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SCIENCE-POLICY PERSPECTIVES

Sustainability nexus analytics, informatics, and data (AID): Drought

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Abstract
Drought occurs globally and can have deleterious effects on built and natural systems and societies. With the increasing human footprint on our planet, so has increased the anthropogenic influence on drought and water scarcity, leading to the development of notions of "anthropogenic drought" and "water bankruptcy". Understanding the human dimension of drought is complex and requires a data-driven nexus approach to better understand the involved processes and address the implications of water deficits around the world. Just as it transcends scales and geographical boundaries, drought is neither restricted to a single hydrologic state in the water cycle nor are its effects confined to one sector. Drought impacts the water, energy, and food sectors, ecosystem services, socioeconomics, public policy, politics, etc. from local to regional and global scales. We argue that drought mitigation strategies and policy developments must be addressed with a multidisciplinary perspective that benefits from a nexus approach rooted in analytics, informatics, and data (AID). The United Nations University (UNU) Sustainability AID Programme employs such an approach to aid the monitoring, forecasting, and projection of drought, both from climatic and anthropogenic perspectives, and its multifaceted impacts across a variety of sectors and spatiotemporal scales. After a broad overview of this UNU Programme's vision, and to support stakeholders and decision-makers, we present a drought resource database for drought-related information, data, and analysis tools. Our aim is not to compile an exhaustive list of all available data and tools. Instead, we prioritize mature datasets and AID tools while actively highlighting opportunities to develop new data and tools, fostering nexus research.

Keywords Analytics · Informatics · Data · Drought · Sustainable development · Water · Nexus

1 Why drought matters

Drought is a complex global issue with (direct and indirect) impacts on interdependent systems/sectors, feedbacks, and compounding dynamics, causing globally and/or regionally networked risk (Blauhut et al. 2016; Hagenlocher et al. 2023; Puma et al. 2015; Qi et al. 2022; Zaveri et al. 2021, 2023). Although the impacts of drought can be long-lasting and widespread, it usually has a gradual onset and slowly propagates through the hydrologic cycle as the water deficit evolves in space and time (Mishra and Singh 2010; Teutschbein et al. 2023b; Walker et al. 2024). It is one of the costliest natural hazards (World Meteorological Organization 2021), causing over US$8 billion per year in economic losses across the United States alone (NCEI 2024). For instance, during the 2021 drought, the state of California experienced an estimated US$3.9 billion in economic damages (gross revenue loss), the loss of more than 14,700 jobs, and over 150,000 ha of fallowed land (Medellín-Azuara et al. 2022). While droughts occur in the global north and the global south, they do so with various impacts and differing levels of severity associated with those effects (King-Okumu et al. 2020; Teutschbein et al. 2023a; Zaveri et al. 2023; Newman and Noy 2023). Indeed, an overwhelming majority of people affected by drought, approximately 85%, live in low- or middle-income countries (Tsegai et al. 2023). Developing countries such as India, have already witnessed a decreasing trend in agricultural production due to recurring droughts (Nath

Extended author information available on the last page of the article et al. 2017). Somalia, another developing country, has experienced widespread food insecurity resulting in loss of life and livelihood, and even famine driven by drought (Dahir 2023; Hillbruner and Moloney 2012; UNHCR 2022). The impacts of droughts are not limited to one sector (e.g., drinking water, agriculture, economics, tourism, energy and utilities, import/export of food and goods, manufacturing, etc.) (De Brito et al. 2024; Tsegai et al. 2023) nor do they merely have local effects (Chen et al. 2013; Smith et al. 2024; Wang et al. 2014). This is complicated by warming global temperatures that are projected to lead to more severe and persistent droughts across many parts of the world (Chiang et al. 2018, 2021; Cook et al. 2020; IPCC 2021; Konapala et al. 2020; Padrón et al. 2020; Pokhrel et al. 2021; Trancoso et al. 2024; Zhou et al. 2023). Furthermore, losses due to drought are expected to rise under climate change (Chiang et al. 2021; Rossi et al. 2023) as demonstrated in China, for example, where the estimated loss is projected to increase tenfold in a sustainable development pathway at 1.5 °C of warming in comparison to 1986–2015 (Su et al. 2018).

