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Priority questions in multidisciplinary drought research

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ABSTRACT: Addressing timely and relevant questions across a multitude of spatio-temporal scales, state-of-the-art interdisciplinary drought research will likely increase in importance under projected climate change. Given the complexity of the various direct and indirect causes and consequences of a drier world, scientific tasks need to be coordinated efficiently. Drought-related research endeavors ranging from individual projects to global initiatives therefore require prioritization. Here, we present 60 priority questions for optimizing future drought research. This topical catalogue reflects the experience of 65 scholars from 21 countries and almost 20 fields of research in both natural sciences and the humanities. The set of drought-related questions primarily covers drought monitoring, impacts, forecasting, climatology, adaptation, as well as planning and policy. The questions highlight the increasingly important role of remote sensing techniques in drought monitoring, importance of drought forecasting and understanding the relationships between drought parameters and drought impacts, but also challenges of drought adaptation and preparedness policies.

KEY WORDS: Drought climatology · Climate change · Drought monitoring · Drought forecasting · Drought adaptation · Drought planning · Drought mitigation

1. INTRODUCTION

Among climate variables, drought has had the largest adverse impacts for mankind throughout history. Examples of severe harvest failures and famines are abundant (Ljungqvist 2017) and include the collapse of the Akkadian Empire in the Middle East ca. 4200 yr ago (Anderson et al. 2007) or the medieval 'mega-droughts' hitting Classic Maya Civilization (Douglas et al. 2016) and the Ancestral Pueblo culture (Bocinsky & Kohler 2014) in today's Mexico and the US. More recent examples include the Little Ice Age monsoon failures that caused famines with countless deaths in China (Yang et al. 2014), India (Sinha et al. 2011), and Southeast Asia (Buckley et al. 2010) and the El Niño-related droughts that caused tens of millions of famine-related deaths in the late 19th century (Davis 2001). During the period

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1995–2015, droughts affected over 1 billion people (CRED & UNISDR 2016), which more than justifies research addressing future droughts and their potential impacts.

Research on droughts is interdisciplinary, requiring meteorological, climatological, hydrological, modeling, and socio-economic expertise (Wilhite 2000). Thus, drought research covers a wide range of topics, including coupled atmosphere–ocean mechanisms and processes (e.g. García-Herrera et al. 2007, Barlow 2012); observations of the spatio-temporal variability and trends in drought frequency and severity (Hoerling et al. 2012, Sheffield et al. 2012, Spinoni et al. 2015, Ljungqvist et al. 2016); and impacts on agriculture (Lobell et al. 2015, Lesk et al. 2016), hydrology (Fleig et al. 2006), the environment (Nicholson et al. 1998, Ciais et al. 2005, Allen et al. 2010, Camarero et al. 2013), public health and famine (Mortimore 1989, Nathan et al. 1996, Haile 2005), power generation (Beniston 2012, Jerez et al. 2013), and transportation (Marengo et al. 2011).

Understanding the indispensable role of drought proxy data (e.g. tree rings, historical documents, speleothems, and lake sediments) is critical, as the drought frequency in records is relatively low and instrumental data records can be too short. Thus, studies have identified the variable spatial and temporal severity of drought in different regions using paleoclimatic records (E. Cook et al. 1999, 2010, 2015, Pfister et al. 2006, Esper et al. 2007, Büntgen et al. 2010, Camuffo et al. 2010, Domínguez-Castro et al. 2012, Brázdil et al. 2013, B. Cook et al. 2014, Smerdon et al. 2017), which allow a better understanding of drought severity in a historical context.

Uncertainties exist in recent drought severity trends (Vicente-Serrano et al. 2014, Van Loon et al. 2016). The last AR5 IPCC (Hartmann 2015) report stated a medium level of confidence in drought trends at the global scale because of the large data and model uncertainties associated with objective drought quantification (e.g. Seneviratne et al. 2012, Trenberth et al. 2014). Some recent studies (Sheffield et al. 2012, Greve et al. 2014, Nasrollahi et al. 2015) indicate that the 'wet-getting-wetter and dry-getting-drier' paradigm (Held & Soden 2006) is too simplistic and that drought-related changes might be more complex during global warming than previously thought (Ljungqvist et al. 2016).

Independent of recent global-scale drought trends, evidence of increased drought severity exists in different regions as a consequence of precipitation decreases (e.g. Hoerling et al. 2012) and/or increased atmospheric evaporation (Vicente-Serrano et al. 2014, Trnka et al. 2015). These trends, in combination with increased societal vulnerability, have led to a noticeable increase in drought-related societal impacts (Meehl et al. 2000, Lesk et al. 2016). The environmental impacts of droughts have also increased and are attributed to the enhancement of drought severity by climate change (Breshears et al. 2005, van Mantgem et al. 2009, Allen et al. 2010, Brázdil et al. 2015). Therefore, improving our understanding of the resistance, resilience, and vulnerability of different economic sectors under current and future climate scenarios is important. In-depth research of drought phenomena will improve the planning and societal responses to drought (Wilhite 1991). Prior drought research has led to improved drought monitoring and early warning systems (Svoboda et al. 2002), reducing ecosystem vulnerability via management strategies (López et al. 2009) and introduction of cropping systems, crops, and cultivars with high drought resilience (Olesen et al. 2011).

What are the important questions and challenges related to future drought studies and projects? Here, we present the outcomes of focus group discussions of experts from various sectors and disciplines in order to identify a set of priority questions in multidisciplinary drought research. This methodological approach has been applied to advance the field of multiple disciplines (Sutherland et al. 2006, 2009, 2011, 2013, Pretty et al. 2010, Grierson et al. 2011, Petrokofsky et al. 2013, Walzer et al. 2013, Seddon et al. 2014, Armstrong et al. 2017). Most of these studies initiated discussion amongst researchers, but more importantly 'mapped' knowledge gaps, which is particularly important for stakeholders and funders. To serve a similar purpose, we present a synthesis of drought-related workshops held at the Global Change Research Institute, Czech Academy of Sciences, which have provided 60 priority research questions to guide future scientific efforts.

2. MATERIALS AND METHODS

At the first Global Change Research Institute workshop in July 2014, a questionnaire and a set of instructions were developed (see Supplement 1 at www.int-res.com/articles/suppl/c075p241_supp/) along with the work plan (Fig. 1) to foster the formulation of research questions, and an open application process followed. The authors contacted research organizations and individual researchers by email, asking them to contribute to the study based on their past publication record or current work on drought-

