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Cross-regional comparison of drought impacts and social responses: case studies in Germany and Jing-Jin-Ji Region (China) since the 19th century

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Abstract. Droughts, as one of the costliest weather-related disasters, have been and will continue to be part of the common human experience. However, insufficient endeavors have been made to investigate the similarities and differences in drought-society interactions under different climatic systems and sociocultural contexts. In light of this, this study took Germany and the Jing-Jin-Ji Region (China) as examples, where have abundant written documents and distinct socio-environmental contexts, and compared drought impacts and social responses in three pairs of extreme drought events since the 19th century. Based on area-specific reconstructions of dry-wet indices and multilingual written documents, drought events were first selected according to the relative extremity of precipitation deficits within each study area, then depicted in terms of five impact categories and five response attributes presented in a common impact-response structural framework, and finally compared with particular attention to the unchanging nature and dynamics of drought-society interactions during the transformation from agrarian to modern societies. The comparisons revealed that: (1) Abnormally dry and hot conditions, vegetation damage, unsatisfactory crop performance, insufficient river flow, food insecurity, and social instability were drought impacts independent of climate systems (i.e., marine climate and monsoon climate) and were well documented by different societies regardless of their severity. (2) Tackling socioeconomic issues within drought-stricken areas by balancing the supply and demand of scarce goods was a common responding preference of societies under different circumstances. In this case, actions were often reactive and needed the participation of governments. (3) The diversification of documented drought manifestations in the socioeconomic category was observed in both study areas as society developed, owing to increasingly complicated economic sectors and the wider range of social concerns. (4) Early and multiple reactive interventions reduced the threat of food insecurity to individual survival in recent droughts, as they successfully stopped the development from harvest failures to food crises. However, in any of the study areas, they have not been sufficient to eliminate survival-threatening manifestations of compound drought-heatwave events with regard to water security (i.e., drinking water scarcity) and health (i.e., morality in vulnerable populations). The results not only provided empirical evidence of climate-environment-society nexus that go beyond period-specific experiences but also demonstrated the feasibility of conducting documentary-based cross-regional comparative studies in spite of linguistic differences.

1 Introduction

Droughts are thought to have the largest adverse impacts of all climate variables throughout human history, with far-reaching effects documented on each inhabited continent (Kchouk et al., 2022; Trnka et al., 2018). As a recurring feature of all climates, a drought usually begins with a period of inadequate precipitation and/or increased

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atmospheric water demand and then spreads to almost all sectors of social-ecological systems as direct and indirect impacts accumulate (Cammalleri et al., 2023; UNDRR, 2021). In history, numerous cases evidenced the destructive power of drought, which resulted in water scarcity, agrarian crises, economic depression, migration, conflicts, institutional failure, regime collapse, and even the demise of civilizations (Camenisch et al., 2020; Hakenbeck and Büntgen, 2022; Hornbeck, 2023; Kennett et al., 2012; Pribyl et al., 2019; Watanabe et al., 2019; Zheng et al., 2014). In the recent past, drought-related events contributed to 34% of disaster-related deaths during 1970–2019, although they only accounted for 7% of all the disaster-related events (WMO, 2021). In the near future, anthropogenic climate change is projected to increase the likelihood and severity of droughts in many parts of the world, leading to increased population and natural resource exposures and more negative outcomes across all economic sectors (Elkouk et al., 2022; Runde et al., 2022).

Motivated by the growing recognition that both natural hazards and human responses can incur risks (IPCC, 2022), drought studies exhibit increasing interests in exploring human-nature interactions by analyzing meteorological processes, natural and socioeconomic consequences, and ensuing social responses based on a variety of documentary evidence (Brázdil et al., 2018; Savelli et al., 2022). Of these studies, many focused on a single event, reconstructed its course in detail, identified the cascading effects of drought across socio-ecological systems, and depicted how society addressed them at the moment (Chen et al., 2022; Gergis et al., 2010; Metzger and Jacob-Rousseau, 2020; Van Der Schrier et al., 2021; Zhai et al., 2020). Some revolved around a specific topic, such as famine (Seyf, 2010), epidemics (Burns et al., 2014), migration (McLeman et al., 2022), and conflicts (Elkouk et al., 2022; Klein et al., 2018), and discussed their nexus with drought. A few took a long-term perspective, investigated a series of drought cases in a particular place, and retraced drought impacts and social responses over time (Erfurt et al., 2019; Moerman, 2024; Noone et al., 2017). The abundant studies have shown the disruptive and complex nature of drought, enriched the understanding of drought propagation that take human actions into account, and demonstrated the contributions that historical research could make, such as providing baseline and contextualization for climate change adaptation options (Adamson et al., 2018).

However, as studies generally emphasize place-specific experiences, little is known about the similarities and differences between individuals or groups in different socio-environmental contexts when facing the same climatic stimulus (i.e., precipitation deficit). In addition, rare attention is paid to investigating the commonalities among drought events, which reveal the unchanging nature of drought and provide a bridge between the past and present. These, to some extent, hinder the comprehensive understanding of the general mechanism through which human societies interplay with natural systems during droughts, thereby limiting the potential for identifying and sharing effective mitigation or adaptation strategies that go beyond place- and period-specific experiences.

This study aims to close the abovementioned gaps by attempting comparisons of impacts and social responses to drought in Germany and the Jing-Jin-Ji Region (China), where both have rich written documents but differ in climate systems, sociocultural backgrounds, and languages. To achieve this purpose, this study first selected three extreme drought events in each study area, representing drought scenarios at different social development stages since the 19th century. Then, a common impact-response structural framework, which comprised five impact categories and five response attributes, was developed to help extract and integrate textual information on selected drought events from various types, forms, and languages of written documents. Next, the progression of each

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drought event was established under the same structural framework to make multiple drought cases comparable. Finally, cross-time and cross-regional comparisons were conducted among the six events, with a focus on the immutable nature and dynamics of impacts and social responses to drought. The results are expected to provide empirical evidence of drought risks and coping strategies during the transformation from agrarian to modern societies and, meanwhile, demonstrate the feasibility of cross-regional comparisons on climate-society interactions involving distinct environmental conditions, sociocultural circumstances, and actors based on written documents in different languages.

2 Study areas

Germany is situated in the central part of the European continent (Fig. 1). Its contemporary territory is 35.7×104 km2, 90% of which is covered by the Elbe, Weser, Ems, Rhine, and Danube River basins (Huang et al., 2013). Forests, grassland, and arable land account for 30%, 13%, and 33% of the overall territory, respectively, and the latter two are both used for agricultural purposes. With regard to cereal farming alone, which is generally dominated by sowing in spring and autumn and harvesting since July, 57% of its yields are used as fodder. This confirms animal husbandry as a mainstay of Germany's agricultural sector (BMEL, 2020). Germany is characterized by a humid temperate climate with warm summers (i.e., Cfb class in Köppen-Geiger climate classification) (Kottek et al., 2006). Due to the maritime influence, it has a relatively mild climate compared to other areas at similar latitudes, as evidenced by a relatively narrow annual amplitude of temperature (16–25 °C) and sufficient annual precipitation (around 800 mm) evenly distributed in four seasons. However, obvious regional differences in precipitation and groundwater recharge exist since continentality gradually increases from the northwest to the east. This puts the eastern part of Germany, such as the Elbe River Basin, under higher water stress in the summer, when evapotranspiration is at its highest and the water level of rivers is relatively low (Gebhardt et al., 2013; Glaser et al., 2007).