Drought losses and impacts occur worldwide; yet, they are systematically reported in comparatively few countries and regions of the globe (UNISDR 2011), leading to an underestimation of the implications of drought (Newman and Noy 2023). This means that drought does not always receive the appropriate level of attention or urgency, which can thereby result in less political, economic, and/or media visibility, especially when poor communities and vulnerable rural households are affected by drought (UNISDR 2011). Also, drought risk is partially influenced by underlying socially-constructed factors, contributing to reactive as opposed to proactive approaches and policy, as well as inequalities (David and Hughes 2024; Savelli et al. 2022; Tsegai et al. 2023). Consequently, some regions may not be able to adequately implement the disaster risk reduction strategies, management, policies, and governance that can alleviate drought impacts and associated feedbacks.

In numerous global regions, drought and water stress find their roots in human activities, rendering them inherently "anthropogenic" (AghaKouchak et al. 2015b; Barnett et al. 2006; Di Baldassarre et al. 2017; Sivapalan 2015; Wheater and Gober 2015). Notably, recent drought events in areas like California, Brazil, China, Iran, Spain, and Africa are primarily attributed to human-induced factors such as excessive surface and groundwater usage, urbanization, deforestation or other land use-land cover changes, and the impact of human-driven climate change (Ashraf et al. 2019; Diffenbaugh et al. 2015; Jiang 2009; Qiu 2010; Silva et al. 2015; Tripathy et al. 2023; Van Loon et al. 2016, 2022; Van Loon and Van Lanen 2013; Williams et al. 2020; Xu et al. 2015; Yuan et al. 2018). The extensive human alteration of the hydrologic cycle and climate system has led many communities and regions worldwide into a continual state of water scarcity due to the stark disparity between supply and demand (Kelley et al. 2015). This imbalance results in water shortages persisting even during typically wet years.

Throughout the mid-nineteenth century until now, the confluence of population growth and substantial industrial and agricultural advancements, has notably increased water consumption and vulnerability to droughts across the globe. This surge therefore amplified the economic toll of significant droughts (Di Baldassarre et al. 2018; Etienne et al. 2016; Kreibich et al. 2019; Liu et al. 2018; Marengo and Espinoza 2016; Winsemius et al. 2018). Furthermore, this scenario serves as a catalyst for societal tensions and political unrest (Kelley et al. 2015; Savelli et al. 2022). Droughts, in turn, significantly contribute to a region's heightened demand for emergency relief and food aid, and conflicts have worsened the impact of drought on food insecurity (Anderson et al. 2021). In fact, across Africa, roughly half of all emergency food assistance occurs in response to natural disasters, and primarily is drought-driven (African Risk Capacity 2016). Not only does drought contribute to food insecurity in some regions of the world, but it also results in five times as much migration as flood events, often disproportionately affects lower income households, and has the potential to exacerbate inequalities (Ceola et al. 2023; Hallegatte et al. 2017; Savelli et al. 2023; UNDRR 2021; Winsemius et al. 2018; Zaveri et al. 2021). For example, drought internally displaced more than 266,000 people in Afghanistan during 2018 as agricultural losses and drying rivers, streams, and wells left more than 10 million people, equivalent to about half of the rural population, to face food insecurity in November of that year (FAO 2018; IFRCRCS 2018). Such conditions necessitated humanitarian efforts and emergency response to aid the displaced individuals and families, and those facing food insecurity (FAO 2018; IFRCRCS 2018). The World Health Organization (2023) estimates that by 2030, drought will place up to 700 million people at-risk of being displaced. However, current drought monitoring systems do not provide information on the potential impacts (AghaKouchak et al. 2023).