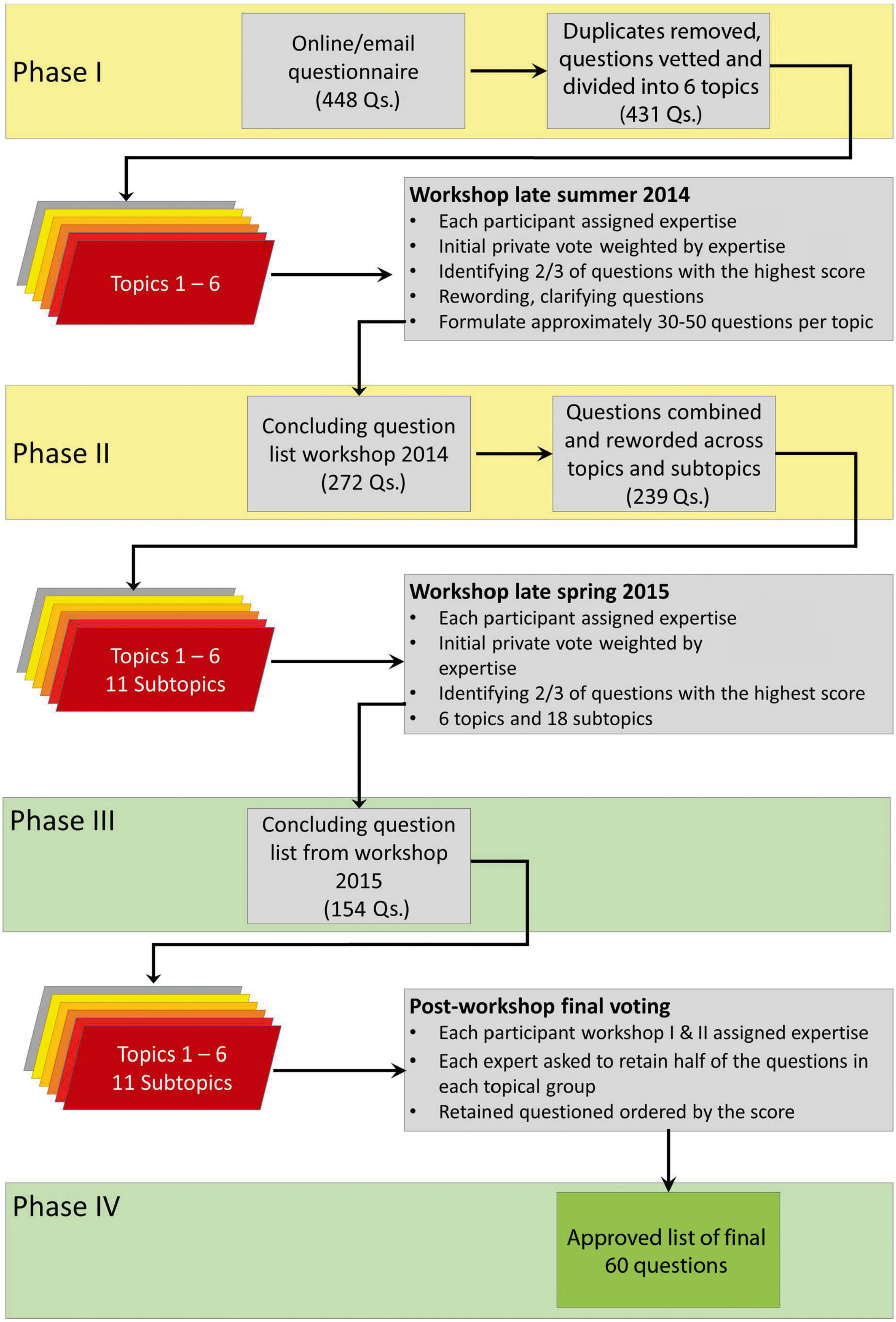


Fig. 1. Schematic overview of the procedure used to reduce 448 submitted questions to the final 60 highest-priority questions in interdisciplinary drought research

related issues. The authors attempted to ensure the disciplinary and geographical representativeness of the participants. The contacted researchers/organizations were encouraged to disseminate the questionnaire to partner organizations over a period of 2 months. This approach followed a modified chain referral method to strategically identify participants for the questionnaire (Penrod et al. 2003, Sutherland et al. 2011). The questionnaires were screened by the lead author to determine the clarity of the proposed questions, and the participants were contacted for amendments when necessary. Phase I (Fig. 1) resulted in 448 questions, which were submitted during June–August 2014, either directly during the workshop or online from 65 individuals, research institutes, and organizations in 21 countries across Europe, Asia, Australia, and the Americas, along with several drought researchers actively focusing on Africa. The 448 questions were screened by the 4 lead authors for redundancy, and the number of questions was reduced to 431. The 431 questions were then divided into 6 topics (Table 1). In the Phase I, each expert who contributed research questions was asked to identify two-thirds of the questions as 'higher priority.' This process resulted in a set of 272 questions. During Phase II, the remaining questions were compared by the first 4 authors for content, and semantically similar questions were reformulated and merged, which decreased the number of questions to 239. The questions that were similar were combined, and the language and clarity of the questions were reviewed by the 4 lead authors. In Phase III, the 239 questions were evaluated by a panel of 18 experts during the second drought workshop in June 2015 using a 6-point scale. Their responses to each question were made comparable by standardizing the total number of points given by each expert to the median of all the experts to maintain approximate parity among the panel members.

Because the questions represented a fairly broad range of research fields, the expertise of each expert was considered and double weight was given to

Table 1. Research topics and subtopics with the numbers of questions in the individual phases. The sequence of the phases for prioritizing research questions can be seen in Fig. 1, and includes Phase I: collation of all questions with simple redundancy check; Phase II: first round of question ranking with 2/3 of questions retained and combined, questions organized according to topic; Phase III: second round of ranking with 2/3 of questions retained, subtopics introduced; Phase IV: final voting to determine the top 60 questions

Topic	Subtopics	Phase I	Phase II	Phase III	Phase IV final questions
1. Drought monitoring		–	48	28	7
	Monitoring drought severity, frequency, and duration	–	–	8	3
	Understanding user applications of drought monitoring tools	–	–	20	4
2. Drought impacts		–	76	56	19
	Overall	–	–	23	7
	Crops and plants	–	–	21	6
	Trees and forests	–	–	8	2
	Socio-economic impacts	–	–	4	4
3. Drought forecasting and prediction		–	19	10	3
4. Drought climatology		–	38	17	15
	Climatology and paleoclimatology	–	–	10	9
	Climate change	–	–	7	6
5. Adaptation strategies for drought		–	40	36	12
6. Drought planning and policy		–	18	7	4
In total		431[a]	239[b]	154	60

[a]The list of 431 questions was obtained by removing redundant ones from the original set of 448 questions
[b]The list of 239 questions was obtained by combining and rewording the original set of 272 questions

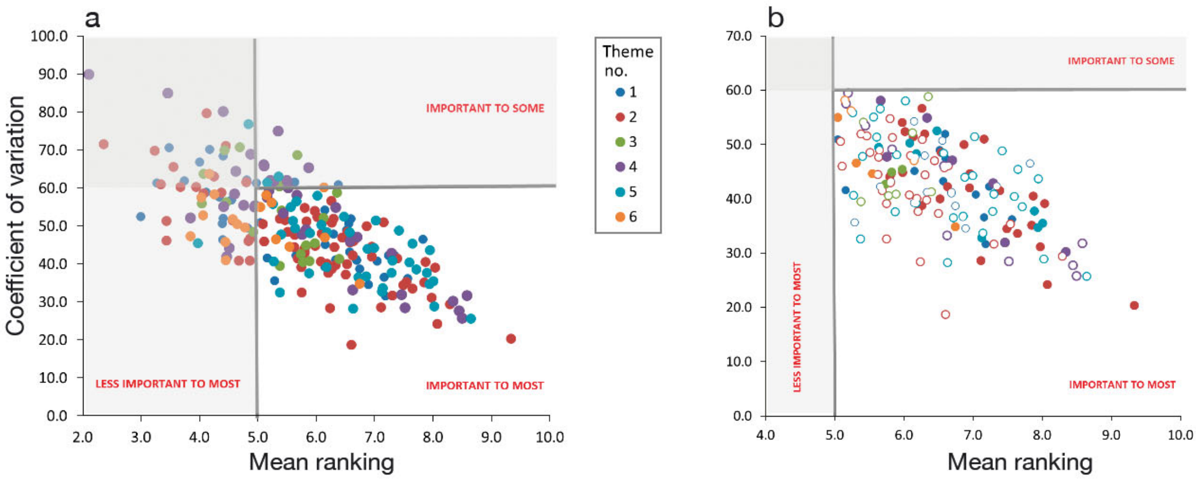


Fig. 2. (a) Scoring results of the individual questions after normalization and weighting by expertise. 1: Drought monitoring; 2: Drought impacts; 3: Drought forecasting; 4: Drought climatology; 5: Adaptation to drought; 6: Drought planning and policy. The shading shows questions that were not considered further based on the mean ranking of the responses and coefficient of variation. (b) Original scoring of set of 154 questions in Phase III. The questions that were most frequently retained are left as solid colors and represent the final set of 60 questions. The open dots represent questions that were considered less important within the given theme

questions related to their self-selected research strengths compared to those related to other subtopics. The top scoring 154 questions were selected (see Supplement 4) by participants of the 2015 workshop. During Phase IV in early 2016, the experts involved in any of the previous phases were asked a final time to identify half of the questions within each theme that they considered 'top priority' and to remove the rest. In all phases, senior researchers (lab leaders, professors, etc.) dominated the field of experts; however, several accomplished younger researchers with 6–10 yr of research experience were also among the group. Based on their evaluation, the final list of 60 questions was compiled based on the priority ranking during Phase IV. These questions are identified in the text by reference to their number (e.g. [Q1]) and are not ranked but rather grouped thematically.

Fig. 1 and Table 1 show how the number of questions was refined through each of the individual phases during the evaluation process. In Phase I, the number of questions was reduced by approximately 45% and grouped into individual main topics. The scores and their coefficients of variation (Fig. 2) show that the majority of questions were considered important across themes (i.e. experts with various fields of expertise considered similar questions to be important). A lower ranking of questions in comparison with other themes only occurred in the 'Drought planning and policy' topic. Although experts in 'drought policy' ranked other themes relatively high (and considered them important as crucial inputs to proper drought policies), the drought policy-related questions were not viewed as critically important by the majority of the other experts relative to the other themes. However, this imbalance was evened out in Phase IV, when more than half of the remaining questions were retained. The final set of 60 priority questions is presented in Box 1.

