CROSSDRO

Deliverable

6.1 & 6.2 Stakeholder Engagement and Capacity Building

Introduction

Work package 6 aimed to foster linkages between the scientific community, policymakers, NGOs, managers, and end-users. A top-down and bottom-up approach was adopted by means of dissemination of project outputs and progress to key stakeholders in each country and through a sustained bottom up engagement with local and national level stakeholders to understand needs and drought perceptions. This close collaboration with relevant end-users and managers will ensure that the research outputs are used in operational practice in the different selected study cases.

Within the project four partner countries contained case study catchments through which stakeholder engagement was performed. These included Ireland (Boyne Basin), Spain (Aargon Basin), Germany (Elbe Basin) and Moldvoa (Prut Basin). Stakeholder engagement and capacity development took a unique focus in each basin given the different levels of advancement of drought planning and understanding. For example, in the Aaragon and Elbe drought planning and understanding is at an advanced level and focus was placed on linking the project outputs with key stakeholders. In the Prut Basin, given the importance of agriculture and the expertise of our partner the Selectia Research Institute in this area, attention was focused on building capacity around understanding of drought for adaptation purposes with local scale farmers and national level decision makers. In Ireland, drought planning is relatively new and attention was placed on understanding drought perceptions and needs within the Boyne Basin and nationally. In Ireland, focus was placed on developing long term engagements via interviews with a body of stakeholders representing diverse sectors to understand their needs. In this way, a tailored approach to work package 6 was implemented, ensuring that we met the needs to end users in the most appropriate way and that adoption of a one size fits all approach did not result in sub-optimal outcomes in any basin.

In addition to the direct stakeholder engagement the knowledge generated in the project was translated into layperson language to be accessible to the public. This was achieved through several routes. Periodic newsletters were made available from the project´s web site to inform about relevant news concerning CROSSDRO (see associated newsletter deliverable), the evolution of the project and its main outcomes, as well as of relevant news concerning cross-sectorial drought impacts in Europe. Diffusion of the project results and expertise to the public was also achieved by means of various media communications as opportunities arose, including blog posts, videos, television, and newsprint media. In expanding beyond the project focus areas, PIs from the project also developed a special issue of an international journal concerning advances in drought monitoring and modelling to better underpin adaptation to climate change. Lastly, to ensure that expertise from the project can be leveraged in other catchments and projects, we developed a review paper, summarising the literature and our expertise, on the barriers and opportunities for co-creation of better drought knowledge in addressing drought risk.

The COVID-19 pandemic impacted on our initial stakeholder engagement plans which were based on face-to-face meetings with stakeholders. The pandemic emerged as we held or project kick-off meeting in Moldova in February 2020 and persisted through various

lockdowns and restrictions on travel and meetings through much of the project. It also impacted on the time that stakeholders had to give us given the multiple demands on their time and their own efforts at transitioning to online work and additional burden that costs. Nonetheless we improvised, innovated, and leveraged available opportunities. We are thankful to all stakeholders who gave of their time, insight and expertise during this unprecedented and difficult period.

The outputs detailed in this deliverable include:

1. Outputs from on deep engagement with stakeholders in the Boyne catchment and Ireland on drought perceptions and needs.
2. Review of barriers and opportunities for co-creation of better drought knowledge.
3. Overviews of stakeholder engagement and capacity building activities in each country for each year of the project.
4. Summary of the special issue published in the journal Frontiers in Earth Sciences.
5. Summary of media engagements undertaken for public dissemination.

1. Drought perceptions and impacts in Ireland: stakeholder insights from recent drought events

Sam Grainger and Conor Murphy

1.1 Introduction

Droughts are the result of complex interactions between physical, biological and social systems (Wilhite and Pulwarty, 2017). In this human-dominated era, prolonged dry spells pose serious threats to society and the environment (Wilhite, 2012; Van Loon et al., 2016a). While often associated with water shortages, their broader impacts are difficult to characterise as they often emerge slowly and affect sectors and individuals in myriad ways (Van Loon et al., 2016b; Vicente-Serrano et al., 2020). Droughts can deplete water resources and increase the risk of wildfires which can have adverse effects on ecology, water supplies, agriculture, infrastructure and businesses. At an individual level, these impacts can affect people's livelihoods, recreational activities and ultimately their well-being (Grainger et al., 2021). Impacts can emerge slowly and vary in severity and spatial extent. Unlike floods, they can affect very large regions, sometimes entire countries and continents simultaneously. While prolonged periods of abnormally low rainfall are often caused by natural variability, more frequent and severe meteorological droughts are expected in a changing climate.

Drought means different things to different people depending on their specific interests, experiences and context (Grainger et al, 2021). At their most abstract, droughts are periods of time characterised by adverse effects from an absence of water. They usually stem from periods of below average rainfall that are long enough to cause adverse effects to water-sensitive sectors, groups or environments (Jedd et al., 2018). The complexity of these effects has fostered the development of specific disciplinary detection techniques, standardised indices and severity thresholds (Bryan et al., 2020; McEwen et al., 2021). Meteorologists may focus on temperature or precipitation deficiency. For example, in Ireland, a meteorological drought is defined as a period of 15 or more consecutive days with less than 0.2 mm of precipitation. Hydrologists and public water suppliers might be concerned with surface and groundwater levels (Hayes et al., 2012). Agronomists, foresters and farmers monitor plant stress and growth as well as soil water capacity (Brown et al., 2008). Economists calculate whether societal demand for water exceeds supply. Ecologists may focus on the impact of dry conditions on wildlife or ecosystems (Wilhite and Glantz, 1985; Mishra and Singh, 2010). While such perspectives may have value scientifically and for early

drought detection, they are limited in characterising the myriad ways drought is perceived and experienced. Indeed, such limited metrics may actually work to downplay drought risk in multiple and vulnerable sectors. Once drought sets in, a cascade of impacts is triggered across society. Understanding these impacts is key to increasing the capacity to cope with and recover from drought (Wilhite and Buchanan-Smith 2005).