Drought classifications conventionally encompass meteorological (often describing a deficit in precipitation), agricultural (deficit in soil moisture), hydrological (deficit in runoff, streamflow, groundwater level, and total water storage), and socioeconomic (deficit in water supply relative to the human water demand leading to societal impacts) droughts (Dai 2011; Mehran et al. 2015; Mishra and Singh 2010; Tijdeman et al. 2022; Van Loon et al. 2016; Wilhite and Glantz 1985). More recently, snow drought (deficit in snow water equivalent or the amount of water stored in the snowpack) (Huning and AghaKouchak 2020), ecological drought (considering specific ecological impacts) (Crausbay et al. 2017), human-induced and/or human-modified hydrologic drought (Van Loon et al. 2016), and more broadly, anthropogenic drought or water stress caused or intensified by human activities (AghaKouchak et al. 2021), have been gaining more attention—see Fig. 1 for a noncomprehensive timeline showcasing significant drought datasets (highlighted in purple), indicators (marked in red), advancements in models (depicted in blue), and technological innovations (highlighted in green). However, most of these classifications, indicators, and datasets predominantly treat drought as a climatic force, focusing on quantifying deficits in water-related aspects caused by natural variability. This approach overlooks the human dimension of drought and fails to integrate compounding factors like anthropogenic climate change and local water and land management practices and policies within an inherently linked human-nature system (AghaKouchak et al. 2021; Dale 1997; Hagenlocher et al. 2023; Van Loon et al. 2016; Wens et al. 2019).

Recent notions of anthropogenic drought (AghaKouchak et al. 2021) define drought as a multidimensional, multi-scale phenomenon resulting from interactive processes between humans and nature (Pande and Sivapalan 2017; Rachunok and Fletcher 2023; Sivapalan et al. 2012). This understanding underscores the potential for anthropogenic droughts to trigger water bankruptcy in human-water systems (Madani et al. 2016), a trend anticipated to grow more prevalent amid current development paths and climate change trends. Addressing these complexities and fulfilling the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations 2015, 2019) necessitate a nexus approach that amalgamates diverse perspectives, leveraging new data and tools to advance drought monitoring while linking these insights to potential societal impacts (Hagenlocher et al. 2023). Since drought affects a broad range of environmental and societal factors, monitoring, better understanding, and preparing for drought (directly or indirectly) contribute to achieving a number of UN SDGs (UNDRR 2021) such as SDG 2 “zero hunger”, SDG 6 “clean water and sanitation”, SDG 11 “sustainable cities and communities”, SDG 13 “climate action”, and SDG 15 “life on land”. In fact, building and strengthening sustained cross-sectoral partnerships within a data-driven nexus framework for improved drought resilience, as described herein, is well-aligned with SDG 17 “partnerships for goals”. Overall, a holistic, data-driven nexus approach to drought is needed for developing and implementing informed disaster risk reduction strategies (Ward et al. 2020; Di Baldassarre et al. 2019) at local, regional, national, and transboundary scales, that will help achieve the UN SDGs in a variety of ways (e.g., supporting food security, ensuring water availability, reducing drought risks, improving response to the devastating effects of drought hazards, and combating desertification and water scarcity).