3. RESULTS AND DISCUSSION

3.1. Monitoring

Drought monitoring is a critical component for drought early warning systems and a key instrument in timely risk management and drought planning (WMO 2006, WMO & GWP 2016). However, the methods used by various countries for drought monitoring range from virtually no systematic monitoring, through simple drought indices (or even percentiles of precipitation) to complex process-based modeling tools. Few studies have analyzed the ability of different drought indices to identify impacts in a variety of sectors (e.g. Hlavinka et al. 2009, Vicente-Serrano et al. 2012, Bachmair et al. 2015, Stagge et al. 2015, Brázdil et al. 2016). Overall results show that drought indices calculated on different time scales can be successfully used in the identification of different impacts, but a critical need remains for understanding the pros and cons of available methods, as well as the pros and cons of simple versus complex modeling, for the wide variety of sectors and decision making [Q1].

Drought Monitoring

Severity, frequency, duration

Q1. Which indicators are most useful for multi-sectoral management of drought?

Q2. What new strategies and new drought monitoring techniques should be added into drought monitoring and early warning systems?

Q3. What improvements need to be made in various climate databases from regional- to local-scales so that hydrological droughts can be effectively monitored?

Improved monitoring

Q4. How can drought impacts be connected to remote sensing-derived indicators?

Q5. Can an effective indicator(s) of rapid-onset drought be developed using remote sensing?

Q6. How can the observational record of key satellite variables (e.g., NDVI) be extended into the future using observations from various satellite instruments?

Q7. What are the specific infrastructural needs for an effective drought early warning system?

Drought Impacts

General

Q8. What indicators are appropriate for linking with drought impacts?

Q9. What kinds of data on drought impacts are needed for decision-making?

Q10. How does vegetation respond differently to long-term, low-level drought compared to short episodes of intense drought?

Q11. What are the thresholds or tipping points for various drought impacts such as those related to bark beetle outbreaks/windstorms/snow breakage/fire as the most relevant disturbance agents?

Q12. How does drought affect ecosystem diversity and function?[a]

Q13. What is the best approach to drought vulnerability and impact assessment, and how can this aspect of drought preparedness be improved and systematized?

Q14. How are drought impacts modified by water management interventions and water supply systems?

Crops and Plants

Q15. How does drought impact regional agriculture, crop yield, and crop quality?

Q16. What are the different impacts of droughts on feed crops versus grasslands?

Q17. What are the effects of drought on pests, diseases, and weed pressures?

Q18. Which drought bio-indicators can be implemented to assess plant stress?

Q19. What are the effects of drought when combined with other crop stresses?

Q20. How does drought affect national food security?

Trees and Forests

Q21. Where are current droughts influencing forest ecosystem functioning and productivity?

Q22. How does resilience to drought events vary between different vegetation types?

Socio-Economic Impacts

Q23. What are the socio-economic implications of drought?

Q24. What is the impact of human activity on drought and the associated drought impacts?

Q25. How can the awareness of stakeholders be increased with regards to drought and its

Q26. What are the effects (both negative and positive) of drought on politics and politics on drought impacts/resilience?

Drought Forecasting and Prediction

Q27. How well have the current climate forecast systems done in predicting recent droughts over short to seasonal timescales?

Q28. What are the predictabilities of droughts, and are these regionally specific?

Q29. Can identification of teleconnections and multidecadal modulations improve the forecasting of local/regional drought?

Drought Climatology

General

Q30. What are the frequencies of large-scale droughts?

Q31. What are the typical durations of large-scale droughts?

Q32. What are the influences of decadal climate variability on drought occurrence?

Q33. Can the existing climate models and downscaling methods adequately simulate drought development (spatial and temporal) and characteristics (frequency, severity, and persistence)?

Q34. What are the impacts of atmospheric–land interactions on drought conditions?

Q35. What are the climate forcings/drivers, that are influencing the occurrence and severity of droughts and is their influence constant over time?

Q36. What is the relationship between seasonal short-term drought occurrence and large-scale climate variability (e.g., ENSO and East Asian monsoon)?

Q37. What are the influences of land use and land-use change on drought formation at regional scales?

Q38. Are we able to identify past "megadroughts" according to documentary sources and paleodata, and do any analogues from recent time periods (from the instrumental period) exist?

Drought and Climate Change

Q39. What is the level of confidence associated with assertions that recent changes in drought frequency and intensity were caused by human factors?

Q40. How can dynamical downscaling or higher resolution GCMs be used to improve drought projections?

Q41. What are the projections of future changes in drought occurrence, duration, and intensity using RCM simulations (East Asia, Europe, the whole world)?

Q42. Which drought index is better for evaluating the response of drought to climate change?

Q43. What are the effects of changing drought frequency/duration/severity on soils under climate change?

Q44. Does improving soil health with long-term strategies as a drought mitigation action reduce future drought impacts?

Adaptation Strategies for Drought

Q45. What are adequate indicators of drought resilience and how do we evaluate their validity?

Q46. How can regional drought vulnerability and resilience be determined?

Q47. How can the research and practitioner community improve the linkages between monitoring and early warning/forecasting and operational drought preparedness plans?

Q48. How might catchments (watersheds) be managed in an integrated manner to conserve water resources and allow for their use by a complete range of stakeholders?

Q49. What are successful adaptation options to drought impacts in different sectors (water management, agriculture and forestry, energy sector, etc…)?

Q50. What are the benefits of drought mitigation and drought planning?

Q51. How can drought management be incorporated into national risk management policies?

Q52. How can urban design help communities adapt to drought?

Q53. How can ecosystems be managed for increased drought resilience?

Q54. How can improving irrigation and farm management reduce future drought impacts?

Q55. What is the cost of irrigation development as an adaptation strategy to drought conditions?

Q56. Can we use maps of vulnerability to water stress to improve risk management?

Drought Planning and Policy

Q57. What are the linkages between indicators, appropriate triggers, impacts and the decisions that can be made in response to (and ideally within) a droughht plan?

Q58. How do agriculture and food-related policies contribute to or detract from drought resilience?

Q59. What are the most important factors for facilitating paradigm shifts in drought policy and management (e.g., from reactive to proactive)?

Q60. How do you best communicate and deal with uncertainty in future climate when planning for drought?

[a]This question helps with the understanding of responses and the degree of resilience of ecosystems to drought (including the effects of recent global warming)

Box 1. Overview of final set of 60 drought research priority questions divided into 6 topics

The development of new methods and their implementation to improve timely and effective decision making are also needed [Q2]. Additionally, new observation networks and technologies are needed to provide fresh information (e.g. Martínez-Fernández et al. 2016, Sánchez et al. 2016) for drought indices used in drought monitoring and management. Although numerous climate drought indices exist, the use of this information for hydrological drought monitoring in existing drought monitoring systems is usually non-direct and involves a separate set of indices (e.g. streamflow or snow pack data). The propagation of climatic droughts throughout the hydrological cycle is complex and depends on several factors, including lithology, water consumption, and water regulation (López-Moreno et al. 2009, Barker et al. 2016), among other factors, which makes it necessary to focus on the development of hydrological drought indices. An excellent example is the water status index developed for drought monitoring at the basin scale in Spain (Andreu et al. 2015), illustrating the potential for developing hydrological drought indices [Q3].

Drought monitoring based on Earth observation data has advanced since the 1980s, when the first high temporal resolution satellite imagery became available. Drought monitoring applications using remote sensing technologies evolve rapidly (Hayes et al. 2012), leading to products such as new soil moisture estimations (Sánchez et al. 2016). Here, the critical question of connecting remote sensing-derived drought monitoring to impacts resonates in [Q4], while the search for an early identification of drought onset is the focus of [Q5]. Currently, satellite data time series used for drought monitoring (e.g. that of the Advanced Very High Resolution Radiometer) span more than 2 decades. As satellite technologies improve, challenges associated with data continuity arise since newer sensors often have spatial, temporal, and radiometric characteristics that are inconsistent with those of earlier sensors. Research into transitioning between technologies involved in constructing long-term satellite records remains a high priority [Q6]. Equally important is the development of spatial fusion techniques that can be used to achieve high spatial resolutions (e.g. as shown in Fig. 3). However, this merged information is not yet ready for operational use in drought monitoring.

As a new generation of satellites with a multitude of more accurate and higher-resolution sensors (e.g. hyperspectral or microwave radar) becomes available, the development of associated infrastructure (e.g. to address the sheer volume of data and calculation time) is important [Q7] to many respondents.