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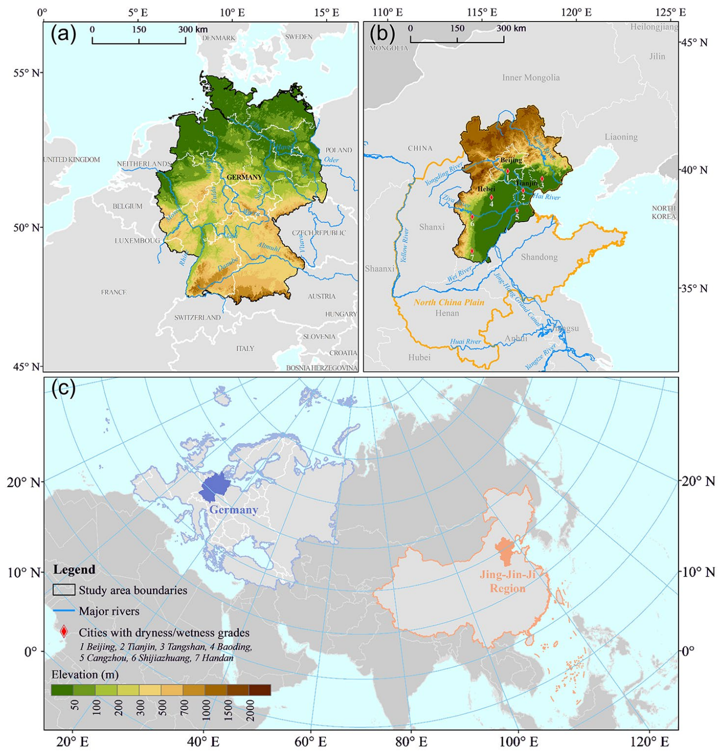

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Figure 1 Study areas: (a) Germany, (b) the Jing-Jin-Ji Region, and (c) their relative locations on the Eurasian continent

The Jing-Jin-Ji Region includes three present province-level administrative divisions of China, namely Beijing municipality (abbr. Jing), Tianjin municipality (abbr. Jin), and Hebei province (abbr. Ji). The total area is 21.6×104 km2. It is located in the northern part of the North China Plain (Fig. 1) and is mostly covered by the Hai River basin (Guo et al., 2019). Arable land accounts for 35% of the whole region and occupies most of the plains, while forests and grassland are mainly distributed in the mountainous areas and account for 35% and 9%, respectively (National Bureau of Statistics of China, 2023). Crop cultivation is the traditional livelihood of farmers in this region. Three-quarters of the annual yields come from crops sown in spring and harvested in autumn, and crops sown in autumn and harvested in the following summer contribute to the remaining quarter (Xiao, 2020). Most of this region has a continental climate with dry winters and hot summers (i.e., Dwa class in Köppen-Geiger climate classification) (Kottek et al., 2006). As deeply influenced by the East Asian Monsoon, climate here is characterized by a relatively large annual amplitude of temperature (30–32 °C), annual precipitation (400–800 mm) concentrated mostly in hot months (i.e., June to September), and four distinct seasons. During March to May, the rapid warming, months-long rainless period, and frequent windy days often lead to high evapotranspiration, insufficient surface runoff, and low groundwater levels and result in severe water stress in the spring. Additionally, the onset of the wet season varies from April to early August in different years, which depends on the strength of the summer monsoon, thus increasing the risk of consecutive seasons of drought (Wei et al., 2016; Zhao et al., 2015).

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3 Material and methods

3.1 Data sources

In the context of climate change, the interactions among climate, ecosystems, and human society are not only producers of emerging risks but also providers of future opportunities. However, the complex nature of climate risk, the varying exposure and vulnerability of affected socio-ecological systems, and the diverse human responses make it difficult to capture those interactions by using a single metric (IPCC, 2022). Therefore, multiple sources of data are desired for gaining comprehensive and holistic insights into climate-related hazards and repercussions.

Two groups of data sources were adopted in this study (Fig. 2a). The first was (semi-) quantitative reconstructions of past dry and wet conditions, namely indices that could reflect the occurrence and extremity of precipitation deficits. Priority was given to good temporal continuity and full spatial coverage when picking the suitable index for each study area. For Germany, the annual standardized precipitation index (SPI-12 for December) from 1800 to 2022 was chosen, which was reconstructed by integrating hermeneutic information from written documents in 1500–1996 and official instrumental records from 1881 onwards (Glaser and Kahle, 2020). As for the Jing-Jin-Ji Region, annual dryness/wetness grades at seven stations (Fig. 1) were available from 1800 to 2018, which were semantic-based reconstructions and were extended with official instrumental data after 1951 (Chinese Academy of Meteorological Sciences, 1981; Weather China and National Climate Centre, 2019; Zhang et al., 2003; Zhang and Liu, 1992), and were converted into to a regional dry-wet index (Fig. 2b) by Eq. (1).

$$DW(t) = \left(\frac{m+n}{N}\right) \times \left[\sum_{i=1}^{m} \beta_5 \times A(i,t) + \sum_{i=1}^{n} \beta_4 \times A(i,t)\right] + \left(\frac{j+k}{N}\right) \times \left[\sum_{i=1}^{j} \beta_2 \times A(i,t) + \sum_{i=1}^{k} \beta_1 \times A(i,t)\right], \quad (1)$$

Where $DW(t)$ is the dry-wet index for the whole Jing-Jin-Ji Region in year t. N is the number of all stations in the Jing-Jin-Ji Region. m, n, j, and k denote the number of stations reporting very dry (grade 5), dry (grade 4), wet (grade 4), and very wet (grade 1). $A(i,t)$ is the grade anomaly at station i in year t. β refers to the coefficient for each grade (i.e., $\beta_5 = -2$, $\beta_4 = -1$, $\beta_2 = 1$, $\beta_1 = 2$). Stations with grade 3 (normal years) and no data are excluded in the calculation, because they reflect a situation that is neither dry nor wet.

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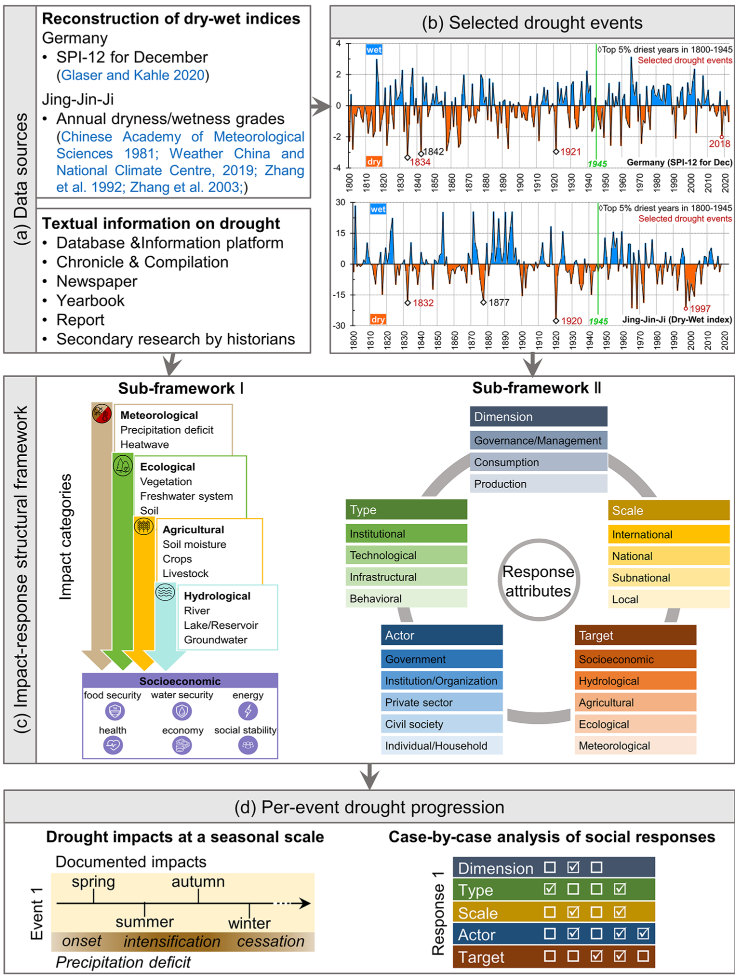