Since drought cuts across disciplines, it follows that approaches to building institutional capacity emphasize understanding the full range of impacts, particularly with regard to how they affect society (Wilhite et al. 2007). How we define drought can draw out pre-conditioned biases and a priori alienate or empower different stakeholders, indicating which impacts, sectors and types of knowledge have greater legitimacy in a policy or decision-making process (Grainger et al., 2021). Managing these risks requires long-term collaboration between diverse groups with different values, interests and forms of knowledge. Despite posing significant risks to livelihoods and wellbeing, drought remains an overlooked hazard in Ireland. Historically Ireland has been prone to periods of prolonged dry weather, the Boyne catchment being no exception. With increased demand for water resources across multiple sectors in the coming decades, it is crucial that we document different perceptions and experiences of drought to inform the development of sectoral and national adaptation plans.

Risk perception and reaction to drought are strongly linked to past experiences and memories of drought events (Taylor et al., 1988; Solano-Hernandez et al., 2020). Given the high likelihood that drought will impact Irish society with greater frequency in the future, there is a need to understand how individuals and sectors perceive and experience drought to assist in developing tailored coping strategies and building institutional and sectoral-level capacity. CROSSDRO sought to conduct interviews with individuals and sector representatives impacted by drought in the Boyne catchment and nationally to better understand drought meanings, perceptions and impacts using social science methods. We sought to understand how drought risk is perceived in Ireland, how drought has been experienced and lessons for better preparing for drought in future.

1.2 Research design

We follow a mixed methodological approach as used in previous studies examining drought perceptions (Dessai and Sims, 2010; Weitkamp et al., 2020). First, an online survey was

performed as part of an initial scoping study before interviews were conducted to obtain richer qualitative information. The focus of this study was on individuals with either a direct sensitivity or professional interest in drought at the Boyne catchment and national-level. A total of 40 semi-structured interviews were conducted between February and July 2021. Interviewees can be broadly divided into three groups: individuals with a direct interest in drought from a livelihood perspective (n=6); individuals with a direct interest in drought from a recreational or general perspective (n=8); and those with an indirect professional interest (n=24). Most of our interviewees with professional interest work for state organisations or agencies operating at the national scale (n=26). All interviews were conducted remotely either via telephone, zoom or a similar virtual meeting platform. Interviews ranged from 30 to 100 minutes in duration and were conducted by the same interviewer. Interview questions sought to examine drought sensitivities and understandings, past drought experiences and coping strategies, as well as concerns around future drought risk. Semi-structured interview protocols were tailored to each interviewee depending on their type and scale of interest. Interviews were recorded and transcribed. A thematic analysis was conducted to identify and code key themes from the interviews. The first round of coding identified specific drought events reported by each interviewee, commonalities, and differences in how drought was discussed and understood; and their specific connection to drought impacts. Analytical coding was then performed, where additional patterns and categories were identified through an inductive and interpretation exercise (Bryman 2008).

1.3 Results

We report commonalities and differences in interviewees experiences of drought, future concerns and potential coping strategies. Illustrative quotes are presented within the text. To protect interviewees' identity, names are replaced by codes. Most interviewees reported some kind of experience, memory or knowledge of historical drought events in Ireland (32/40). In terms of specific droughts, summer 2018 and spring 2020 were most frequently mentioned. Some interviewees also referred to memorable droughts in the 1950s, 1970s and the hot and dry summers of 1995, 2006 and 2013. While these reports may not all necessarily be considered drought events from a meteorological perspective, they represent the temporality in which drought-related impacts were perceived. The most frequently identified drought-related experience or concern related to impacts on rivers and waterways (18/40), water management (15/40) and dairy farming (10/40).

Interviewees across the sample commented on the increased climate variability and more frequent extreme weather in Ireland in recent years:

> *"I have noticed in the last 10 years definitely things are getting more erratic. Erratic in winter as well as summer."* (Interviewee A from Waterways Ireland)

> *"Over the past four or five years, you can't go by the calendar any more."*
> (Interviewee from Coillte)

> *"*[We've seen] *a regime shift in terms of climate… you are looking at two completely different worlds."* (Interviewee from Atlantic Salmon Trust)

> *"2018 is a very good example where at the start of February you had 1 in 100 year floods… followed three months later by very short sharp drought and the fact that you can go from one to the other in such a short space of time is quite shocking."*
> (Interviewee from Environmental Protection Agency (EPA) Scientist)

For the remainder of this section, interviewee responses have been grouped based on four primary drought perspectives identified by interview analysis: agriculture, water management, environment, and river and waterway use.

