irrigation purposes at the same time reduces the water availability for energy production, waterway transportation and ecosystems, potentially complicating water treatment and compromising the domestic water supply (e.g. [82, 145]). Information and communication of water scarcity as well as limiting the extraction of water, both on short-term, was an adaptation measure often used to reduce water use and prioritize critical sectors. However, limiting water use in the medium term has not proven successful as seen with the multiyear drought in Cape Town. On the contrary, the withdrawal of a minimum amount of free basic water may have even caused an increase in inequalities and vulnerability among parts of the city's population. Cape Town's strategy focused entirely on demand management instead of supply increase or diversification, which in retrospect proved inadequate [120]. The water crisis was exacerbated by insufficient drought resilience planning, a mismanagement of existing surface-water infrastructure and the failure to diversify water supply by utilizing existing groundwater sources, water recycling or desalination [84, 146]. At the same time it was found that the access to alternative water sources (e.g. desalination plants and household bores) in Perth during the Millennium Drought in Australia de-emphasised personal responses to household water conservation [97] and that the predominance of investments in boosting supply was to the detriment of action to reduce demand [137].

Losses in the agriculture and livestock sector, arising from compound heat and drought extreme events and exacerbated by adaptation policy that restricts water use for irrigation have caused marked responses with impacts on regional, national and international economies. For example the extreme heat and drought event in Russia in 2010, causing the country to ban grain exports [80], led to negative economic consequences for Europe [145]. Evidence shows that decreases in agriculture yields lead to more import and have the potential to cause shortages or influence prices in the exporting countries [80]. In a highly interconnected world, regional economies are susceptible to spill-over effects from impacts and adaptation actions occurring outside the region's territory [145]. As in the present globalized world countries are dependent on trade for food security, the international commodity market affects local market prices. Globally connected supply chains allow failures to be spread through the global food system with greater ease [147], which makes the disruption to food trade a systemic risk with global impacts [2]. For example, when grain yields were affected in Russia and Eastern Europe in 2010, India restricted rice exports, driving its price up with impacts across Asia [2].

While compulsory stocks for feeding stuff and energy proved to appease shortages in the short term [67], they should not be expected to significantly reduce the vulnerability of the whole system. Similar to the water resources sector, we found that the energy sector was adversely affected by both the impacts of compound heat and drought extreme events as well

as by several of the adaptation actions taken in other sectors (e.g. [17, 45, 82, 105, 106]). Decreases in electricity production and energy import caused by heat and drought extremes paired with a higher energy demand for cooling in summer can be expected to cause energy production and consumption peaks to change and shift (e.g. [98]). It is important to consider such changes when assessing the capacity of energy systems to cover energy demand. Interestingly, while the analyzed literature did recognize the vulnerability of the energy sector, it did not report on any specific adaptation measures to compound heat and drought extreme events, except reducing capacity if required. For example [52] report that even though electricity failures are known to have caused wildfires during elevated fire risk in Australia, only South Australia has legislation that allows disconnection of electricity grids when there is a high-risk posed to the public. Similar to other sectors, an integral approach to ensuring electricity supply and preventing wildfires, appears to be missing.

5. Discussion

We analyzed historical heat and drought extreme events in terms of their impacts on different sectors and systems of human society to gain a better understanding of the risks they can pose when propagating through those systems. We find that of the eleven sectors we assessed, for all except for the internet and communication sector, direct and/or indirect impacts were reported (cf. tab. 2). The sectors most affected by direct impacts of heat and drought extremes are the health sector and the agriculture and food production sector. In addition, the energy sector, the transport and mobility sector as well as the economy and financial system are also strongly affected if indirect effects that emerge from cascading impacts are also taken into account. Sectors that were given less attention in the analyzed literature, but have themselves strong potential to affect other sectors are water resources, ecosystems as well as critical infrastructure and buildings. The most important cascading processes and interlinkages we found, are centered around the health sector, the energy sector and the agriculture and food production sector. The interlinkages between some systems are hard to disentangle, mainly for (i) human health, the state and public service, and society and culture as well as (ii) for those between the energy sector, the infrastructure and building sector and the transport sector, and (iii) for those between the agriculture and food production sector, the water resources sector, the transport and mobility sector and the economy and financial system. Eventually, all impacts propagating through the system can be expected in one way or another to end up compromising the economy, the state and public services and thus society and culture.

The analysis of response and adaptation measures to heat and drought extremes for our cases reveals that the complexity of system interconnections further increases. We found that the direct and indirect impacts of heat and drought extremes led to manifold responses and adaptation measures, which expands the possible connections and interlinkages that can emerge between the sectors. Some of the most impacted and impacting sectors were also those in which most response and adaptation measures were taken, namely the health sector, the agriculture and food production sector, the water resources sector and the transport and mobility sector. However, for the energy sector for instance, we found only little evidence of adaptation. A critical finding is that some responses to impacts in one sector can lead to adverse effects in other sectors. We found examples of maladaptation for the energy sector, the water resources sector, the economy, society and culture and for ecosystems.

The analyzed cases have shown that the big majority of the adaptation actions and policy implemented to respond to compound heat and drought extreme events has so far been of responsive nature rather than focused on a general reduction of vulnerabilities and weaknesses within the system. This is in line with the findings of a recent publication [148] stating that the majority of

literature on heat adaptation report on individuals or communities autonomously adapting, hinting at a prevalence of individual and communal coping strategies over planned adaptation measures. While according to [148] this is the case especially for low- and middle-income countries, we also encounter this lack of integrated adaptation planning in high-income countries.