Figure 2 Conceptual framework

The second group of data sources were multiple types of written documents listed in Supplement A, which could provide details on the development of precipitation deficits, subsequent impacts, and actions taken by humans. The original content of drought-related descriptions was either directly obtained from subject-specific databases and information platforms or newly extracted from chronicles and compilations, local or national newspapers, official yearbooks, and formal or informal reports. For instance, specific records could be searched in the Collaborative Research Environment tambora.org (Riemann et al., 2015) and the Integrated Natural Disaster Information System of Qing Dynasty (Fang et al., 2020; Xia, 2015) by disaster type, time of occurrence, and position, while textual information on the social focus at a given moment needed to be captured manually from newspapers such as the *Freiburger Zeitung* and *People's Daily*. Meanwhile, secondary research (e.g., peer-reviewed papers, monographic studies) by historians was adopted as a supplement when the original materials were unavailable.

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3.2 Selection of drought events

The selection of drought events were based on the extremity of dry conditions and the representativeness of different social development stages. In other words, for a selected event, its precipitation deficits should be severe enough to be considered as a crisis and its occurrence should be at a certain episode in the profound transformation from agrarian to modern societies that human society experienced over the last 200 years (IPCC, 2022).

Before setting the criteria for selection, a couple of differences across regions or over time should be noted, which include:

(1) There are fundamental differences between Germany and the Jing-Jin-Ji Region in terms of climate systems and usable proxies for long-term climate reconstructions. This makes it nearly impossible to simply compare the dry-wet indices available for the two study areas and select events with close meteorological features.
(2) As dry-wet indices for both study areas absorbed official instrumental data at certain points, uncertainties introduced by non-climatic influences on weather stations are also noteworthy, such as possible changes in standard procedures, observation techniques, network densities, and station locations over time (Brugnara et al., 2020, 2022). This challenges the identification of events with the same intensity of precipitation deficits at different periods within one study area.
(3) The pace of social transformations and consequent environmental changes differed from time to time, which have accelerated considerably after the Second World War, i.e., in the post-1945 period (McNeill and Engelke, 2014). This hints at the need for developing selection criteria segmentally.

Thus, starting from the definition of crisis—a deviation from the state of normal (Steg, 2020), this study gave up seeking events with similar dry conditions, turned its attention to the most significant deviations (i.e., the driest years) reflected in the dry-wet indices applied to each study area, and set criteria independent of the location and data. Additionally, distinctive selection criteria were applied for periods before and after 1945:

(1) For the period from 1800 to 1945, in each study area, all years with a SPI-12 or dry-wet index < 0 were first identified as dry years. Then, those dry years were ranked according to the specific value of the index. Next, the top 5% driest of all dry years were picked out, and events covering those extremely dry years were considered as potential options. After that, two events were selected among them to represent drought in agrarian society and during industrialization, respectively.
(2) For the period after 1945, the most recent drought events with prolonged and severe precipitation deficits were selected for each study area, aiming to best reflect the context of modern society.

Ultimately, three pairs of drought events were selected (Fig. 2b), namely the Germany 1834 (SPI-12 = −3.33) and Jing-Jin-Ji 1832 (dry-wet index = −18.81) events in agrarian societies, the Germany 1921 (SPI-12 = −2.95) and Jing-Jin-Ji 1920 (dry-wet index = −27.58) events during industrialization, and the Germany 2018 (SPI-12 = −2.02) and Jing-Jin-Ji 1997 (dry-wet index = −21.68) events in modern societies. These events were named after the driest years they witnessed, and their durations were determined as described in Sect. 3.4.

3.3 Development of impact-response structural framework

Comparability is an important issue in documentary-based comparative studies involving different areas at different periods, as the type, character, complexity, and information density of data sources are always varied

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(Erfurt et al., 2019). Conducting comparative analyses under a common structure reflected in all cases can be a feasible strategy for ensuring comparability, which has been applied in domains such as human response systems in the face of natural hazards (Knight, 2001). Following this strategy, this study formulated a common structural framework to guide the characterization of drought progression in multiple cases, which consists of two sub-frameworks as below.

In the sub-framework I (Fig. 2c), five categories of negative drought impacts were generalized from the various textual information on drought manifestations, with reference to the meteorological drought, agricultural drought, hydrological drought, groundwater drought, and socioeconomic drought defined by Bernhofer et al. (2015). To better serve documentary-based research from a historical perspective, this study created a separate category for ecological drought, merged groundwater drought into the hydrological category, and developed comprehensive sub-categories with typical manifestations (Table 1).

Table 1 Categories and manifestations of negative drought impacts

Categories	Sub-categories	Manifestations
Meteorological	Precipitation	Deficit, severe deficit (described by degree adverbs such as unprecedented, rare, extreme, severe, great, very, etc.)
	Temperature [a]	Heatwave (abnormal hot weather lasting from several days to months or extreme maximum temperatures recurring in a short period)
Ecological	Vegetation [b]	Abnormal phenological period, poor plant growth, plant death, decreased vegetation cover, insect plague, wildfire
	Freshwater system	Increased water temperature, deteriorated water quality, fish death
	Soil	Dust storm
Agricultural	Soil moisture	Insufficient moisture, cracks in land
	Crop	Difficulty in sowing, growth affected, poor quality, harvest failure
	Livestock	Lack of fodder, lack of bedding material, decrease in production, death
Hydrological	River	Low water level, reduced flow, cutoff
	Lake & Reservoir	Shrinking water body, decreased water stock, dry up
	Groundwater	Dropped water level, insufficiently derfilled aquifer, wells dry up
Socioeconomic	Food security	Affordable (price), available (supply), famine
	Water security	Drinking water (supply, quality, price), hygiene and sanitation, other usage (daily life, agriculture, industry, etc.)
	Energy	Fuel (cooking, heating, other usage), electricity (generation, supply, price)
	Health	Malnutrition and decreased labour capacity, injury (fire disaster), heat-related illness, epidemic, mental health, death
	Economy [b]	Private property losses (fire disaster), infrastructure damage, decrease in income, increase in expenditure, obstruction of transport, limitations on other economic activities
	Social stability	Conflict, displacement and migration, crime, moral and ethical collapse

a. Considering the positive correlation between abnormal high temperature and drought severity (Zscheischler et al., 2018), compound heatwaves were incorporated into the meteorological category.

b. The forestry industry is an important economic sector in Germany but not a major livelihood in the Jing-Jin-Ji Region. Thus, instead of setting a separate (sub-) category, this study classified drought impacts on forestry into either ecological or socioeconomic categories based on specific descriptions. For example, impacts described as trees in poor condition

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belong to the vegetation subcategory in the ecological category; while, impacts described as decreases in income due to damaged trees belong to the economy subcategory in the socioeconomic category.