1.3.1 Agriculture and Forestry

This group is composed of local-level farmers, growers and producers in the Boyne catchment and national-level scientific and governmental stakeholders from the agricultural, forestry and peat sectors. In terms of historical drought events in Ireland, the 1970s, 1995, 2018 and 2020 were the most frequently mentioned, with thirteen out of fifteen interviewees directly referencing impacts from the summer of 2018:

> *"There have obviously been a few events in the last 10 years but the very first one I remember is 1995… that really went on, it felt like it went on forever. I remember the* [Boyne] *river being really low, being able to walk over it. And people… hadn't really experienced anything like that for a long time. People* [have also said] *there was one in the 70s."* (Interviewee from rapeseed oil producer in Co. Meath)

> *"*[2018] *was the first time for such a long drought. The previous drought before that was 95... There have been many droughts but when you talk to a farmer it's 95 and 2018."* (Interviewee from IFA / dairy farmer)

While drought was generally considered to go hand in hand with hot weather, one farmer also recalled a cold drought event in Spring, several years ago:

> *"There's been cold droughts… very long periods of cold weather… easterly winds, that blocking event that they are talking about, sudden stratospheric block… you don't get any rainfall. Next thing, you're worried about your water, but it's cold and it's not the idea of a drought that we all have."* (Rapeseed oil producer in Co. Meath)

Within this group, the most frequently identified drought-related experience or concern related to dairy farming (8/15), income (6/15), water management (5/15), horticulture and crop production (5/15), and forestry (3/15). Local level stakeholders were primarily concerned with the impact of prolonged dry weather on their land and the effect it might have on their livelihoods (7/8), while national level stakeholders were more concerned with the broader impacts on the agri-food sector in Ireland (5/8). Among the agricultural drought impacts identified, the most frequently mentioned were those related to grass growth, fodder management and water availability for dairy farming. Interviews with farmers, Teagasc, the Irish Farmers Association (IFA) and Dept. of Agriculture (DAFM) indicate that dairy production is particularly at risk from drought in the Boyne and nationwide. According to a dairy farmer, drought is synonymous with poor grass growth over a 21-day period and shortages of crops for fodder and bedding:

> *"When your 21 day rotation doesn't replenish you with grass... your grass isn't being replenished on the standard rotation length and that means then farmers have to go in with buffer feeding and concentrate feeding which is more expensive."* (Interviewee from IFA / dairy farmer)

Interviews reported that grass growth dropped dramatically in 2018, particularly on free draining soils and well drained catchments in southeastern counties:

"In 2018, grass would have been very, very severely stunted." (Interviewee C from DAFM)

"People on dry sandy soils. They ran out of grass." (Interviewee A from DAFM).

This had implications for the availability and cost of feed and bedding materials for livestock, and ultimately milk production:

"You would hear of lads having to reduce their stock because they couldn't feed their animals and that's not sustainable." (Interviewee B from DAFM)

"In times like that sometimes straw would be fed just as a feed to keep animals ticking over. Even in that year there was a shortage of straw." (Interviewee C from DAFM)

A grassland scientist from Teagasc summarised the acute nature of drought impacts on dairy farming as follows:

"The practical consequence of drought for a farmer is how do you get through that period when the forage crashes. Because once the rain comes back, the grassland growth will recover real quick. But how do you get through that hungry period?" (Interviewee from Teagasc)

Several interviewees mentioned that the extremely wet calendar year and cold spring preceding the 2018 summer drought extended the winter livestock housing period and exacerbated the fodder crisis. Some interviewees reported how unprepared the dairy sector in Ireland was during this event. Farms with large herds, operating at maximum capacity, were considered to be particularly vulnerable to climate extremes:

"We had pretty significant issues particularly in the really intensive large dairy herds… To find feed for 50 or 60 cows that's kind of doable but for 600 cows now you have to buy silage bales in large volumes… you're very dependent on the market " (Interviewee A from DAFM)

> *"Since 2015 there's* [been] *huge dairy expansion and … everyone was pushing out to the maximum and trying to maximise the stocking rate and not really considering how the climate could actually jeopardise the systems and that came to the fore then in that drought in 2018."* (Interviewee B from DAFM)

Several interviewees were also concerned about the potential impact of water shortages on animal welfare and farmer wellbeing. Dairy production is very water intensive, particularly in the summer months. Dairy cows require up to 70 litres a day and additional water is required for the milk production process and all the cleaning of the equipment and buildings. Water shortages impact on the behaviour and welfare of their livestock as well as the wellbeing of farmers:

> *"If you don't have enough water and enough trough space you tend to get aggression and dominance issues which are also welfare challenges"* (Interviewee A from DAFM)

> *"When you have cows looing for water or feed… any farmer will tell you, that's more stressful than anything"* (Interviewee from IFA / dairy farmer)

Many farms rely on private or community-owned group schemes for their water supply. According to an interviewee from the National Federation of Group Water Schemes (NFGWS), the 2018 summer event alerted farmers to the potential vulnerability of their group water schemes and private wells:

> *"We would have had issues pre-2018 obviously but not to the same extent and I think that kind of opened our eyes and we… probably were a little bit unprepared."* (Interviewee from the NFGWS)

During both the 2018 and 2020 events, water demand across all schemes increased by 20-30%. This meant that in some places demand was greater than the volume of water that could be pumped and processed by treatment plants. As a result, many rural water users were concerned their supplies were close to running dry:

“Water levels in the source reduce or go down very slowly and do not recover to the same extent that they would normally do. Obviously, panic can set in at that stage.” (Interviewee from the NFGWS)

In terms of adaptation or strategies to cope with future drought, the dairy farmers interviewed highlighted the importance of fodder management and access to affordable imported feed when required. They also suggested various approaches to improve the resilience of their water supply including investment in irrigation equipment, conserving water and accessing more water from either rivers or new wells. According to one farmer, the commercial damage caused by the 2018 drought has had a significant impact on dairy farmer attitudes to drought risk in Ireland:

"Farmers have become more aware of drought [since 2018]. They planned for more buffer feeding and more of a reserve so instead of having a six week reserve they have a three month reserve." (Interviewee from IFA / dairy farmer)

This interviewee also suggested that Irish dairy farmers are open to new practices or technology that might increase resilience to drought:

"We’re very receptive to advice and as advice changes… Before you would have never measured grass. You would have just followed your rotation and never thought anything more. Now farmers are walking their farm once a week, measuring their grass twice a week during periods of high growth." (Interviewee from IFA / dairy farmer)

Interviewees from national-level scientific and governmental agencies stressed the importance of European-level financial support during drought events and the potential need for ‘weather insurance’ in the future so that dairy farmers can be compensated for droughts losses:

"[It is] *only a matter of time before there is an investment of insurance premium into the protection of the grassland resource."* (Interviewee from Teagasc)

A senior official from DAFM also stressed the importance of engaging the farming community about drought:

> *"It's also about communicating in some way to farmers that this is a risk that you have to consider... dairy cows drink maybe between 40 and 70 litres a day depending on how high yielding they are. If you have 500 or 600 cows, that's a lot of water."* (Interviewee A from the DAFM)

This interviewee also suggested that grasslands made up of a mixture of different species could improve drought resilience. Referring to sectoral or national-level planning, they also expressed alarm at the apparent lack of awareness shown by farming leaders of any strategic planning for drought going on during a recent public event on drought:

> *"*[Somebody] *asked a question at the end… about how well prepared they think the industry is to face these kinds of pressures in the future. And there was a complete silence from the whole panel. And it was really a clear conclusion that nobody is prepared. There are short term emergency responses to try and muddle through as best as possible. But there is no plan, nobody has a plan, nobody is thinking about this on a systematic basis and that's really worrying."* (Interviewee from Teagasc)

According to farmers and DAFM staff, the prolonged dry weather in summer 2018 and spring 2020 also impacted crop production in terms of yield and quality (e.g., potato, oilseed rape, oats, straw and grain). The most severely affected farms were in the southeast of the country, where free draining and heavily tilled soils struggle to retain enough moisture. According to an interviewee from the DAFM climate adaptation team, a focus on continuous cereals in recent years (e.g., oats, wheat, barley, malt) has damaged the soil structure and reduced climate resilience on these farms:

> *"Soil is massively important for* [increasing] *resilience to climate and if your soils are completely drying out because maybe they have been over tilled for decades… there's no structure to that soil. You are changing that whole land-water dynamic so if the soil is all broken up it's dry and you're exposing it to erosion from wind and rain."* (Interviewee B from the DAFM)

Several interviewees mentioned that the extremely wet calendar year and cold spring preceding the 2018 summer drought caused sewing windows for a lot of spring crops to be missed. According to a tillage inspector at DAFM, irrigation is becoming more necessary in recent years particularly for potato farmers in the southeast of the country:

> *"A lot of potato farmers are already irrigating… Back to 2018… guys would have been spending large amounts of money on pumps and irrigation systems to make sure that they fulfil their contracts."* (Interviewee C from the DAFM)

There is also concern from interviewees about the emergence of new diseases, pests and weeds as drought events become more frequent:

> *"As we experience more droughts, crop diseases are going to move from wet weather diseases to dry weather diseases. New pests and weeds too. We don't have experience of those."* (Interviewee C from the DAFM)

In terms of adaptation or strategies to cope with future drought, this interviewee suggested that Irish tillage farmers should try to diversify away from traditional commodity crops (e.g., malt and barley) to not only build commercial resilience to extreme events but also enhance soil quality and moisture content. Several interviewees also emphasised the potential role of the state advisory service (Teagasc) and importance of farmer to farmer learning for awareness raising and knowledge exchange.

The forest sector also reported significant impacts on newly planted forests in 2018. An inspector from the Forest Service, who visited sites during the summer of 2018, reported severe stress and 100% failure on some sites for the first time in his career:

> *"I have a few sites in my mind… they would have been planted in native woodland in February/March and went out in July/August and there were no trees. They were all gone. 100% failure of trees and I have never come across anything like that. That was the first time we had come across it."* (Interviewee from Forest Service)

DAFM set up a financial support scheme so that landowners and foresters could replant young trees that had failed. According to a private consultant from PTR forest, young broadleaf forests planted in free draining mineral soil were particularly susceptible:

> *"Sites all across the south east were just withering away and dying and the mortalities were excessive across sites."* (Interviewee from PTR Forest)

A manager from Coillte reported how prolonged dry spells have inhibited growth on his tree nursery. Irrigation is seen as helpful tool but cannot be relied on as a substitute for regular rainfall:

> *"The irrigation will keep things alive… but it's no real substitute ... A good drop of rain is far better than any irrigation system. Again, it's a tool we need, we have to have it because we can't rely on the weather to get rain and moisture at the time of sowing."* (Interviewee from Coillte nursery manager)

In terms of adaptation or strategies to cope with future drought, all interviewees from the forest sector suggested foresters need to diversify planting, while considering species and provenances that can withstand more extreme climate and the resulting changes in pests and diseases.