3.2. Impacts

Although droughts often have a large spatial extent and affect many regions and sectors, the hardships caused by drought are local and primarily defined by the impacts on a local region and sector. Therefore, considerable attention is paid to addressing the question of drought impacts and the building of drought impact archives (e.g. Wilhite et al. 2007, Stahl et al. 2012, 2016, Blauhut et al. 2016). Linking particular drought indicators with drought impacts is considered a critical question [Q8] that needs to be better addressed, and one aspect of the question is whether a single indicator should be used to estimate various types of impacts or whether different drought indices are necessary to identify drought impacts in different sectors and territories. As a representative example, different studies have used the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010) to estimate the impacts on crop yields (e.g. Potopová et al. 2015, Wang et al. 2016), hydrological drought (e.g. López-Moreno et al. 2013, Barker et al. 2016), forest growth decline (Camarero et al. 2013), desertification processes (Vicente-Serrano et al. 2012b), or even multiple sectors at once (e.g. Vicente-Serrano et al. 2011a, Blauhut et al. 2016). However, the SPEI is not typically produced at local spatial scales. Even more importantly, identifying the most relevant impact data is critical for effective decision making [Q9]. Drought is a multifaceted extreme event with various durations. For instance, events can last a season, several years, or several decades, whereas so-called 'flash droughts' are much shorter (Hunt et al. 2014). The time dimension needs to be considered when drought impacts are assessed [Q10] and combined with proper knowledge of the 'tipping' points of specific societies and ecosystems (Fernald et al. 2015, Reyer et al. 2015, Huang et al. 2016) [Q11]. The cumulative drought impact is a function of not only the drought intensity and duration but also the ecosystem resilience and vulnerability, which need to be better understood [Q12–13] since the response of natural vegetation to drought is varied both in terms of resistance (Vicente-Serrano et al. 2013, Ivits et al. 2016) and resilience (Gazol et al. 2017). The impact of human activity on drought occurrence and impacts is particularly obvious in the area of water management, in which the frequency and patterns of drought are purposefully modified to suit human needs (e.g. Fig. 4) [Q14].

Agriculture and forestry have known sensitivities to drought both globally (e.g. Lesk et al. 2016) and regionally (e.g. in 2012) (Rippey 2015), and there is more to learn [Q15], including differences in drought

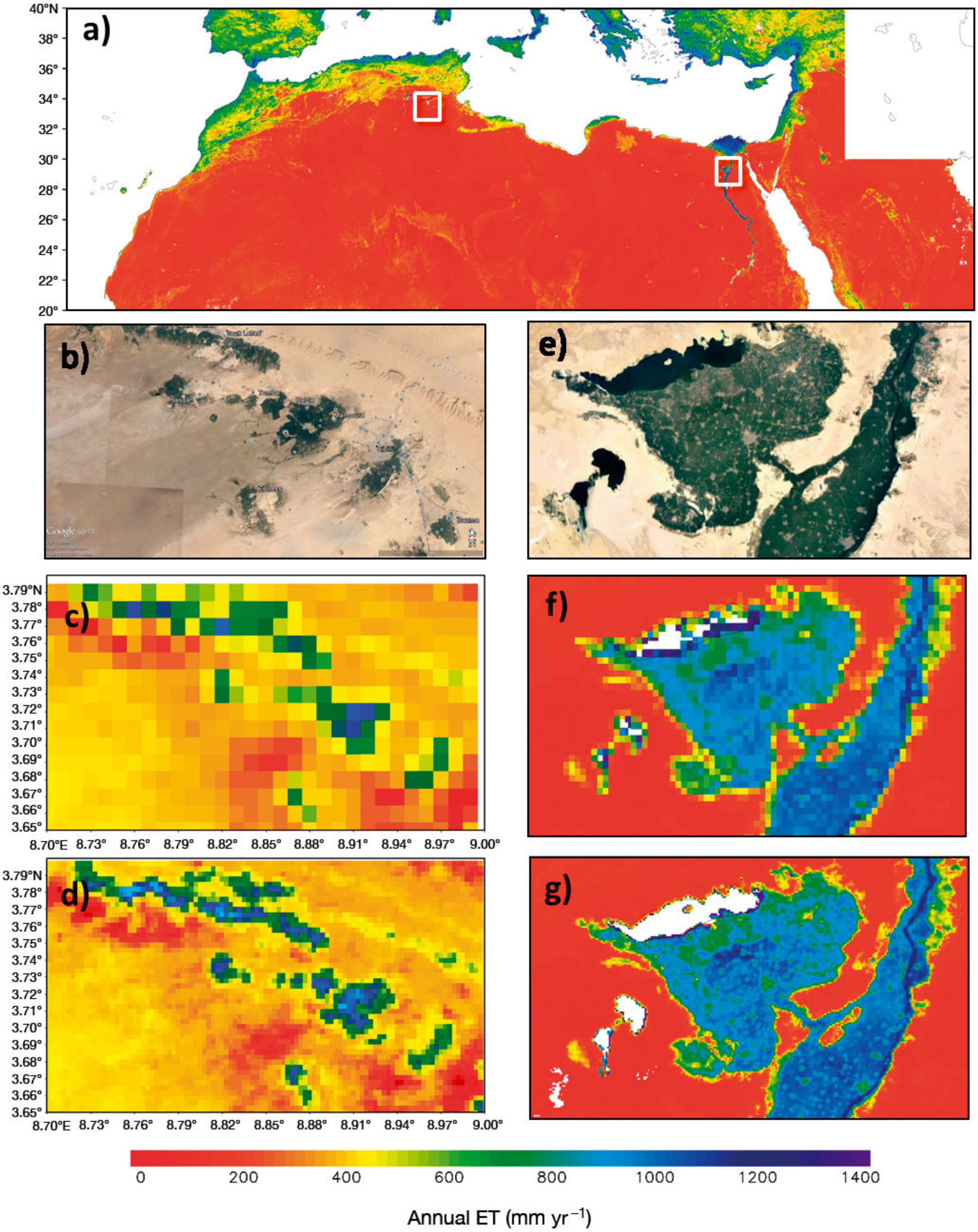
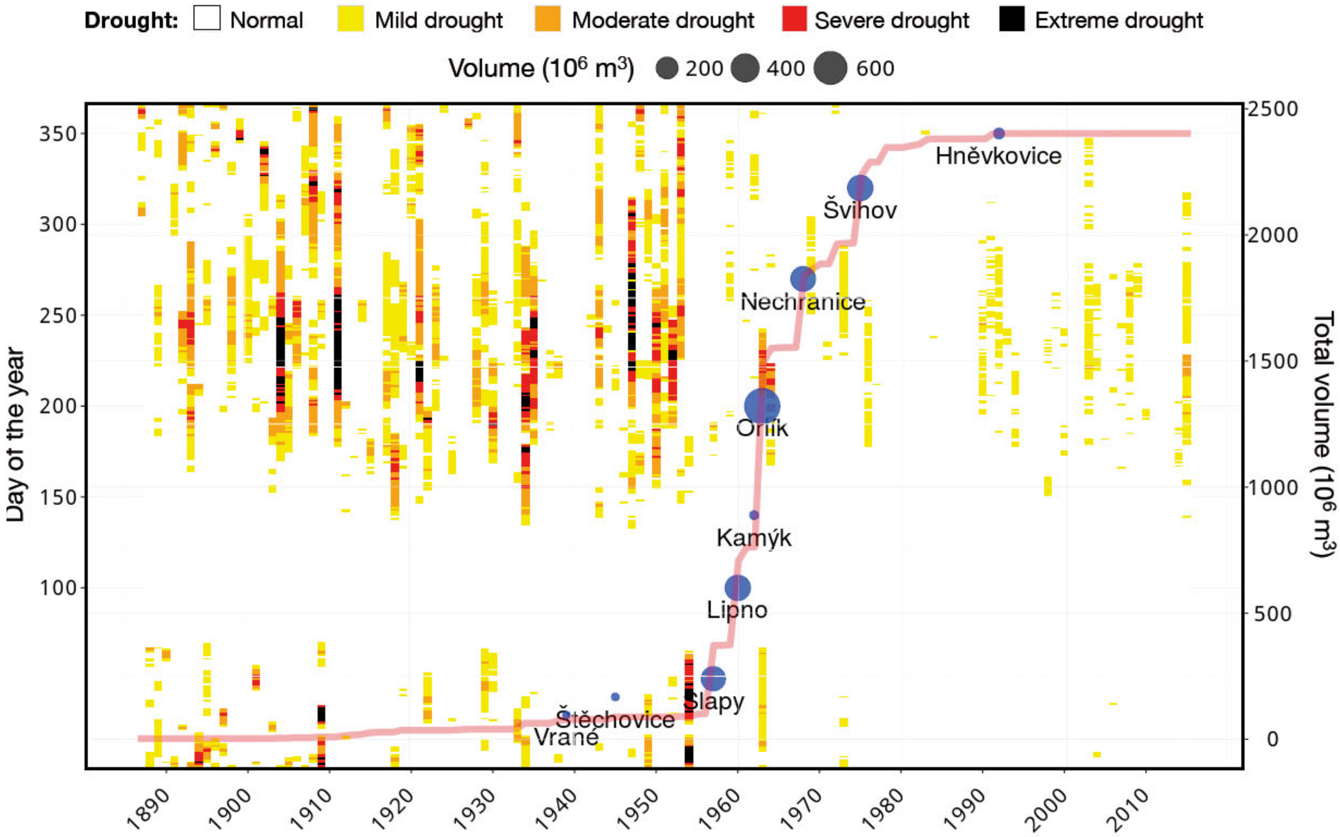