The sub-framework II (Fig. 2c) depicted five general attributes of social responses to drought, based on which diverse responses could be comparable to each other after appropriate abstraction:

(1) *Dimension* demonstrates the levels of social responses. Production-level responses intend to minimize drought impacts on producing primary products by taking remedial actions based on current resources or exploiting environmental potentials. Consumption-level responses aim to balance the supply and demand of a particular good or service by expanding supply, reducing waste and/or outflow, increasing purchasing power, restraining demands, adjusting allocation strategy, and finding substitutes. Governance/management-level responses attempt to maintain or recover the function of social-ecological systems through assessment, intervention, coordination, and social innovation, which, in many cases, are designed from a top-down and comprehensive perspective (adapted from Fang et al. (2024)).

(2) *Type* specifies the manner in which a social response is conducted. Behavioral responses involve attempts to mitigate risks or repercussions directly, such as praying for rain, irrigation, emergence slaughter, transporting life necessities to and relocating from drought-stricken areas, and temporarily relaxing or restricting regulations. Infrastructural responses refer to the investment, construction, and maintenance of equipment and infrastructure, such as firefighting equipment, water facilities, transport infrastructure, and power supply systems. Technological responses comprise implementing monitoring and early warning systems, improving farming practices and water-saving technologies, breeding and planting climate-resilient plants, providing technical assistance and training, and updating coping concepts. Institutional responses include creating long-term policies and programmes, establishing laws and regulations, and setting up permanent institutions or organizations (adapted from Berrang-Ford et al. (2021)).

(3) *Scale* characterizes the spatial extents of social responses. Actions can be taken within the affected place (i.e., local scale); engage less-affected areas, such as neighboring provinces or states (i.e., subnational scale); be supported by the central government or have nationwide influence in present-day territories (i.e., national scale); and involve other countries and/or international organizations (i.e., international scale).

(4) *Actor* indicates who undertakes social responses. It ranges from individuals or households to civil society, the private sector, institutions or organizations, and multiple levels of government.

(5) *Target* identifies the categories of drought impacts (i.e., from meteorological phenomena to socioeconomic impacts) that a given social response aims to address. This attribute was designed to show the original intentions of each social response, whether or not those intentions were achieved in the end.

3.4 Establishment of the drought progression for each selected event

Guided by the abovementioned structural framework, drought progression of the six selected events was established individually and described in general terms due to space limitations. Details on each drought impact and responding way have been elaborated in Supplement B and Supplement C, separately.

This study took the onset and cessation of precipitation deficits as the beginning and end of an event. Other drought impacts, as sequels to abnormally dry conditions, might not occur or be noticed in every drought, or could continue in inconspicuous manners for an unmeasurable time after precipitation returned to normal. Subsequently, for each

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drought event, different categories of impacts were identified at a seasonal scale according to the following principles:

(1) For an impact with records detailed to the date or month, the season to which the date or month belonged was adopted.
(2) For an impact that had records with clear seasonal information, the documented season was adopted directly.
(3) For an impact described as a persistent manifestation across several seasons, all the mentioned seasons were taken into account.
(4) For an impact without clear seasonal information but derived from time-sensitive sources (e.g., newspaper), the season in which those sources were published was chosen.
(5) For an impact that was only documented as existing in the event, it was omitted here.

Social responses were analyzed on a case-by-case basis, as actions might be taken before, during, or after a drought, with influences lasting from days to decades. For a given drought event, all responses mentioned were first analyzed according to the five attributes and then tallied in terms of the number of different ways to respond, the share of classes in the *Dimension* attribute, and the proportions of classes in other attributes within each dimension. Finally, response preferences in different social structures were discussed.

4 Results

4.1 Recurring summer droughts in agrarian societies

The Germany 1834 drought event occurred two decades after the Napoleonic Wars. In this context, Germany had undergone a series of territorial reshufflings and social reforms, which are believed to lay the foundations of the modern state and society, but had not been unified into a nation-state. Moreover, some important parts of its traditional structure remained in place during the post-Napoleonic era, such as the nobility's local power and the irreplaceable role of agriculture among all livelihoods (Grab, 2003; Slicher van Bath, 1963). This event was marked by recurring hot summer droughts. It spanned from autumn 1833 to summer 1836 and culminated in summer 1834 with 16 drought manifestations in 11 sub-categories (Fig. 3a, Supplement B). Of those 12 seasons, 58.33% were considered too dry due to insufficient precipitation, with heatwaves occurring in 42.86% of the abnormally dry seasons; a quarter observed ecological impacts in the form of damage to vegetation; 30.77% saw drought affecting agriculture, manifested as difficulties in crop production and livestock feeding; and 58.33% reported low surface water and groundwater levels in the hydrological category. Meanwhile, seasons in which drought spilled over into socioeconomic systems accounted for 41.67%, and food supply risk, water insecurity, economic losses, and water conflicts depicted the challenges that society faced at the time.

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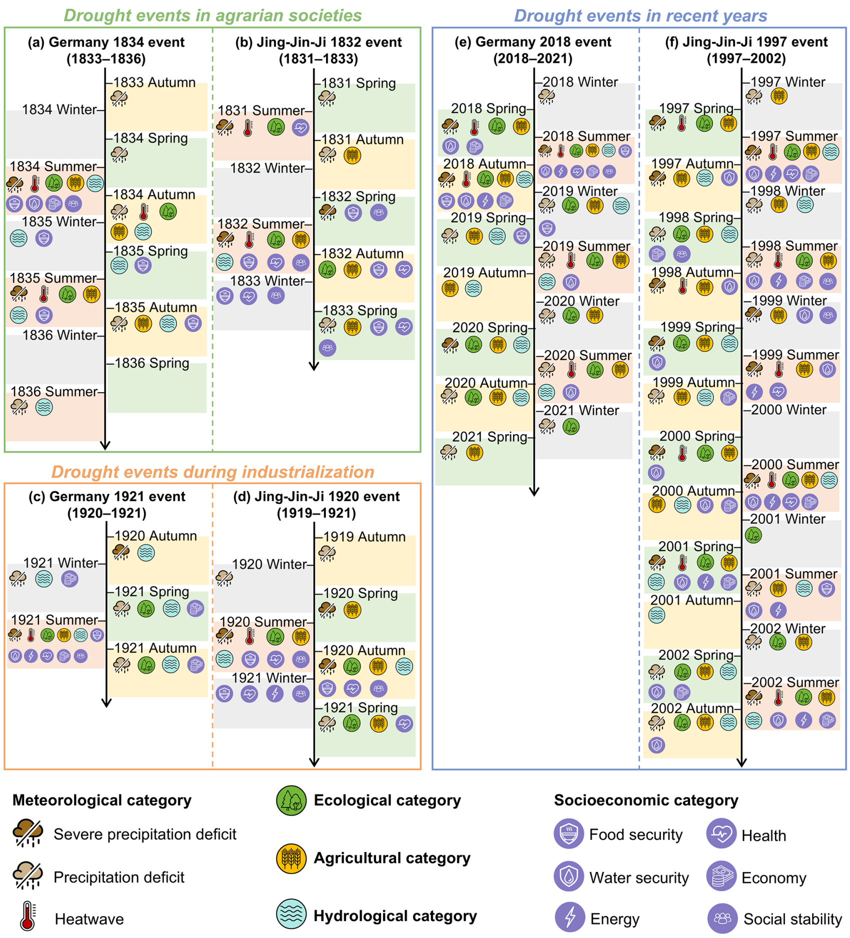

Figure 3 Progression of extreme drought events in Germany (abbr. DE) and the Jing-Jin-Ji Region (abbr. JJJ), depicted by different categories of impacts at a seasonal scale. For each event, the beginning and ending seasons correspond to the first and last mentions of precipitation deficits, respectively.