Highly urbanised areas are projected to be at an increased risk of heat stress compared with surrounding areas [145]. This is particularly critical as exposure and vulnerability are already high in densely populated regions and as the aged population is growing, which increases health concerns during heatwaves [149]. Further demand for adaptation action, and increasing strain on the health system related to heat and drought extremes must thus be expected. While information and communication in cases of compound heat and drought events have shown to be a good tool to reduce vulnerability (e.g. [84, 122, 150]), awareness must be raised on impacts of heat and drought extreme events in a more preventive way. In addition to heat warnings, short-run incentives or water extraction restrictions reported in the literature we analyzed, education, planning and strategies for example on lowering water consumption in the long term, may be needed.

Our analysis indicates that in many countries recently experiencing an increasing number of concurrent heat and drought extremes, longer-term urban planning and infrastructural measures against such events are not very common yet. However, our assessment has shown that this is required in order to address the urban heat island effect, the logistical difficulties of water distribution, or the vulnerability of electrical transport systems. Green urban planning, climate proofing of infrastructure and buildings, green or cold roofs, energy and water saving as well as the improvement of water distribution systems and the diversification of water extraction and harvesting are just some of the possible approaches we found throughout our analysis.

It is essential to be aware that while historical cases can offer insight into past impact propagation, which is valid for future occurrence, the changing climate [12], exposure [151] and vulnerability may cause impacts to become stronger, new impacts to develop or new sectors to be affected when cascading impacts are exacerbated in the future. Some sectors may not appear in this study, as, historically, they have not been affected. But it is important to not let these sectors out of sight, as they are very likely not just irrelevant. The sector of communication and internet, for instance, was not mentioned in any of the analyzed historical events. But it is strongly dependent on electricity and thus on the energy sector, and would essentially impact all of the other sectors. In cases of critical infrastructure failures that were not related to climatic factors, this sector was strongly affected before and it is importantly linked and embedded in the cascading dynamics we here analyzed [152]. Systems like the energy sector or the sector of communication and the internet are gaining importance in an increasingly connected and technology-relying world. Electricity has become indispensable for the functioning of all other human systems (from financial and banking, to water and wastewater treatment, transportation, telecommunications, health services) [153]. We need to be aware that as the environment we live in changes, the way and the extent in which extreme heat and drought events affect relevant sectors and assets will probably widen and at fast rate. It is thus essential to consider sectors, assets and potential connections, even if they have so far not been in the main focus when reviewing affected systems and connections of extreme heat and drought events.

6. Conclusion

In this study we analyzed eight extreme heat and droughts events in Europe, Australia and Africa over the past 20 years to improve our understanding how such climatic extreme events affect and propagate through different sectors. Important sectors strongly affected include

health, agriculture and food production. The financial losses from such events can be very significant, and in our cases range from several hundred millions to several billions US\$, and in extreme cases, such as during the 2019/2020 Australian bushfires, up to an order of magnitude of 100 billion US\$, equivalent to more than 5% GDP loss. We have also been able to show that the impact of compound heat and drought is not just the sum of their separate impact on different systems, rather we found that the concurrent impact of both heat and drought were crucial for several systems and sectors, including energy, agriculture and food production, ecosystems, water resources, transport and mobility.

Moreover, we identified an interconnected web of sectors that interact in direct and indirect ways and cause additional losses and damages in several other sectors, centered around health, energy and agriculture and food production. This multilevel interconnectedness makes the risks of compound extreme events so complex and critical. We found that cascading impacts emerging from compound events but also from responses to such events can propagate through numerous sectors with far reaching consequences for critical systems, potentially being able to destabilize complete socially relevant systems, for example causing global trade instability. We found evidence for maladaptation in several cases, i.e. where response measures for one sector had negative effects on other sectors, specifically for the energy and water resources sectors, the economy, society and culture as well as for ecosystems. In line with recent large adaptation evaluation efforts in the framework of the Global Adaptation Mapping Initiative (GAMI) [154], our analysis reveals that adaptation measures taken were mostly responsive and of limited scope and depth. There is clearly a need for stronger efforts and investment in adaptation, and deeper (including transformative) changes. The problem of maladaptation requires both more research and more attention in adaptation planning. This, however, implies a stronger engagement with the interconnected and cascading nature of impacts of compound heat and drought events. More efforts should be concentrated on the analysis of such cascading risks and eventually on ways to interrupt such chains of impacts. We suggest that rather than to compartmentalize risk assessment into single extreme events, impacts and sectors, it is essential to systematically consider the interconnectedness of sectors and systems. Our qualitative network-type analysis of past events should contribute to a more comprehensive understanding and foster further quantitative analysis and modeling of impacts, including a prospective perspective towards the future. In fact, as unprecedented compound extremes are likely to occur in the future, cascading impacts that go beyond historical precedence and experience are expected and need careful analysis, as a fundamental support for adaptation planning. Our study has revealed the complexity of adaptation and response measures in interconnected systems, and more research and policy efforts are crucial to improve adaptive capacity and resilience of affected regions to compound heat and drought events.

Supporting information

S1 Table. Initial search key words used for the literature search on Scopus and Web of Science. The column ‘search years’ indicates the time for which publications were searched and in the column ‘# Scopus’ and ‘# Web of Science’ the number of hits is given for each literature search platform is given.

(DOCX)

S1 Fig. Detailed scheme of cascading impacts and interconnectedness of systems, sectors and assets affected by heat and drought extreme events. The arrows point from the event or sector that affects another sector or asset to the sector or asset that is affected. The colors of the arrows identify the main driver of the impact, blue meaning heat and brown meaning drought

being the main driver, and black meaning concurrent extreme of heat and drought acting as main driver. The width of the arrows is representative for the importance of the impact. It reflects the number of associated interconnections or mentions found in the literature. (TIFF)

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