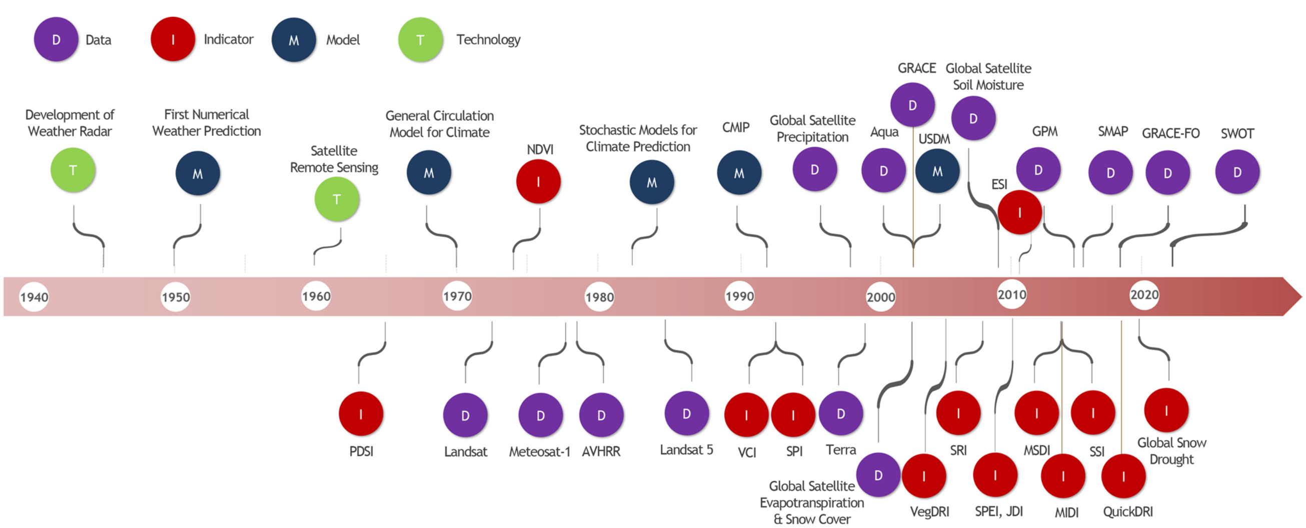

Fig. 1 A noncomprehensive timeline showcasing significant drought datasets (highlighted in purple), indicators (marked in red), advancements in models (depicted in blue), and technological innovations (highlighted in green). GPM: global precipitation measurement; AVHRR: advanced very high resolution radiometer; SWOT: surface water and ocean topography; SMAP: soil moisture active passive; GRACE-FO: gravity recovery and climate experiment follow-on; SPI: standardized precipitation index; SPEI: standardized precipitation-evapotranspiration index; NDVI: normalized difference vegetation index; PDSI: palmer drought severity index; VegDRI: vegetation drought response index; VCI: vegetation condition index; SRI: standardized runoff index; ESI: evaporative stress index; MSDI: multivariate standardized drought index; JDI: joint drought index; MIDI: microwave integrated drought index; QuickDRI: quick drought response index; SSI: standardized soil moisture index; USDM: the United States drought monitor; CMIP: Coupled Model Intercomparison Project (modified after AghaKouchak et al. 2023). (Color figure online)

2 The need for a nexus approach

A nexus approach to analyzing and monitoring drought can move us beyond a siloed mentality to more comprehensively address the UN SDGs. The complex and interdisciplinary nature of drought places it at the intersection of several fields including meteorology, climatology, hydrology, agronomy, and ecology as well as economics, sociology, public policy, and political science. Both the drought hazard and its impacts should therefore be treated as multidisciplinary, multisectoral issues (Rossi et al. 2023). The cause of a drought may originate in one sector, but its effects can be observed in various other sectors (Wilhite and Pulwarty 2014). This is important to keep in mind since droughts are commonly discussed categorically or as a deficit in a particular hydrologic state or set of states (Heim 2002) as mentioned above. Furthermore, the inclusion of human's role in drought is also critically important, yet it is often not accounted for in many drought studies and applications (Van Loon et al. 2016). To gain a holistic picture of drought as these moisture deficits propagate in space and time and to address drought impacts, a nexus approach (Brouwer et al. 2024) should be implemented. Cross-sectoral impacts will likely be amplified by climate change, so that the nexus approach becomes even more pertinent for comprehending cause-and-effect relationships and implementing associated adaptation and mitigation strategies.

Efforts dedicated to enhancing drought monitoring systems have predominantly concentrated on developing novel top-down drought indicators, encompassing climatic, hydrologic, and/or biophysical aspects, or on amalgamating indicators, data, and models. Indeed, over a decade ago, Zargar et al. (2011) reported that there were more than 100 drought indices. Yet, they continue to be developed to characterize this complex phenomenon and can often result in fragmentation of the overall hazard as well as its effects. Nevertheless, the limitations inherent in conventional drought indicators, especially in capturing interconnected hazards along with their systemic risks and repercussions, strongly advocate for the establishment of a coherent global framework for multifaceted drought monitoring and impact evaluation to facilitate preemptive actions (Pulwarty et al. 2020). Specifically, there is a pressing necessity to bridge drought information with its potential consequences—establishing a connection between monitoring tools and the collection and assessment of impacts (e.g., Bachmair et al. 2015; Blauhut et al. 2016). This concept is known as impact-based drought monitoring (AghaKouchak et al. 2023).