Ten response ways were documented in this event (Fig. 4a, Supplement C), 60% of which were taken at the consumption level to deal with inadequate supplies of fodder and water by expanding supply, reducing demand, or adjusting allocation strategy. The local government was the most engaged actor who dominated 50% of responses at this level, while the individual/household and civil society also took a few actions to prevent livestock starvation and secure community's drinking water supply, separately. At the production level, farmers attempted to compensate for summer cereal failures by replanting; meanwhile, community wells were carefully protected to ensure water accessibility for the whole community. While at the governance/management level, precautionary water storage in community cisterns and the activities of fire brigades were endeavors to protect local socio-ecological systems from fire threats. Private sector was the only actor not acting in this event.

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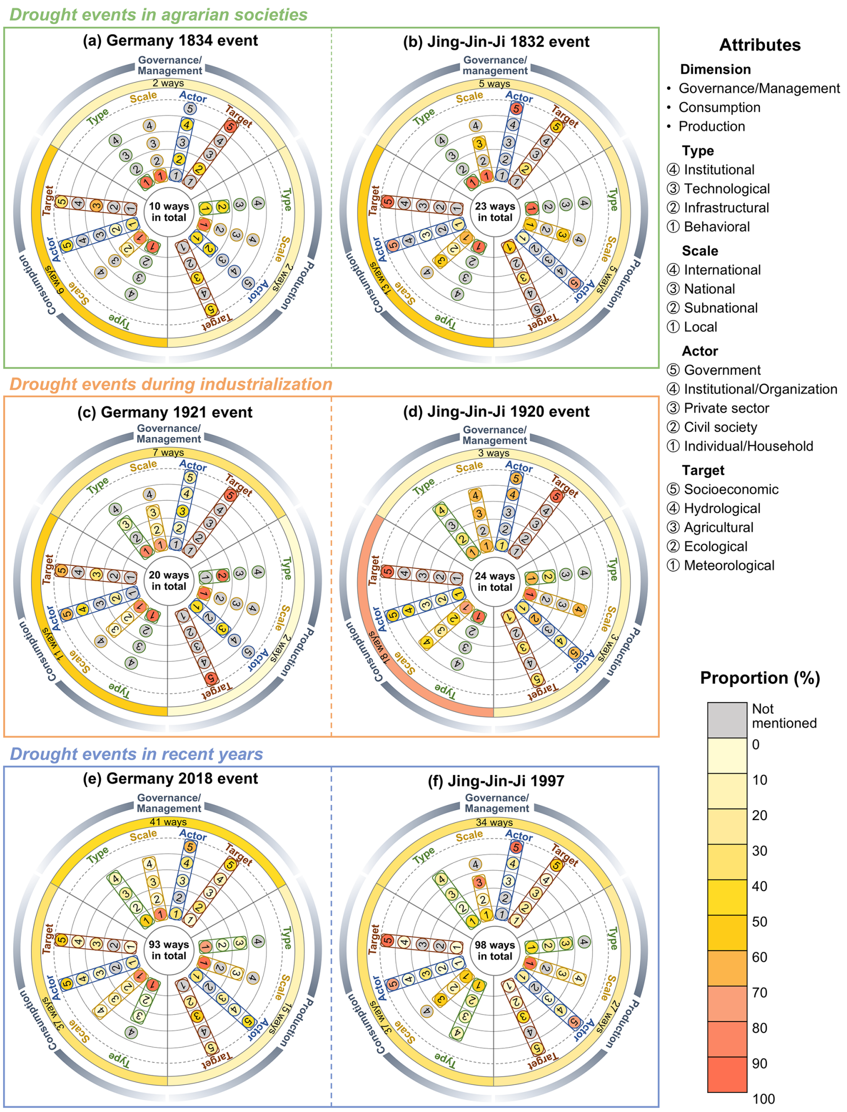

Figure 4 Per-event statistics of social responses. Classes in attributes except for *Dimension* are not mutually exclusive. In other words, in each event, the sum of the proportions of the three classes in *Dimension* should be 100%, but within each dimension, the proportions of the mentioned classes in a given attribute could sum to more than 100%.

Roughly two years earlier, recurring summer droughts compounded with heatwaves were also documented in the Jing-Jin-Ji Region, where drought-affected groups lived very close to the center of power of the Qing Dynasty and their livelihoods largely relied on crop farming. The Jing-Jin-Ji 1832 drought event began with precipitation deficits in spring 1831, peaked in summer 1832 with 13 manifestations in eight sub-categories, and ended with sufficient rainfall in the early summer of 1833 (Fig. 3b, Supplement B). From spring 1831 to spring 1833, rather dry conditions prevailed 66.67% of the time, with one-third of all abnormally dry seasons also accompanied by heatwaves. Among the nine seasons, 33.33% mentioned ecological impacts described as vegetation damage;

44.44% witnessed impacts on agriculture highlighted by harvest failures of crops; and 11.11% reported river cutoff, the only impact belonging to the hydrological category. Additionally, drought impacts on socioeconomic systems were recorded in two-thirds of the seasons, with particular concerns about food security, health, and social stability. The displacement and death of individuals due to drought-induced famine and the consequent rise in crime put considerable pressure on society.

During this event, 23 ways of responding were observed (Fig. 4b, Supplement C). Here, responses belonging at the consumption level were the most common (56.52%), mainly designed to mitigate drought impacts on food security through actions at local, subnational, and/or national scales. Similar to Germany, expanding supply and adjusting allocation strategy were also the main approaches adopted by both governments and individuals. Additionally, production-level responses and governance/management-level responses both accounted for about 20%. The former mainly responded to abnormal meteorological phenomena and difficulties in local agricultural production, while the latter focused most on the assessment and control of locust plague, food insecurity, and social instability. As for actors, the central and local governments participated in over 80% of all responses. While the individual/household, despite being the second-most active participants, was about 65 percentage points lower than government in terms of involvement.

4.2 Yearlong drought during industrialization

The Germany 1921 drought event occurred in the initial years of the Weimar Republic, when the country had benefited from the technological progress of the Industrial Revolution but was also limited by the burdens of the First World War (Erfurt et al., 2019; Streb et al., 2006). Overall, below-average precipitation persisted in five consecutive seasons from autumn 1920 onwards, 40% of which coincided with heatwaves, and summer 1921, when this event came to a peak, witnessed up to 28 drought manifestations in 16 sub-categories (Fig. 3c, Supplement B). By the autumn of 1921, 60% of the seasons had observed ecological impacts, involving threats to both vegetation and freshwater systems; 20% of the seasons had seen drought affecting agriculture in terms of soil moisture, crop, and livestock; all seasons had experienced at least one of the impacts in the hydrological category, i.e., low water levels in major rivers; and 80% of the seasons had reported impacts on socioeconomic systems, such as economic losses. In addition, summer 1921 was described as a serious challenge for society. At that moment, troubles arose in all six sub-categories, ranging from unaffordable food prices to illegal profiteering, some of which worsened the living conditions of vulnerable groups and led to a remarkable increase in infant mortality.