Fig. 3. (a) Examples of changing annual actual evapotranspiration (ET) based on different sensor characteristics and impacts on drought monitoring in northern Africa. White area (top-right) was not processed. The left white square represents pilot area: the Chott el Djerit basin in Tunisia depicted in detail at (b)–(d); the right white square shows the ancient Fajum Oasis (Egypt) depicted in detail at (e)–(g); the VIIRS sensor (d,g) is the successor to MODIS (c,f) and provides significantly higher spatial resolution in the thermal band used for mapping water use and crop stress. However, it is difficult to effectively exploit this higher resolution in anomaly products given that the baseline (normal) conditions must be determined from the lower-resolution MODIS data. Images in (b,e) from Google Earth



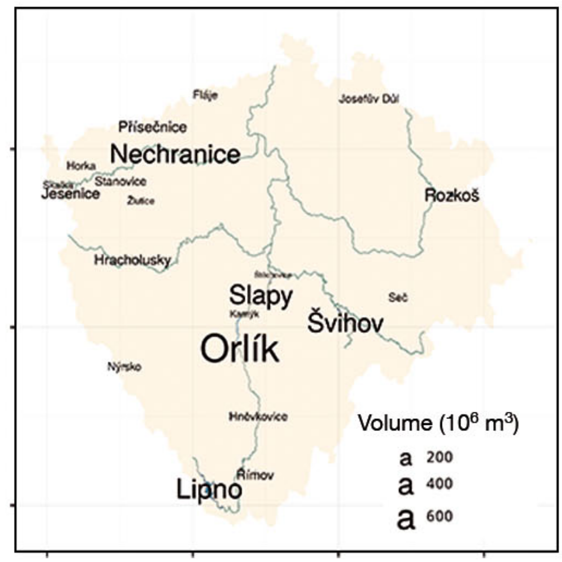


Fig. 4. Chronology of hydrological drought on the River Elbe at the Děčín station over the period 1888–2015, arranged with respect to various thresholds of daily discharge (above). A clear drop in drought frequency is apparent after 1950, when major upstream damming projects were completed. Blue spots represent the relative size of the reservoirs, and the pink line indicates the total volume dammed within the Elbe River catchment. An overview of the catchment with the location of the dams is shown on the right

sensitivity related to agriculture type [Q16]. The drought–yield relationship is modulated by a number of factors, including the pests, diseases or weed pressure [Q17], and need exists to separate drought from other influencing factors [Q18] and to understand feedbacks between drought and other adverse factors negatively affecting crops [Q19]. The combined effects of drought and warming are known to reduce global crop production (Lobell et al. 2013, 2014). The close relationship between drought and other confounding factors is illustrated in Fig. 5, which shows a marked increase in the sensitivity of wheat to high temperatures during anthesis under drought conditions (K. Klem et al. pers. comm.). This relationship is important given the projected increase in drought occurrence/intensity under projected future climate

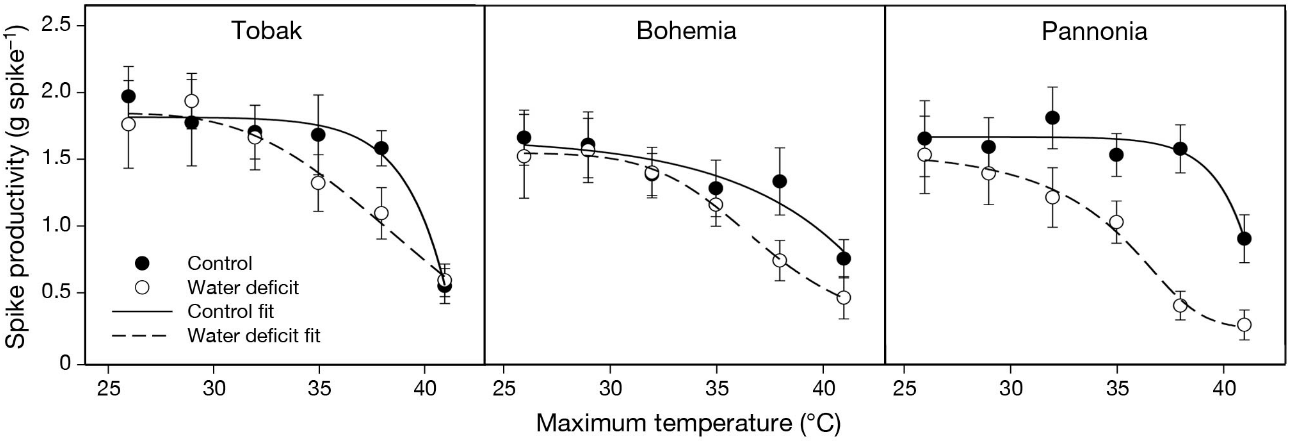


Fig. 5. Compiled results of recent growth chamber experiments showing the amplifying effect of drought on the wheat spike weight and demonstrating the crucial role of drought in wheat sensitivity to heat stress during anthesis. The significant difference in the response among the 3 cultivars ('Tobak,' 'Bohemia,' and 'Pannonia') indicates that varying coping strategies for different adaptations should be taken into account

conditions (e.g. Dai 2013, Feng et al. 2017). Drought has affected global food production over the past decade (e.g. Lobell et al. 2011), and the link between drought and food security ranks high among the priority questions [Q20].

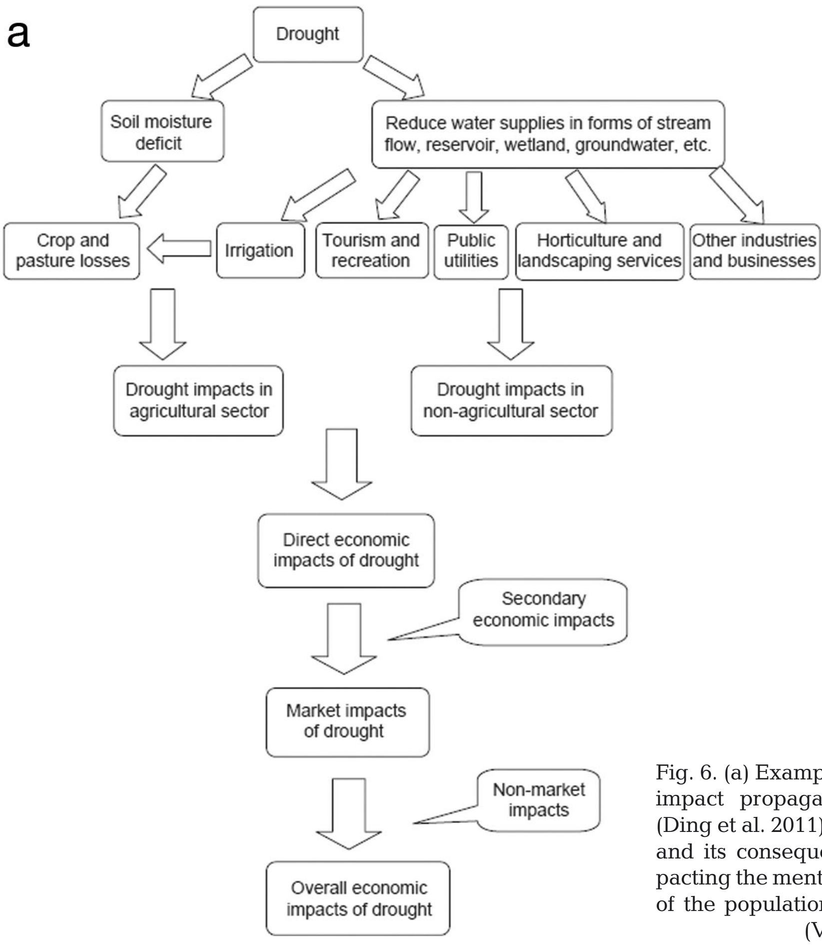
In addition to the provisioning of food, the ecosystem services provided by forest ecosystems and forest productivity need to be addressed [Q21], as large uncertainties are associated with future forest growth in climate scenarios characterized by more severe and more frequent drought events (Williams et al. 2013). Therefore, the knowledge of factors that determine forest resilience to drought should be deepened [Q22] because large differences exist at the global scale (Anderegg et al. 2015, Gazol et al. 2017).