> *"We need... mixed species in the future and planting the right tree in the right place, moving away from this sitka spruce planted everywhere because it's the quickest return on your investment."*

1.3.2 Water management and navigation

This group is principally composed of scientists and engineers working for governmental organisations and civil society organisations (CSOs) operating at a national scale. In terms of historical drought in Ireland, the summer of 2018 was by far the most frequently reported event (eight out of twelve interviewees). The most frequently identified drought-related experience or concern related to water supply and wastewater management (8/12), streamflow and water quality in rivers (5/12). Governmental actors were concerned with the impact of prolonged dry periods on rivers and water resources, while CSOs were more

concerned about the impact of drought on public and community-owned water supplies. Regarding impacts on rivers, several governmental actors mentioned how low flows reduce water quality as dilution of pollutants and the river's ability to assimilate wastewater diminishes:

> *"where you are discharging wastewater into a stream or river that now has less capacity because there is less water in it … your impact … may be more."* (Interviewee from Dept. of Housing)

> *"The ability of our rivers to have enough flow in them to maintain their ability to assimilate the wastewater… is really, really important and the Liffey and the Boyne are good examples of that.* (Interviewee from EPA Scientist)

> *"Higher nutrient content combined with the low flow… exacerbates everything"* (Interviewee from the Local Authority Waters Programme)

Several interviewees also remarked that often, when there is heavy rainfall after a dry spell as was the case in the summer of 2018, recently applied agricultural fertiliser and wastewater solids that build up in pipes are flushed into river systems:

> *"The assimilation capacity just wasn't in the rivers… you get build-up of silt and solids and grease and all the rest of it in pipes. And when rain comes, it flushes it all out."* (Interviewee from Climate Action Regional Office)

An EPA scientist also explained how during dry periods authorities are constantly having to abstract water for domestic water and navigation while also maintaining the water level for wastewater management and water quality:

> *"When you get droughts you have to keep abstracting your water for domestic water supply. So you end up pumping water because the water has fallen below the outtake level and you absolutely have to do that but you also have to maintain the water in the river to sustain the ecology and to dilute the wastewater and there's also a navigation abstraction on the Liffey at the Leinster Aqueduct and at the Boyne at the Boyne aqueduct, Irish Water take water for the Royal Canal or Waterways Ireland. So you*

are spinning plates in that situation where you are trying to balance what you take out and leave enough that it will safely dilute what's put back in." (Interviewee from EPA Scientist)

Interviews with the Dept. of Housing and others with an understanding of public water supplies suggest that, while there has been broad agreement of systemic problems with Ireland's supply network for a long time, the 2018 and 2020 drought events were a wake-up call for the public water supply sector. We reported concern over the sustainability of existing supply infrastructure and how recent events brought home our vulnerabilities and focused minds within the Department of Housing:

"the experience of 2018 and 2020... has brought home to us here in Ireland the vulnerabilities that we have that maybe weren't so front and centre and I guess the frequency of two such severe droughts so close together has really focused minds." (Interviewee from Dept. of Housing)

"if we haven't had any rain for three or four weeks after March... in an Irish context there's so little storage in the ground that hydrological droughts can happen really, really quickly." (Interviewee from EPA Scientist)

Unsurprisingly, Dublin was considered particularly at risk due to the lack of storage capacity and increasing demand.

"Well I suppose the most immediate risk is in supplies like Dublin City where you have very, very little headroom. So you are operating on a 2 to 3% headroom. International practice would be nearer to 15 or 20%" (Interviewee from Dept. of Housing)

Several stakeholders highlighted how supplies that rely on flashy catchments in the West can also be vulnerable even during short dry spells like the one in 2020:

"In the south west of the country we have a lot of run of the river supplies which are very vulnerable to this type of situation where the river drops. [In 2020] *the river needed to be sandbagged and you can just get the pipe to be able to extract the water*

out of it. In some very small supplies we were tankering the water in... So we had a hosepipe ban put in place so it was a difficult enough situation and fairly touch and go at times. We were reducing the pressure during the night and turning off certain areas." (Interviewee from Dept. of Housing)

Multi-year events were also highlighted as some reservoirs and aquifers need time to recharge. In terms of the Boyne catchment, public water supplies don't seem to be an immediate concern, but there are general concerns that development of the Dublin-Belfast economic corridor could bring pressures in the long-term.

In terms of adaptation or strategies to cope with future drought, several interviewees suggested a mixture of demand management, engineering-based (e.g., water transfers, reservoirs, repairing leaky infrastructure, groundwater exploitation) and nature-based solutions (e.g., peatland restoration and natural water retention measures). An interviewee from the EPA highlighted how challenging it is to engage politicians and the public on water management issues in Ireland in context of larger scale crises such as COVID-19 and climate mitigation actions:

"Communicating effectively and actually achieving resonance with policy makers and the wider public on the importance of [drought] *is a problem… First of all you have to win the argument that it's worth doing something about... The engineering solutions are there and in a stepwise way you can do several things depending on how bad the situation gets… Winning the society argument is the key.... Climate action is the big fish in the pond at the moment. If we don't get that right, what we're doing with rivers is only gardening really. We have to sort that out. We have to convey to people very effectively and it's not easy to do, that these things are all mutually supportive... what we do in terms of adaptation has to support mitigation and vice versa."* (Interviewee from EPA Scientist)

An interviewee from the Department of Housing also commented that the main challenge for water planners when calculating future water supply scenarios is *"settling on a common picture… prediction of the future"* (Interviewee from Dept. of Housing). Despite not being mentioned by other interviewees in the water management group, two interviewees from Waterways Ireland (WI) highlighted the impact of dry weather and water shortages on

Ireland's network of inland navigable waterways. They seem to define drought in terms of having access to enough water so that the waterways can function from both a navigational and ecological perspective:

> *"Our canals run on water; water is the key element here. There isn't an ecology without water… often at times in an organisation like ours … we fail sometimes to see the water… There's only so much of the pie and with climate change our concern particularly with regard to drought is that the pie is shrinking…I think the right amount of water is incredibly important to us in the canals and we already have issues with drought."* (Interviewee B from Waterways Ireland)

Without a reliable supply of water, WI may not be able to maintain waterway levels which has consequences for navigation, recreation, and ecosystem health. They described how as the water levels drop, more light reaches the canal bed, resulting in weed growth. A combination of shallow water, limited boat traffic and weed growth can prevent their machinery from clearing weeds and maintaining the functionality of the waterway infrastructure:

> *"Weed growth is massive because we can't get our machines to work on the level of water in the canal so that means the weeds start to grow* [further]*."* (Interviewee A from Waterways Ireland)

> *"Managing that weed is important for the ecological interest as well. It's not just so our boats can go down there."* (Interviewee B from Waterways Ireland)

WI also reported concerns about the structural integrity of canal embankments and bridges as water levels drop and they dry out and crack:

> *"My embankments are cracking in the dry and then when they become saturated that crack becomes a flow for water to leak."* (Interviewee A from Waterways Ireland)

The Royal Canal, which cuts across the country from the midlands to Dublin, and is fed by the Inny catchment / Lough Owel also supplies the town of Mullingar (Co. Westmeath).

Interviewees suggested that this supply is becoming less and less reliable as Mullingar grows and we experience more frequent and longer periods of dry weather:

> *"In 2017… we had such dry weather in the Inny catchment, that our levels are down maybe 600 mm. They are impassable"* (Interviewee A from Waterways Ireland)

> *"We are already under pressure with regards to getting water for our canals. Significant pressure. We have it every year"* (Interviewee B from Waterways Ireland)

During prolonged dry periods in recent years, WI have regularly had to divert water from the Boyne river to maintain a navigable level on the Royal Canal:

> *"We're pumping water out of the Inny and the Boyne and that's not sustainable in the long term. "* (Interviewee A from Waterways Ireland)

In terms of adaptation or strategies to cope with future drought, WI engineers plan to reduce water leakage from their canals and try to curtail weed growth by using machinery to muddy the water during dry periods. At a more strategic level they are also looking at ways to optimise their control systems so that they are not pumping water unnecessarily.

1.3.3 Environment

This group is composed of ecological scientists, policy actors and local biodiversity champions in the Boyne catchment. Five out of seven interviewees directly referenced a specific period of drought, 2018 being the most frequently reported. Within this group, the scientists and local champions all identified drought-related experiences or concerns related to peatland ecology (5/7), wildfires on peatlands (5/7) and wildlife (5/7). The policy actors were more concerned with the broader discourse around climate and the environment. Interviewees concerned about peatland health highlighted that extended periods of dry weather are likely to further destabilise and degrade wetlands and peatlands that already have limited resilience:

> *"Drought will.. increase the degradation I would say but also make it more difficult to restore* [peatlands]*."* (Interviewee from an Irish University)

"All those systems are really badly drained, they are badly damaged. So there is no water in the system, so you are depending on a constant supply of rain to even have areas that are relatively intact, in anything like good condition. So the problem we have now is [with] *more frequent periods of drought, it's going to be harder to restore these systems."* (Interviewee from National Parks and Wildlife (NPWS)

Several interviewees observed surface drying and cracking in 2018, attributing this to an absence of a moss or algae layer that you would find on healthy peatlands:

"In 2018… [bogs] *I have never seen dry were suddenly dry… You could walk across* [the bog] *in sandals and you see the cracking of the peat and the drying out and the crumbling."* (Interviewee from an Irish University)

"I was very struck by how dry the planted bog vegetation was. It was almost like the bog had lifted off the surface of the mountain so to speak. And I was walking over it and it was like parchment paper, I was breaking through it, breaking through the vegetation, it was almost like the vegetation had peeled away from the peat below. And obviously that's because things had dried out to such a degree that it had lost that kind of resilience." (Interviewee from Bord na Mona)

Historically, the state company responsible for harvesting turf from the bogs (Bord na Mona) welcomed dry weather as it increased productivity. However, as they move towards a policy of restoration or rehabilitation, interviewees report they are going to need to carefully manage water levels which will be challenging as droughts become more frequent and demand for water resources increases. Several interviewees were concerned about fires starting on drained, harvested peatlands during periods of prolonged dry weather:

"Because the peat is dry and it's dry everywhere, you set it off and it starts spreading." (Interviewee from NPWS)

An interviewee also suggested that compound extreme events (i.e., dry weather followed by intense rainfall) are also likely to create conditions for more serious bogslides in Ireland which, apart from the ecological damage, can impact on local property, water quality and biodiversity downstream. Some interviewees also highlighted the impact of drought on

wildlife. Dry conditions and resulting fires can have short-term effects on insect and bird populations. Some aquatic birds, the Freshwater Pearl Mussel and Natterjack Toad were highlighted as species that can be very sensitive to reductions in surface water levels. However, an interviewee from NPWS argued for drought to be defined according to the specific ecological context:

> *"Drought needs to be defined as well, because that will differ between different habitats… you've got to contextualise it for its own particular environment… drought is relative, one month of very low or no rainfall in the west can be detrimental to something like a freshwater pearl mussel."* (Interviewee from NPWS)

In terms of adaptation or strategies to cope with future drought, the three professional ecologists in this group all suggested that restoration and rewetting of peatlands may improve future resilience. However, they highlighted that this approach will not be effective in every case, and that we should carefully weigh up the potential restorative benefits with the potential impacts of such interventions on local livelihoods and communities.