Present drought indicators (Fig. 1) and existing monitoring systems (e.g., the United States Drought Monitor) primarily focus on recognizing drought occurrences and appraising their characteristics, such as frequency, duration, spatial extent, and severity. Nonetheless, to make informed and actionable decisions, decision-makers need reliable and timely information about drought locations and intensities, as well as the projected repercussions associated with them (Sutanto et al. 2019, 2020). These repercussions encompass a broad spectrum of factors, including alterations in crop yields, soil health, food security and trade, water quality, forest conditions, greenhouse gas emissions, ecosystem health and biodiversity, energy generation, and unemployment arising from agricultural sector impacts.

To transcend the confines of drought monitoring and effectively gauge the potential effects of drought, better integrated existing models and/or additional new ones often become imperative. For example, there are numerous existing statistical and physically-grounded crop models tailored to predict crop yields subject to a diverse set of climatic scenarios or to analyze the dependency between crops and snowmelt, alongside their attendant risks (Anderson et al. 2016; Kuwayama et al. 2019; Madadgar et al. 2017; Peters-Lidard et al. 2021). However, such crop models still must be integrated into current drought monitoring systems to provide more holistic impact and early warning information.

Even regional droughts in significant food-producing nations can yield far-reaching worldwide impacts. As an example, snow droughts and shifting snowmelt patterns (timing and amount) can leave snowmelt-dependent agricultural regions experiencing a shortfall relative to the historically-used water sources for irrigation (Qin et al. 2020; Huning and AghaKouchak 2018, 2020). Namely, in the Hindu Kush Himalaya region, early snowmelt is projected under climate change, suggesting adverse consequences in downstream meltwater-dependent agricultural areas (Lutz et al. 2022; Nepal et al. 2021). In other words, many of the major agricultural basins around the world may need to meet the irrigation demand by turning to alternative sources of water, especially during drought periods and as temperatures continue to warm around the world (Lutz et al. 2022; Qin et al. 2020). This can have significant global implications as international trade reshapes the exposure of food supplies to changing snowmelt patterns, such that countries not receiving snow are actually exposed to the changing snowpack through the import of agricultural products (Qin et al. 2022). As another example at the intersection of society, human activities, and the natural system, anthropogenic drought accounts for the two-way interactions between humans and drought through the complex interplay of anthropogenic drivers (e.g., human-driven climate change, land use-land cover changes like agricultural development, and rising water consumption as populations expand and urbanization occurs) and natural drivers and hydrological processes (e.g., meteorological, agricultural, and hydrological drought) (AghaKouchak et al. 2021; Wens et al. 2019). The need for a nexus approach is further exemplified as drought can lead to conflict and transboundary issues over water. Drought can exacerbate existing civil unrest within a region as well (Di Baldassarre et al. 2018; Hoch et al. 2021; von Uexkull et al. 2016). Also, rapid succession of extreme events, such as drought followed by flood, strains our current systems and challenges management strategies that focus on a single hazard (Brunner et al. 2021; Matanó et al. 2022). Furthermore, drought risk management can affect other hazards such as flood and vice versa (Ward et al. 2020). These examples are only a few of those that highlight the need for a nexus approach, but also warrant impact-based drought monitoring and analysis (AghaKouchak et al. 2023).

3 The aid of analytics, informatics, and data (AID)

Both in-situ measurements and remote sensing observations (e.g., from satellites) help us monitor a variety of relevant variables (e.g., precipitation, snow water equivalent, soil moisture, streamflow, groundwater, reservoir water levels, vegetation health) for identifying and tracking drought, with some data sources having better temporal and spatial coverage and less uncertainty than others. When these data sets are combined with state-of-the art models, techniques, and resources (e.g., coupled land–atmosphere models, supercomputing, machine learning, data assimilation), significant advancements in drought monitoring have been made (Fig. 1) (e.g., AghaKouchak et al. 2015a, 2023; Balti et al. 2020; Hao et al. 2017, 2018; Alahacoon and Edirisinghe 2022). They also provide the foundation for further innovation and opportunities in drought research, forecasting, and applications. Despite the numerous observational and computational advances in drought monitoring of recent decades, many regions still do not have the access to reliable, timely data and analytics, informatics, and data (AID) tools for decision-making (United Nations 2023).