Understanding and quantifying the socio-economic impacts of drought remain challenging. Therefore, the Integrated Drought Management Program has begun investigating the benefits of action and the costs of inaction in addressing this challenge (WMO & GWP 2017). The final set of questions within this thematic group relate to identifying the socioeconomic impacts in regions [Q23] and the relationships among these impacts and human activity and decision making [Q24]. Question [Q25] illustrates the challenge of enhancing stakeholder awareness to the different characteristics of droughts compared to other natural hazards. Understanding the linkages between drought impacts and policies was identified as an important question [Q26]. While the concept of drought impact propagation through the individual sectors has been discussed by various authors (e.g. Fig. 6a), further research is needed to understand all of the indirect effects that can result (Ding et al. 2011). A clear need also exists for quantitative studies that mine the available datasets and test existing concepts such as a recent study on seemingly unrelated mental health consequences of drought (Fig. 6b) (Vins et al. 2015).

3.3. Forecasting

While monitoring droughts and drought impacts are critical for efficient drought response [Q27], forecasting and prediction are key for any drought early warning system. Improved forecasting and prediction can assist the timely implementation of drought plans and provide information for targeting drought relief efforts (e.g. Enenkel et al. 2015) or improved farming (e.g. Tadesse et al. 2016). Early warning systems have been implemented in most developed economies (e.g. the National Integrated Drought Information System program in the US) in an effort to reduce costly damage. The forecast and prediction efforts take various forms, ranging from long-term forecasts (Fig. 7a: US drought outlook), through medium-term (Tadesse et al. 2010), to short-term high-resolution forecasts considering ensembles of numerical weather prediction models (Fig. 7b: Inter-Drought – 5 model maps).

Although the relationships between oceanic indices (e.g. El Niño–Southern Oscillation [ENSO] and the North Atlantic Oscillation) and droughts are reasonably well understood, the use of these indices to predict drought requires further research [Q28]. Advancing knowledge of the atmospheric mechanisms



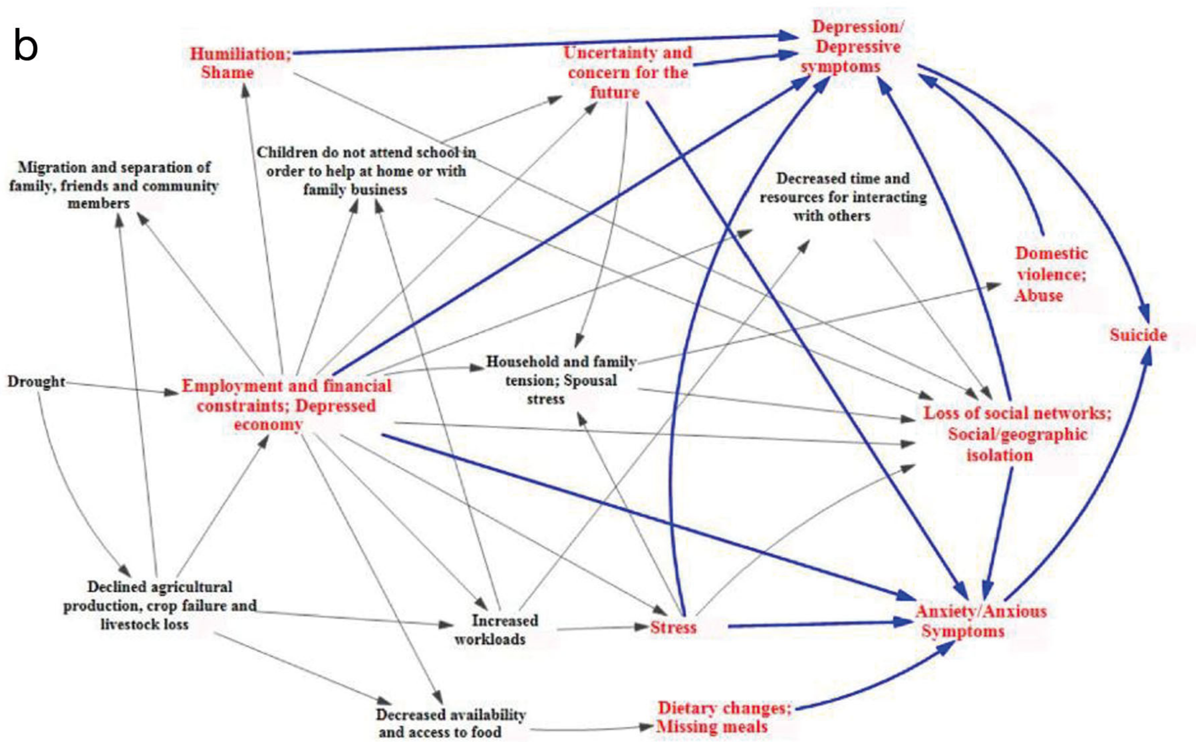


Fig. 6. (a) Example of conceptualized drought impact propagation through the economy (Ding et al. 2011) and (b) pathways of drought and its consequences (black and black) impacting the mental health and behaviour (red) of the population in a drought-affected area (Vins et al. 2015)