1.3.4 River and recreational use

This group is principally composed of anglers and boaters from the Boyne catchment. Five out of six interviewees directly referenced a specific period of drought, 2018 being the most frequently reported. Within this group, the most frequently identified drought-related experience or concern related to the effect of low water levels on river fish health and angling (3/6) and navigation (3/6). Anglers expressed concern about the impact of low flows on fish habitats, movement and health, while boaters were principally concerned about the impact of low levels and subsequent weed growth on navigation and the general aesthetic of the rivers and waterways. From an angling or fisheries perspective, drought was frequently mentioned as a contributor to fish stress and kills due to the compound effect of low flows, increased water temperatures, low oxygen levels, poor water quality, weed growth and increased predation:

> *"This combination between the low flow, high temperature and the oxygen to me is really very, very worrying at this stage."* (Interviewee from Atlantic Salmon Trust)

All anglers reported a drop in river levels and impacts on fisheries during the summer of 2018 and spring 2020. They reported that, during the summer of 2018, salmon movement and health was so badly affected on some rivers that anglers voluntarily stopped fishing until conditions improved:

> *"Inland Fisheries Ireland actually issued press releases telling people to stop fishing that these temperatures have never been seen before"* (Interviewee from Atlantic Salmon Trust)

> *"The fishing was cancelled pretty much for the whole summer because the river was too low and they were worried about stress on fish."* (Interviewee B from Navan Anglers, Co. Meath)

According to one angler, the impacts in spring 2020 would have been as serious as those in 2018 if it had lasted any longer:

> *"We had a similar event in April* [2020]*... another two more weeks of that and we were in serious bother… it was earlier in the year and that's what saved it… if it had occurred a few months later* [the impacts on fish] *it probably would have been every bit as bad as 2018.* (Interviewee from Kells Anglers, Co. Meath)

Another angler mentioned there were far more serious impacts on the River Boyne and its fisheries in the 1950s:

> *"As bad as things were a couple of years ago, they weren't that bad! ... I just came across pictures of it recently and I just went wow! We thought that what we saw a couple of years ago was unprecedented but it wasn't… 1958 if my memory serves me right"* (Interviewee A from Navan Anglers, Co. Meath)

One interviewee was able to provide a national perspective on drought and fisheries. They have observed climate regimes in very flashy catchments in the west of Ireland change from almost daily "*soft rain*" events to more frequent flood and drought events. This has led to drops in fish numbers and other wildlife:

> *"We were seeing effects in terms of the* [fish] *productivity of these streams and also my colleagues have been looking at it in terms of the invertebrates"* (Interviewee from Atlantic Salmon Trust)

They also highlighted the difference between these catchment and the Boyne when thinking about the potential impact of dry weather on low flows:

> *"The water* [in flashy mountain catchments] *runs off very quickly and so it's very different to the Boyne even though the Boyne is destroyed by drainage. At the same time, it still has a capacity to retain water. Whereas, in those particular systems, there is nothing to retain the water except lakes and you really do see the effects very quickly in terms of the streams being denuded of water."* (Interviewee from Atlantic Salmon Trust)

In terms of adaptation or strategies to cope with future drought, one angler stressed the importance of effective abstraction regulation and enforcement:

> *Farmers were blocking up streams to impound them so they could suck water out... and then the next fellow doing the same… and the next fellow… absolutely no consequences. The only law that comes into effect is when the river runs dry."*
> (Interviewee from Kells Anglers, Co. Meath)

Another angler suggested engaging and incentivising the farming community with catchment and peatland restoration as a way to reverse decades of drainage policies:

> *"why don't we make the farmers into water stewards and that's what my training is about at the moment. We are taking young farmers and we're trying to get them to understand the value of the liquid that they have on their farm in terms of water and how they can manage it to their benefit. We as a community should be supporting them to have wet fields and supporting them to have wetlands and to recreate their bogs and that's the only way it's going to work because these people are trying to make an income out of it"* (Interviewee from Atlantic Salmon Trust)

From a boating perspective, the effect of low flows on navigation was also highlighted as a potential concern during interviews with the Heritage Boat Association, a Canoe Club on the Royal Canal (Co. Meath) and a boating tour company in the lower Boyne river:

> *"If the* [canal] *levels are low you cannot navigate. Simple as that… as the water goes down you hit the edges* [of the boat] *very quickly"* (Interviewee from Heritage Boat Association)

> *"If the river is very low your boat is just going to be scraping off stones and it's not going to be much fun, you know what I mean. So there's a danger… if the river levels aren't right." (*Interviewee from a Canoe Club on the Royal Canal (Co. Meath))

Boaters also reported how low water levels can encourage weed growth which has knock-on effects on navigation and the aesthetic value of the waterways:

> *"Low levels to us would be weed growth because the shallower the water, the more weed that grows so certainly that would be an issue"* (Interviewee from Heritage Boat Association)

> *"The effect of the drought conditions is the build up of weeds because of heat. That's the big thing for me… When you get it right and it's crystal clear and… maybe 6 or 7 feet deep … you can actually see fish swimming around you."* (Interviewee from boating tour agency)

1.4 Conclusion

This research sought to better understand drought perceptions and impacts across different sectors and understand key vulnerabilities for better preparing for drought in future. Most reflections on drought amongst the interviewees were drawn from 2018, with very few able to draw on impacts and responses from earlier droughts. As indicated in previous chapters the 2018 drought, while significant is not remarkable in the long-term record. More intense, longer lasting droughts have occurred within living memory, and it is important to draw out impacts and responses from those events. Some interviewees also referred to the dry summers of 1995, 2006, 2013 even though they are perhaps remembered more as heatwaves. This would support findings from the UK that drought is usually associated with warm and

sunny weather during the summer. Having said that, those more dependent on and aware of weather conditions (i.e., farmers) did highlight concerns around dry spells in winter and early spring under cloudy and cold conditions (known as grey or cold droughts).