Out of the top 10 disasters resulting in the most fatalities from 1970 to 2019, an estimated 650,000 deaths resulted from droughts, which exceeds other disasters such as storms, floods, and extreme temperature (World Meteorological Organization 2021). In Africa, 95% of lives lost during this period from natural disasters were driven by drought, yet drought was not the most prevalent disaster to affect the region (World Meteorological Organization 2021). Therefore, it is critical to provide timely information about drought and early warning rooted in AID as well as reduce gaps in data and ensure access to AID tools, training, and infrastructure for people everywhere. Gaps in data and observational networks (e.g., weather observations across least developed nations and island developing states) stymie accurate and reliable early warning systems (World Meteorological Organization 2021; United Nations 2023). Hence, more reliable drought decision support data and tools are needed around the world.

With climate change-induced disasters on the rise, AID tools are fundamental parts of preparing for, monitoring, and addressing drought. For example, AID helps identify and characterize the onset, evolution, and termination of drought. AID also assists in monitoring drought's complex, manifold impacts and will garner the development of impact databases and impact monitoring (Wilhite et al. 2007). Overall, AID enables a quantitative understanding of drought and its effects. AID supports improved early warning systems, disaster risk reduction tools, and disaster management that all help save lives across the globe (United Nations 2023). Without effective communication, policy, and action, the potential power of AID would be undermined (Enenkel et al. 2015; Walker et al. 2022). Therefore, AID should guide discussion and action for innovations in drought monitoring, adaptation, and resilience.

4 Sustainability Nexus AID Programme: Drought

The Drought Module is part of the United Nations University (UNU) Sustainability Nexus Analytics, Informatics, and Data (AID) Programme (https://www.sustainabilityaid.net), which has the primary objective of bridging the gap between science and policy. The Sustainability Nexus AID Programme utilizes a problem-driven coupled or nexus approach to analyze human, natural, and built systems and address global challenges such as the UN SDGs within a data-driven and data-informed framework. To support decision-making and work toward more actionable science, an international network of both scientists and professionals who work at the interface of science, policy, and society is collaborating to address a variety of societally-relevant topics with AID, and in particular, as members of the UNU Sustainability Nexus AID Programme Drought Module team. Drought is only one of the current 15 AID modules (https://www.sustainabilityaid.net/modules), including Air Pollution, Biological Invasions, Flood, Food Security, Greenhouse Gas Emissions, Groundwater, Infrastructure Resilience, Landslides and Land Subsidence, Land Use-Land Cover Change, Sea Level Rise, Soil Health, Storms, Wetlands, and Wildfire.

The vision for the Drought Module within the UNU Sustainability Nexus AID Programme is to synergize efforts with other modules to advance drought monitoring, particularly at the intersection of various fields. Our primary focus is on establishing robust connections between drought occurrences and their tangible impacts. Emphasizing collaboration and interdisciplinary approaches, the Drought Module aims to work in tandem with other modules within the programme. By engaging with fields such as groundwater, soil health, flood management, food security, land use-land cover change, land subsidence, air pollution, and other critical domains, the drought team seeks to create a cohesive approach that bridges scientific understanding with policy and societal needs. Through this collaborative effort, we aspire to enhance the comprehensiveness and effectiveness of drought monitoring, aligning it with the overarching goal of the UNU Sustainability Nexus AID Programme—to address global challenges through a data-driven and problem-focused approach.