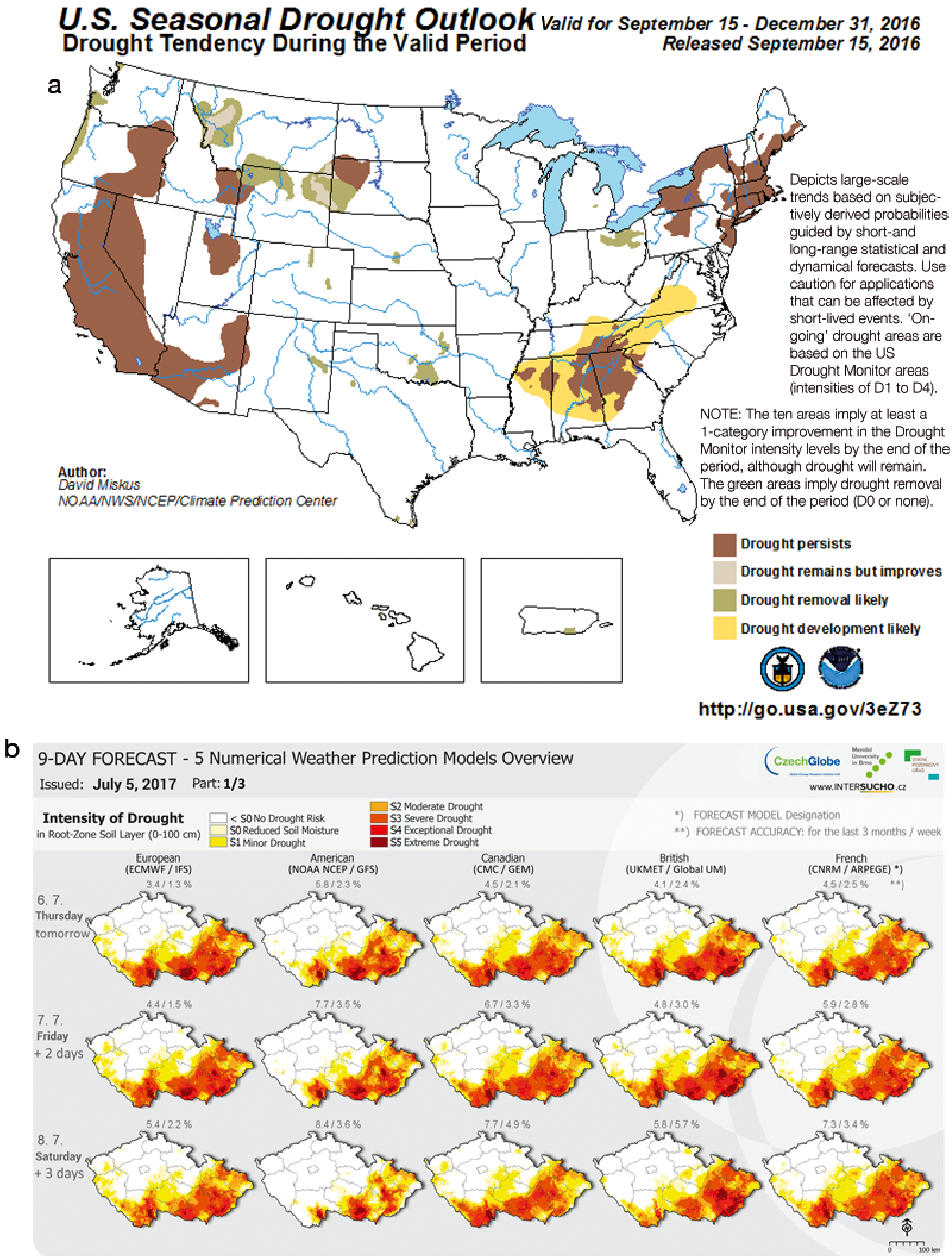


Fig. 7. (a) Example of a long-term 'continental-scale' drought forecast for the USA in comparison with (b) a high-resolution (500 × 500 m) short-term forecast using the ensemble of 5 numerical weather prediction models for the Czech Republic where forecast error (%) is also given for each

that control drought variability and severity could improve drought forecasting skill [Q29]. ENSO is one of the main drivers of climate variability at the global scale, and large areas of the world show a strong drought severity response to these events (Dai et al. 1998, Dai 2011, Vicente-Serrano et al. 2011a).

3.4. Climatology

Large-scale drought events affecting significant portions of a continent, such as the 2010 drought in Russia or the 2012 drought across the central US, highlight the need for enhanced preparedness for future droughts in terms of frequency [Q30], duration, extent, and termination [Q31] (Parry et al. 2016a,b). The recent drought in California (e.g. Seager et al. 2014) demonstrates that even advanced economies are vulnerable to long-term drought, because such events have multiple cascading societal consequences that are difficult to predict. In some regions of the world, drought occurrence has been linked to long-term temporal variability patterns, such as the Atlantic and Pacific multi-decadal oscillations (McCabe et al. 2004, Mohino et al. 2011, Oglesby et al. 2012). Therefore, being able to derive linkages between decadal climate variability and the occurrence of drought [Q32] and properly model drought [Q33] are needed to improve forecasts. Understanding the underlying physical processes requires an understanding of the influence of land–atmosphere interactions ([Q34], Lejeune et al. 2017). Climate forcings/drivers or large-scale climate phenomena (e.g. El Niño) need to be studied [Q35–36] for the same reason because they provide hints about the long-term predictability of drought risk (e.g. Nicolai-Shaw et al. 2016) or allow attribution of drought trends to particular forcings (Brázdil et al. 2015, Gudmundsson & Seneviratne 2016). Some examples (e.g. Davidson et al. 2012) urge researchers to decipher the relationships between drought formation and land-use changes [Q37]. On longer time scales, some researchers are concerned about 'mega-drought' events, such as the medieval 'mega-droughts' in the western US (Cook et al. 2004, 2007), and shorter but still extreme events, such as the 1540 drought in Europe (Wetter et al. 2014). A 12-century-long perspective of Northern Hemisphere hydroclimate anomalies was recently provided by Ljungqvist et al. (2016) (Fig. 8). Although this study did not focus on 'mega-droughts,' such large-scale studies (in terms of both area and time covered) are critical for our understanding of the potential for extraordinary events [Q38], the long-term variation in large-scale drought probability, and the drivers responsible for these events. Understanding drought teleconnections and past drought frequencies is also critical for supporting reported increases in the drought frequency/severity in some regions (e.g. Trnka et al. 2009, 2015, Vicente-Serrano et al. 2014) that have been attributed to climate changes [Q38]. Although some studies (e.g. Trigo et al. 2013, Brázdil et al. 2015) have provided fairly conclusive evidence that increases in drought frequency are linked to increasing CO_2 and no other known factor, this relationship remains to be quantified globally in a comprehensive way [Q39].

Assessing future changes in drought frequency and severity either via new methods of downscaling or higher-resolution global circulation models [Q40] and/or regional climate models [Q41] is also high on the agenda. The development of a new generation of climate models is considered especially important. In recent years, we have witnessed several debates (e.g. Dai 2011, Vicente-Serrano et al. 2011b, 2015, Hoerling et al. 2012, Beguería et al. 2014, Feng et al. 2017) centered around choosing the most appropriate drought index for assessing drought under changing climate conditions; the associated inconsistencies should be clarified [Q42]. Additionally, the drought risks associated with climate change caused by future carbon emissions should be quantified [Q43]. Moreover, the frequently recommended concept of improving soil health as a drought mitigation strategy remains to be objectively tested [Q44].

3.5. Adaptation

Acquiring the capability to enhance long-term drought resilience is a critical part of risk management strategies, as shown by the development of the National Integrated Drought Information System in the US. To promote risk management and to increase resilience, adequate indicators should be used, and their validity should be assessed [Q45]. Increasing local resilience requires a methodological framework to determine vulnerability and resilience [Q46]. Drought plans are viewed as an aspect of enhancing drought resilience (Wilhite et al. 2005). However, in the regions/countries where drought planning and drought monitoring are divided (e.g. between different ministries or governmental levels), the linkages between these 2 critical components of the drought response system should be improved [Q47]. It remains to be seen how much of eventual conflicts might be re-