Twenty ways of responding were mentioned in this event, mostly belonged to the dimensions of consumption and governance/management (Fig. 4c, Supplement C). Specifically, consumption-level responses, comprising 55% of the total responses, sought to address problems with livestock feeding, food price, drinking water, and electricity. Over 80% of them were behavioral responses attempting to mitigate the negative repercussions at a local scale. Responses at the production level only accounted for 10% and water availability remained their primary focus. However, more actions were taken in the manner of infrastructure construction. The share of responses at the governance/management level was 20 percentage points lower than that at the consumption level. Compared with examples of agrarian societies, helping vulnerable groups (e.g., infants) to survive heatwaves became a new concern in this dimension. Additionally, wider participation in social responses was observed during this event.

The government (45%) and institution/organization (35%) were the most engaged actors, while the private sector (20%), civil society (20%), and individual/household (5%) were also involved to some extent.

A year earlier, the Jing-Jin-Ji Region also suffered from a long absence of rainfall. At that time, this region was witnessing the early stage of industrialization, which brought about the development of railways; meanwhile, it was undergoing fractured governance by warlords after the recent fall of the Qing Dynasty (Fuller, 2013). The Jing-Jin-Ji 1920 drought event started with insufficient rainfall in autumn 1919, peaked in summer 1920 with 13 drought manifestations in nine sub-categories, and ended after a brief return of precipitation deficits in spring 1921 (Fig. 3d, Supplement B). Of the seven seasons, 85.71% were identified as abnormally dry seasons, with only 16.67% of such dry conditions accompanied by heatwaves; 42.86% observed ecological impacts characterized by vegetation damage and soil degradation; 57.14% underwent agricultural impacts manifesting as insurmountable obstacles in crop sowing and harvesting; and 28.57% reported hydrological impacts reflected in surface-water bodies. Moreover, drought impacts propagated into socioeconomic systems in 57.41% of the seasons and provoked wide-ranging ramifications in the sub-categories of food security, health, energy, and social stability, including but not limited to life-threatening food crises, epidemics along the railways, massive displacement and deaths, individual mental breakdowns, and the collapse of social ethics.

There were 24 response ways recorded in this event (Fig. 4d, Supplement C). Three-quarters of the responses were adopted at the consumption level to alleviate socioeconomic impacts, particularly food insecurity. Apart from that, limited actions were taken at the production and governance/management levels (12.50% each). Production-level responses include praying for rain, providing seeds to affected farmers, and, digging new wells. While at governance/management level, plenty of efforts were put into maintaining social stability, such as resettling the displaced and reducing human trafficking. Compared to the aforementioned examples, social responses here had a wider spatial extent since actions at all four scales, especially the native and international life-saving relief, were well documented. Self-help was another feature of this event. At the time, the involvement of individual/household (45.83%) was much closer to that of government (58.33%) and civil society (29.71%) became a new important actor.

4.3 Prolonged drought with record-breaking heat in recent years

The Germany 2018 drought event took place in an era where remarkable prosperity coexists with unprecedented challenges. On one hand, the country has developed into a more stable and well-functioning society with comprehensive modern economic sectors and, as a member state of the European Union (EU), deepened cross-boundary collaborations. On the other hand, ongoing climate change has been intensifying climate extremes, and the 2018 event, as a microcosm, has set a new benchmark for exceptional drought in Germany and even on a European scale (Conradt et al., 2023; Rakovec et al., 2022). Specifically, this event started in winter 2017/2018, reached its maximum in summer 2018 with as many as 33 drought manifestations in 17 sub-categories, and lasted until spring 2021 (Fig. 3e, Supplement B). Thirteen of the 14 seasons (92.86%) experienced varying degrees of precipitation deficits that were accompanied by intense heatwaves in 38.46% of cases. Seasons reporting impacts in the ecological, agricultural, and hydrological categories accounted for 71.43%, 85.71%, and 64.29%, respectively. In these three categories, broader repercussions of drought were observed when compared to previous events, as over three-quarters of manifestations in all nine sub-categories were documented. Furthermore, half of the seasons saw socioeconomic impacts, ranging from limited food price increases to short-term water conflicts; meanwhile, water scarcity became the most frequent emergency that society had to face.

Ninety-three ways of responding were taken at this time (Fig. 3e, Supplement C). Responses at the governance/management, consumption, and production levels accounted for 44.09%, 39.78%, and 16.13%, respectively. For the first time, governance/management became the level at which responses were most often taken, with some efforts put into developing long-term strategies and plans (i.e., institutional responses). At this level, the majority of manifestations in all impact categories were addressed to some extent, particular attention was given to aftermaths such as wildfires and heat-induced problems (e.g., heatstroke, infrastructure damage), and government became the most active implementer. Although consumption-level responses dropped below 50% of all responses, they not only remained the most popular option when facing fodder shortages and water insecurity but also served as a way to compensate for income decreases. Production-level responses here were most concerned with agriculture (53.33%), especially crop performance. Farmers, as one of the most engaged actors, made efforts to minimize harvest losses in both behavioral and technological manners, including irrigating fields, postponing harvest dates, changing farming practices, and adjusting planting structures.

The Jing-Jin-Ji Region also had an unforgettable experience with persistent hot and dry conditions in the late 1990s, when society was largely strengthened by improvements in technology and productivity since the 1950s but also increasingly constrained by the growing scarcity of water resources (Zhang et al., 2009). The Jing-Jin-Ji 1997 event spanned 24 seasons from winter 1996/1997 to autumn 2002, culminated in summer 1997 with 16 drought manifestations in 12 sub-categories, and peaked again in summer 2000 with 14 manifestations in 13 sub-categories (Fig. 3f, Supplement B). During this event, lack of precipitation was observed in 83.33% of all seasons, with intense heatwaves occurring in 45% of these abnormally dry seasons. Meanwhile, seasons that witnessed drought affecting ecosystems, agricultural production, and hydrological cycle accounted for 50%, 87.50%, and 58.33%, respectively. In the abovementioned categories, all sub-categories except for freshwater systems were noted to some extent, and unfavorable circumstances for soil moisture, livestock feeding, and groundwater level received attention for the first time. Additionally, 70.83% of the seasons reported that drought disturbed socioeconomic functions. By the end of this event, all six sub-categories belonging to the socioeconomic category were involved, and water scarcity had replaced food insecurity as the most threatening issue.

Ninety-eight responses were documented in this event, with 34.69% at the governance/management level, 37.76% at the consumption level, and 27.55% at the production level (Fig. 3f, Supplement C). Consumption-level responses were the most employed, especially for ensuring food security, balancing water supply and demand, and alleviating the temporary financial stress of drought-affected farmers, companies, and local governments. Local governments, sometimes under the guidance and financial support of the central government, gave most of these responses, while the private sector showed relatively high interest in improving water-saving technologies. Governance/management-level responses were designed to address the majority of documented drought impacts, with particular focus on water scarcity and subsequent water conflicts. The central government played an indispensable role in this case, especially with regard to institutional and technological responses. Production-level responses here showed the greatest concern for agriculture (48.15%) and attempted to reduce crop harvest losses in the manner of behavioral responses (e.g., irrigating fields) and technological responses (e.g., promoting dry

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farming techniques), which was similar to the Germany 2018 event. Nevertheless, plenty of efforts were also invested in the improvement of water facilities to expand usable water and thus alleviate water stress.