The Drought Module team of the UNU Sustainability Nexus AID Programme has compiled various drought and drought-related datasets and tools that are available through: https://www.sustainabilityaid.net/drought. These include some of the most common ways to assess drought using various standardized indices, such as the standardized precipitation index (SPI), standardized soil moisture index (SSI), standardized groundwater level index (SGI), standardized runoff index (SRI), standardized relative humidity index (SRHI), standardized snow water equivalent index (SWEI), etc. We will continue to expand the scope of the content to encompass emerging, updated, or innovative and mature data so as to facilitate a more direct avenue for translating science into action. As such, one goal of the AID Drought Module is to serve as an important step toward unifying the drought community and intersecting fields by providing resources for researchers, stakeholders, and decision-makers in a "one stop shop" for drought-related information, which may be usable for a variety of stakeholder applications. This compilation of drought information and data should be particularly useful for individuals who are unfamiliar with the multitude of drought-related data and tools currently available, but also more experienced individuals should find convenience in the compilation of resources that this module provides to all users. In addition, the AID Drought Module can support the efforts of different UN and intergovernmental agencies by providing drought information that can ultimately assist decision-makers to better understand and act on risk associated with drought and related disasters around the world as communities work to become more resilient to climate change.

5 A set of evolving drought AID tools

Similar to the overarching AID Programme, the Drought AID module aims to facilitate information and data exchange among researchers, policymakers, water managers and various stakeholders at all levels, etc., which thereby supports resource management within the complex and varied coupled human-environmental systems that drought (directly or indirectly) influences across the globe (Fig. 2). As increasing amounts of drought-relevant observations and data are collected, it is not sufficient to simply collect and store the data; rather, data must be made accessible so that it can be extracted, truly harnessed through analysis, and ultimately, used in practical applications. Therefore, the drought AID tools serve as a compilation of existing drought-related data and information that aims to facilitate a better understanding of drought. Although this compilation will be updated based on community feedback, it is not meant to be a comprehensive collection of all drought models and tools. Instead of providing a lengthy description of each of the AID drought resources, we refer the reader to https://www.sustainabilityaid.net/drought.

6 The way forward

Identifying, monitoring, and characterizing droughts remain challenging tasks given the complexity of the phenomena. Additional challenges arise when analyzing drought in the form of potential mismatches between the spatiotemporal resolution of available data and how that aligns with stakeholder and application needs (e.g., operational/management-relevant scales) (Rossi et al. 2023). Although a variety of methods exist for merging different data streams together, this inherently is a non-trivial task and often done on a case-by-case basis. Furthermore, the integration of both human and natural factors along with socioeconomic and environmental impacts remains an important consideration for modeling and assessing drought so that these factors and their interactions, as well as cascading impacts, are incorporated into well-informed decisions. These are critical factors for addressing drought in both the global north and the global south.

To better understand and prepare for the impacts of drought, we must also assess hazard, exposure, and vulnerability as integral components of the drought risk and they are also key elements of working toward more drought-resilient communities. In fact, studies in these areas are needed for the development of disaster risk reduction strategies and policies that are critical for addressing the UN SDGs and the UN Sendai Framework for Disaster Risk Reduction (UNDRR 2015). While drought data, tools, and research are important, it is also vital to build capacity so that people around the world are equipped with the knowledge, skills, and infrastructure to effectively interpret and use various data, models, and tools in their decision-making and applications. We therefore encourage experts in the community to interact with the UNU Drought AID team and help engage stakeholders by developing drought AID tools and capacity