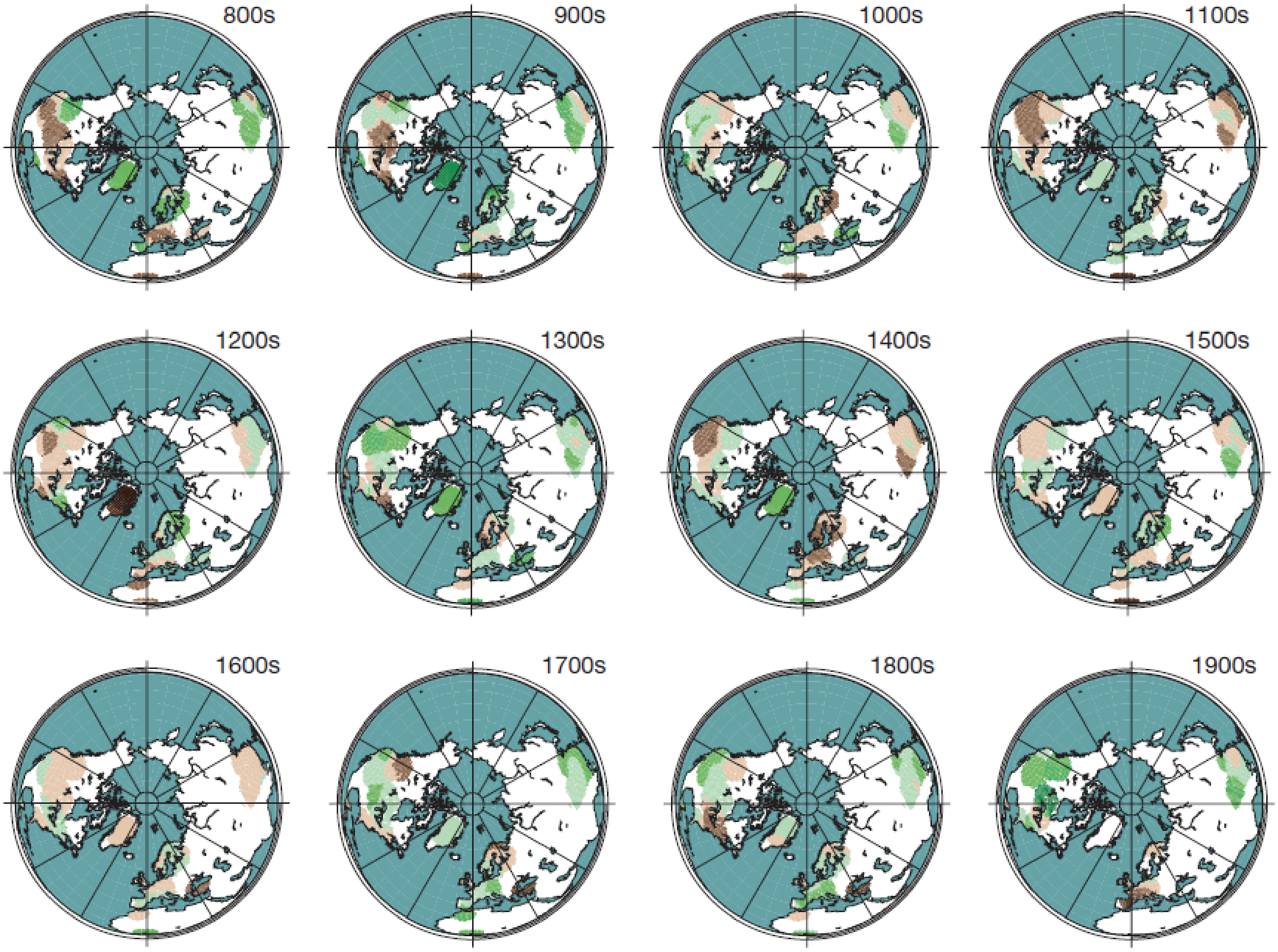


Fig. 8. Spatio-temporal distribution of gridded centennial hydrological proxy anomalies (brown: drought, green: wet) over land areas with at least 3 independent proxies within the estimated centennial correlation decay length for centennial-scale hydrological variability. Anomalies are shown relative to the centennial mean and standard deviation over the 11th to the 19th centuries. The color scale is truncated at –2 and 2, and areas with insufficient proxy coverage to compute a gridded weighted mean value are left white. From Fig. 2a in Ljungqvist et al. (2016)

solved through the integrated use of resources [Q48], and more research is required to identify and rank the available adaptation options [Q49]. The benefits of drought mitigation and drought planning seem to be obvious and have been listed by some researchers, such as Schwab (2013); however, more quantitative assessments are needed in order to demonstrate these benefits and provide officials with the support to take proactive actions. Studies focused on cost–benefit analysis of drought planning and drought mitigation would be highly beneficial when framing public discussion [Q50], as conceptual models (Fig. 9) need to be supported by data.

The proper and functional inclusion of drought into overall risk management policies remains a challenge that needs to be tackled [Q51]. As the overall regional drought resilience can be viewed as a product of the resilience of individual sectors and landscape components, studying and improving the resilience of these factors should also be prioritized [Q52–56]. These sectors/landscape components include urban areas [Q52], managed and non-managed ecosystems [Q53],

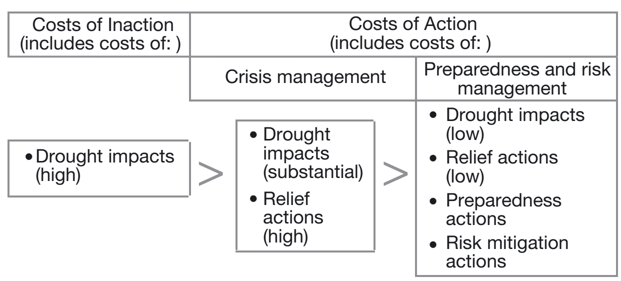


Fig. 9. Conceptual model illustrating the diminishing consequences, moving from left to right, of inaction to drought, drought response with a crisis management approach, and an approach that promotes preparedness and risk management (adapted from WMO & GWP 2017)

and farmland [Q54–56], where irrigation and its associated costs are considered important research questions (e.g. Rey et al. 2017).

3.6. Planning and policy

Planning for drought events is intertwined with drought monitoring, forecasting, and impact assessment; thus, finding the proper relationship among these themes is paramount in drought planning [Q57]. Some studies (e.g. Blauhut et al. 2016) indicate that finding critical thresholds is difficult and requires substantial and widespread analysis of data archives and innovative statistical techniques. In some cases, specific policies might affect drought resilience in undesirable ways (e.g. limiting drought resilience by primarily focusing on drought impact alleviation) [Q58]. The development of and changes in drought policy are usually initiated by a major drought episode, as in 1947 in Central Europe (e.g. Brázdil et al. 2016) or in the late 1990s in the US Midwest (e.g. McLeman et al. 2014). Understanding why some drought events trigger responses at the policy level seemed critical to the respondents [Q59]. The final research question reflects one of the major challenges associated with preparing meaningful long-term drought policy, i.e. ongoing climate change and uncertainty in the magnitude (and in some regions also the sign) of the change [Q60].

4. CONCLUSIONS

This study drew its inspiration from other priority research exercises that have taken place in fields such as ecology (Sutherland et al. 2013), paleoecology (Seddon et al. 2014), and historical ecology (Armstrong et al. 2017). As noted in the preceding exercises, the resulting drought questions are in no way final and definitive. The 431 initial questions were a heterogeneous mix of general and specific questions, and the subsequent 4-phase process generated increasingly universal questions. For example, approximately 30 region-specific questions were translated into several more general questions that are, in our view, more relevant to a wider global audience. In the current structure, the 60 questions may be adapted to various regions of the world and can also serve as a 'check-list' in formulating drought research priorities, starting with identifying appropriate monitoring methods [Q1–7] and drought impact assessment strategies [Q8–26], forecasting drought and understanding drought climatology [Q27–38], and addressing climate change consequences [Q39–44]. While the first two-thirds of the questions represent basic research on drought as a natural science phenomenon, a significant share of the questions cover the societal components of drought. These questions [Q45–60] are more in the realm of applied research, and include adaptation strategies for drought and the planning and policy aspects of the issue. In general, method-oriented questions represent relatively large proportions of the 'Adaptation strategies to drought' theme and the themes dealing with drought monitoring and impact assessment. This pattern is understandable because, while there has been marked development in drought monitoring and assessment tools, much work remains to be done at the science–decision making interface.

While the process of question evaluation was based on robust and tested methodology, the final list of 60 priority research questions is skewed towards those where common agreement could be found. On the other hand, 'provocative' or 'original' questions that drew highly contrasting views, or appealed to a small subset of the participants, naturally fell down in the list due to the question ranking process (e.g. Fig. 2b). For this reason, readers are advised to use Supplement 4 to explore the research questions that did not pass the final 'cut' in which only the most 'consensual' questions were retained. Supplement 3 provides readers with the view of the original set of questions including those that were narrowly focused on a particular region/research field, and thus tended to score lower in the evaluation process.

The formulated questions also show that the criteria selected to define drought must be stated explicitly (Wilhite & Glantz 1985) so that the definition can be evaluated and its applicability to other locations examined (e.g. Lloyd-Hughes 2014 or [Q8]). On the other hand, some of the concluding questions (e.g. [Q59] and [Q60]) indicate difficulty on the part of the research community in reaching out to decision makers, particularly those at the policy levels, to highlight the importance of drought, which was also identified as one of the major research issues 3 decades ago (Wilhite & Glantz 1985).

Despite the continued efforts to understand how drought is defined for different sectors and across various regions, the list does highlight the massive technological advances in the area of remote sensing and ground-based monitoring of drought onset, severity, and impacts. Never in the past have researchers been in the position (at least potentially) to monitor the climate, land use, and societal drivers of drought and drought impacts globally, and at such a high resolution and in near real time. At the same time, the wealth of information on drought variability and impacts over previous centuries to study drought–society interactions has been growing in response to networking and international collaborations. In a way, the set of questions presented by this paper reflects the challenges of such situations, with many researchers feeling that the commonly used approaches are not enough to utilize new information, and that substantial human and computational resources should be devoted to making sense of the available data. We are proposing 3 steps that would, in our view, greatly speed up the process of answering many of the posed questions:

(1) Organize global inter-comparison and improvement projects focused on available methods in the monitoring and forecasting of drought and drought impacts, fostering collaboration among all research labs across continents and disciplines using the experiences of similar efforts in related research fields (e.g. AgMIP project - www.agmip.org/);

(2) Create a multiscale, open-access repository of both ground and remote sensing based drought indicators as well as drought impacts that would be properly documented and updated;

(3) Commission review and position papers as collaborative efforts to leading research labs that would capture the present state-of-the-art, particularly in the fields of drought monitoring (including both ground based and remote sensing), drought impacts, drought forecasting and prediction, drought adaptation strategies, and drought planning and policy.

The list of 60 questions expresses, to a large extent, the interdisciplinarity and the multiple settings of drought research, and it maps at least some of the knowledge gaps that still exist or are perceived to exist. In the case of drought research, the link with stakeholders (and frequently the main funders) should be as close as possible, and the research should directly affect existing policies and legislation. Therefore, closing the known knowledge gap is important, and this list of questions can be used as a guide to define research needs in particular regions/sectors.

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