5 Discussion

5.1 The unchanging nature of drought impacts and responding preference

So far, according to textual information documented in Chinese, English, and German, all six drought events have been portrayed in terms of negative impacts and social responses, and their progression has been built on a common structural framework, respectively. On this basis, a universalizing comparative analysis was first applied, which emphasized similar rules followed in different cases (Tilly, 1984), to reveal the unchanging nature of drought across regions and over time.

Out of 17 sub-categories of drought impacts, seven can be recognized as universal key impacts in both study areas, as they were always mentioned despite the passing of time (Fig. 5a). These sub-categories are precipitation and temperature in the meteorological category, vegetation in the ecological category, crop in the agricultural category, river in the hydrological category, and food security and social stability in the socioeconomic category. Their recurrence across multiple drought cases reveals that anomalous weather, damage to vegetation, unsatisfactory crop performance, insufficient river flow, hunger, and disorder are not only location-independent signals and/or threats of droughts but also inescapable and unresolved challenges from the past to the present. In addition, a number of other case studies on drought further confirmed the widespread nature of those key impacts, at least in other provinces of China (Chen et al., 2022), other European countries (Metzger and Jacob-Rousseau, 2020; Noone et al., 2017), south-eastern Africa (Klein et al., 2018; Pribyl et al., 2019)), the Middle East (Eklund et al., 2022), and North America (Burns et al., 2014; Hornbeck, 2023) during the 19th century to the early 21st century.

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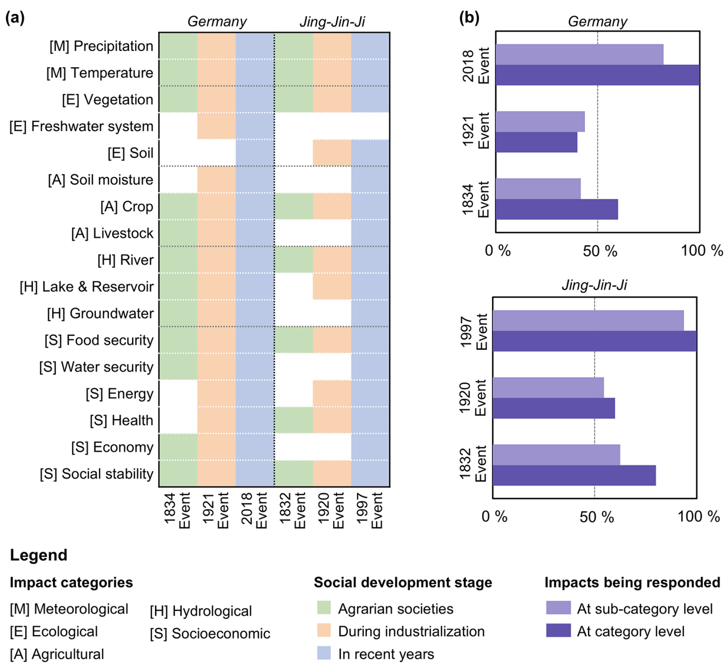

Figure 5 (a) Sub-categories of documented drought impacts and (b) proportions of drought impacts being responded at the category and sub-category levels

In terms of social responses to drought, a common preference for coping strategy can be identified in the two study areas and at all three social development stages, despite the distinct climate systems and varied socio-cultural contexts. It is found that societies often tend to mitigate drought impacts on socioeconomic systems through balancing supply and demand of scarce goods in the drought-stricken areas, with most actions reactively taken at a local scale. Meanwhile, government usually plays an important role in these responding process, indicating a consensus on the need for organization and coordination in the face of natural hazards (Fig. 4).

In other words, drought is drought. Regarding the pathways through which drought affects socioeconomic systems, it typically starts in the parts of human-natural systems that support basic human activities and then leads to imbalances in the supply and demand of life necessities in drought-stricken areas. As the organizational capability is gradually exhausted, the normal functioning of local societies is hindered, which, in some severe cases, causes individual deaths, social disruption, and, ultimately, spillover effects to less-affected areas.

Nevertheless, positive signs for better coping with droughts were observed in both study areas as moving towards to modern societies. The two study areas showed a similar trend in increasing efforts to reduce drought risk and damage through responses at the governance/management level and/or in an institutional manner (Fig. 4), which reflected growing attempts at the integration of short-term mitigation and long-term preparedness and rising interests in non-structural measures. Moreover, in recent events, drought impacts in all categories and over 80% of sub-categories received some degree of response (Fig. 5b), implying that societies became able to react to

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broader concerns beyond the basic needs of drought-stricken groups, although the effectiveness of those actions remains to be assessed.

5.2 Dynamics of socioeconomic manifestations and responding toolbox

To gain insight into drought-society interactions under different circumstances, comparison in this section was conducted with a special focus on the 24 drought manifestations in the socioeconomic category (Table 1). As shown in Fig. 6, during the transformation from agrarian to modern societies, the diversification of drought impacts on socioeconomic systems can be observed in both study areas, reflected by increases in the proportion of documented manifestations and in the number of involved sub-categories. Such changes can be attributed to two possible causes, namely increasingly complicated economic sectors and changing social concerns. The former has contributed to diversifying drought manifestations, particularly in the sub-categories of energy and economy, since more complex economic activities usually involve a greater number of intermediate links and a wider range of actors, leading to increased exposure to drought. The latter may explain why water insecurity was not mentioned in the Jing-Jin-Ji Region until the 1997 drought event, in which food insecurity was no longer the most pressing issue as famine had been eradicated, despite drinking water scarcity being an enduring problem in remote rural areas (Wang, 2002).

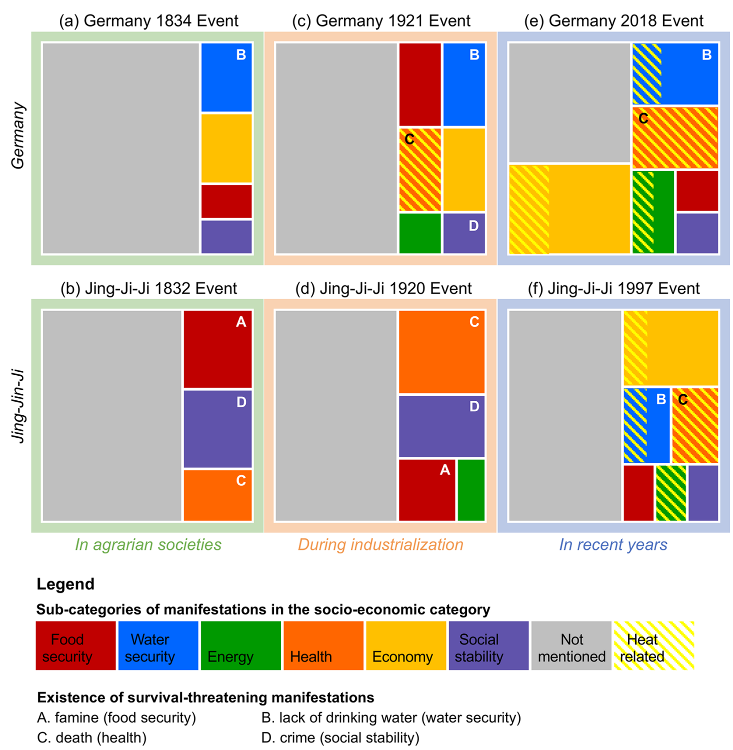

Figure 6 Changes in manifestations of drought affecting socioeconomic systems in (a, c, e) Germany and (b, d, f) the Jing-Jin-Ji Region during the transformation from agrarian to modern societies. For each event, the area of colored or gray rectangles represents the proportion of manifestations that belongs to specific sub-categories or are not mentioned in the entire socioeconomic category, and the area of colored rectangles covered by yellow diagonal lines indicates the proportion of heat-related manifestations in each sub-category