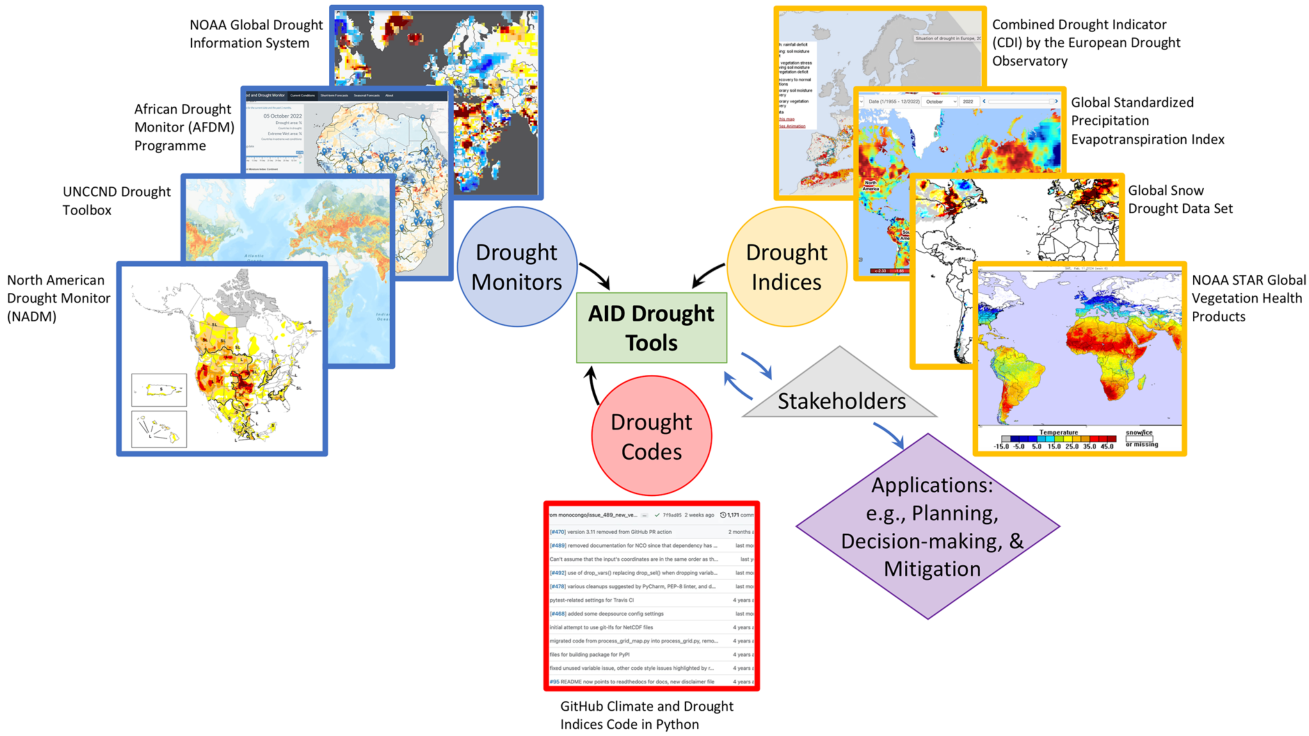

Fig. 2 Schematic depicting sample drought AID tools, including drought monitors/models (blue), indices (yellow), and codes (red). The evolving AID tools in the UNU Sustainability Nexus AID Programme will be updated based on community feedback to provide information for various stakeholder applications. (Color figure online)

building materials that will support actionable science and informed decisions related to drought and its manifold impacts around the world.

Despite the devastating and pressing effects of droughts and their cascading impacts, droughts often do not receive proportionate attention with environmental hazards having direct and rapid visible ramifications (e.g., floods, hurricanes, earthquakes) (Funk and Shukla 2020; Teutschbein et al. 2023a). Also, there is a rising need for more effective drought management practices in a warming climate (Wilhite et al. 2014). So, while there have been recent advancements related to topics such as snow drought, flash drought, compound events (e.g., hot droughts), and anthropogenic droughts, opportunities to better understand such phenomena and incorporate them into management practices are warranted. In addition, the drought community would benefit from global databases to track drought information related to the hazard and its impacts, which aligns with the Sustainability Nexus AID Programme's mission.

To translate drought research, data, and analysis into actionable science, there should be a paradigm shift to perform impact-based drought monitoring as well. With this in mind, we can glean additional insight from bottom-up, top-down, and hybrid approaches (e.g., Mehran et al. 2015) targeted for actionable and informed decision-making. Also, detailed, exploratory, and physically-based analysis that involves existing and/or emerging techniques, such as machine learning, artificial intelligence, and data mining, that are relatively new to drought monitoring should be investigated to gain an improved understanding of this complex phenomenon, and better predict, monitor, and mitigate drought and its impacts.

Additional insight into droughts as they propagate and their impacts cascade in space and time will also be important as communities prepare for future droughts (Rossi et al. 2023). One way to work toward this is by developing and implementing unified monitoring and assessment approaches for droughts. Universally-accepted methods and frameworks would facilitate a better understanding of drought conditions for people around the world. It would also aid in the interpretation of drought-related characteristics across the globe so that one region may garner insight from lessons learned in another area and knowledge transfer is facilitated.

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Declarations

Conflict of interest Coauthor is member of the editorial board/guest editor.

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