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Although manifestations of drought affecting socioeconomic systems have increased in general, food insecurity and social instability, which have been recognized as universal drought impacts independent of climate systems and social development stages, are less survival-threatening than in the past (Fig. 6). This should be credited to the advanced responding toolbox in modern societies, which has made progress in early and multiple interventions in the spread of drought impacts into socioeconomic systems. Specifically, when considering the impact chain of precipitation deficit → harvest failure → rising food prices → crime in Germany, it can be seen that there was no record of actions taken before drought affecting food security in the 1921 event, but 10 measures aiming to reduce or compensate harvest losses were adopted in the 2018 event (Supplement C). As a result, the summer of 1921 witnessed exorbitant food prices (e.g., bread prices rose by 40%), which was exacerbated by subsequent criminal profiteering and the decision to raise wages (Freiburger Zeitung, 1921a, b, c). While in the 2018 event, earlier interventions together with grain imports from France and Eastern Europe (Henning, 2018) successfully ended the abovementioned impact chain with slight increases in food price. As for the Jing-Ji-Ji Region, the impact chain of precipitation deficit → harvest failure → famine → crimes and deaths was a dominant pathway of drought causing mortality and disorder in history. Famine-induced epidemics, displacement, violent crimes, and even massive deaths were frequently mentioned in the 1832 event and the 1920 event, even though a dozen solutions were tried to alleviate massive famines and their aftermaths (Li, 1993; Zhang, 2013). However, those manifestations disappeared in the 1997 event, as the development of famine was interrupted. In this event, the impacts chain stopped at a less severe level of food insecurity (i.e., insufficient food for some rural households (People's Daily, 2000a), thanks to the implementation of 23 measures to mitigate water stress and pest damage to crop performance and the improved capacity for state regulation of grain supply and demand (Supplement C).

In contrast to the successful breaking of pathways from precipitation deficits to food crisis and subsequent social instability through the agricultural system, pathways from precipitation deficits to drinking water scarcity via the hydrological system were still mentioned in recent droughts, i.e., the Germany 2018 event (Fig. 6e) and the Jing-Jin-Ji 1997 event (Fig. 6f). To meet water demand during drought, various coping strategies were adopted in the two study areas, including but not limited to using stored water, transporting water to affected areas, issuing water usage restrictions on the principle of ensuring drinking water, improving water facilities, and promoting water conservation. Simultaneously, actions related to sustainable water management were also taken in both study areas to mitigate present impacts and future risks of drought on the hydrological system such as insufficient river flows, inadequate reservoir storages, and low groundwater levels (Supplement C). In spite of these efforts, the lack of drinking water was widely reported in the two events, as relevant responses were either difficult to maintain in a prolonged drought or required a relatively long time to be effective. This suggests a greater need for anticipatory drought adaptation to ensure water security when compared to food security.

Last but not the least, extreme heat has become increasingly destructive in compound drought-heatwave events since the early 20th century and has gradually replaced precipitation deficits as the main climatic impact-driver of mortality in vulnerable population (e.g., infant, the elderly) (Fig. 6c, 6e, 6f). Furthermore, a wider range of heat-related impacts on water security, energy, and economy were observed in recent drought events (Fig. 6e, 6f), as compound drought-heatwave events became more frequent and intense in both Germany and the Jing-Jin-Ji Region (Fig. 3e, 3f). In addition to directly causing illness, death, and heat damage to infrastructure, heatwaves often

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exacerbate existing socioeconomic issues induced by precipitation deficits, such as increasing consumption of water and electricity and thus worsening supply-demand imbalances (Nicolai, 2018; People's Daily, 2000b). Unfortunately, although the two study areas could recognize and react to the additional effects of extreme heat within a relatively short time, responses including issuing extreme weather warnings, giving health advice on heat and sun protection, and changing consumption habits and working hours were not able to eliminate those tangible and intangible impacts, even in modern societies. This indicates a common adaptation gap in the face of intensifying compound drought-heatwave events.

6 Conclusions

The general objective of this study was to discuss the unchanging nature and dynamics of drought-society interactions in different socio-environmental contexts. Based on reconstructed (semi-) quantitative dry-wet indices and multilingual written documents since the 19th century, this study first selected three pairs of extreme drought events in Germany and the Jing-Jin-Ji Region (China), then established the progression of each event under a common impact-response structural framework, and finally conducted cross-time and cross-regional comparisons among droughts in agrarian societies (i.e., Germany 1834 and Jing-Jin-Ji 1832 events), during the industrialization (i.e., Germany 1921 and Jing-Jin-Ji 1920 events), and in recent years (i.e., Germany 2018 and Jing-Jin-Ji 1997 events).

During the transformation from agrarian to modern societies, seven key drought impacts and a common responding preference were observed in both study areas and at all three social development stages. Despite dissimilarities in climate systems (i.e., marine climate and monsoon climate) and sociocultural backgrounds, abnormally dry and hot conditions, vegetation damage, unsatisfactory crop performance, insufficient river flow, food insecurity, and social instability were always considered drought challenges by societies and were well documented regardless of their severity. Meanwhile, societies often took reactive actions to mitigate drought impacts by balancing the supply and demand of scarce goods (i.e., consumption-level responses) in drought-stricken areas, which in over 50% of the cases were implemented with the participation of governments. Building on the above findings, this study depicted an immutable pathway of drought impacts cascading into socioeconomic systems. Specifically, precipitation deficits first affected the parts of human-natural systems that support basic human activities, then caused supply-demand imbalance in life necessities at a local scale, next exhausted the organizational capability of drought-stricken societies, and eventually spilling over to less-affected areas when social responses failed.

Nevertheless, differences in drought manifestations and coping strategies were visible when comparing the six events with a special focus on socioeconomic impacts. Such differences mainly stemmed from variations between different social development stages rather than from dissimilarities in environmental or cultural backgrounds. As moving towards modern societies, both Germany and the Jing-Jin-Ji Region witnessed an increase in the amount and type of documented drought manifestations and, at the same time, a decrease in the threat of drought to individual survival. The former could be explained by increased drought exposure due to increasingly complicated economic sectors and broader social concerns beyond traditional drought challenges, while the latter benefited from the early and multiple reactive interventions before drought affected socioeconomic systems, which had succeeded in breaking the impact chain of precipitation deficits → harvest failure → food insecurity → social instability. However, in contrast to the remarkable progress made in ensuring food security, survival-threatening manifestations such as drinking water scarcity and heat-induced mortality in vulnerable population were still frequently reported in recent years, as the most effective responses to those manifestations (e.g., adopting sustainable water management, building climate-resilient city) normally took some time to take effect. This revealed a common adaptation gap in mitigating drought impacts on water security and health in the two study areas and urged anticipatory adaptation in the face of intensifying compound drought-heatwave events.

Data availability

All the data used in this study are available in Supplement B and Supplement C.

Author contribution

DZ and RG contributed to the development of research concept and methodology. RG and MK performed the collection and extraction of German documentary data. DZ collected Chinese documentary data, analyzed textual information from both study areas, and prepared the manuscript with contributions from all co-authors. All authors have read and commented on the latest version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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