Very different perspectives of drought impacts were provided across sectors, indicating the challenge of one size fits all approaches to managing drought. Stakeholders from the dairy sector reported that grass growth dropped dramatically in 2018, particularly in Munster and Leinster. They talked of "unfamiliar territory" and "a sector unprepared for such a long drought" as silage and straw prices "went through the roof". Similar conditions across Europe led to the EU and government organising extra imports of feed. However, according to a Teagasc scientist, this safety valve may not be possible in the future given that the EU green deal policies are looking to stop our dependence on the global supply chain of feed, as it is contributing to the destruction of tropical rainforests and carbon emissions. Interviewees were also concerned that future drought could bring serious water shortages particularly if intensification continues. Peak milk production and therefore water demand coincides with the summer. During this period, dairy cows require up to 70 litres a day and additional water is required for the milk production process and cleaning of equipment and buildings. While a lot of farms have access to mains water, many of the larger more intense operations find it more cost-effective to privately manage water supplies. As a result, in 2018 some farms with intensive dairy herds ran out of water and had to abstract from nearby rivers. For other river and waterway users, combined low flows, high temperatures and reductions in water quality can encourage weed growth and adversely impact fisheries, the function of freshwater ecosystems and their cultural and recreational value to society. In general, drought is seen as something that exacerbates existing catchment pressures from agriculture, water management and historical drainage policies.

References

Brown, J.F., Wardlow, B.D., Tadesse, T., Hayes, M.J. and Reed, B.C., 2008. The Vegetation Drought Response Index (VegDRI): A new integrated approach for monitoring drought stress in vegetation. *GIScience & Remote Sensing*, *45*(1), pp.16-46.

Bryan, K., Ward, S., Roberts, L., White, M.P., Landeg, O., Taylor, T. and McEwen, L., 2020. The health and well-being effects of drought: assessing multi-stakeholder perspectives through narratives from the UK. *Climatic Change*, *163*, pp.2073-2095.

Dessai, S. and Sims, C. (2010) Public perception of drought and climate change in southeast England. *Environmental Hazards*, *9*(4), 340-357.

Grainger, S., Murphy, C. and Vicente-Serrano, S.M., 2021. Barriers and opportunities for actionable knowledge production in drought risk management: embracing the frontiers of co-production. *Frontiers in Environmental Science*, *9*, p.602128.

Hayes, M.J., Svoboda, M.D., Wardlow, B.D., Anderson, M.C. and Kogan, F., 2012. Drought monitoring: Historical and current perspectives.

Jedd, T., Bathke, D., Gill, D., Paul, B., Wall, N., Bernadt, T., Petr, J., Mucia, A. and Wall, M., 2018. Tracking drought perspectives: A rural case study of transformations following an invisible hazard. *Weather, Climate, and Society*, *10*(4), pp.653-672.

McEwen, L., Bryan, K., Black, A., Blake, J. and Afzal, M., 2021. Science-narrative explorations of "drought thresholds" in the Maritime Eden Catchment, Scotland: Implications for local drought risk management. *Frontiers in Environmental Science*, *9*, p.589980.

Mishra, A.K. and Singh, V.P., 2010. A review of drought concepts. *Journal of hydrology*, *391*(1-2), pp.202-216.

Solano-Hernández, A., Bruzzone, O., Groot, J., Laborda, L., Martínez, A., Tittonell, P., Easdale, M.H. (2020) Convergence between satellite information and farmers' perception of drought in rangelands of North-West Patagonia, Argentina. *Land Use Policy*, *97*, p.104726

Taylor, J. G., Stewart, T. R., Downton, M. (1988) Perceptions of drought in the Ogallala aquifer region. *Environment and Behaviour*, 20 (2), 150–175.

Van Loon, A.F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A.I., Tallaksen, L.M., Hannaford, J. and Uijlenhoet, R., 2016. Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences*, *20*(9), pp.3631-3650.

Van Loon, Anne F., Tom Gleeson, Julian Clark, Albert IJM Van Dijk, Kerstin Stahl, Jamie Hannaford, Giuliano Di Baldassarre et al. "Drought in the Anthropocene." *Nature Geoscience* 9, no. 2 (2016): 89-91.

Vicente-Serrano, S.M., Quiring, S.M., Pena-Gallardo, M., Yuan, S. and Dominguez-Castro, F., 2020. A review of environmental droughts: Increased risk under global warming?. *Earth-Science Reviews*, *201*, p.102953.

Weitkamp, E., McEwen, L. and Ramirez, P., 2020. Communicating the hidden: toward a framework for drought risk communication in maritime climates. *Climatic Change*, *163*(2), 831-850.

Wilhite, D. and Pulwarty, R.S. eds., 2017. *Drought and water crises: integrating science, management, and policy*. CRC Press.

Wilhite, D.A. and Buchanan-Smith, M., 2005. Drought as hazard: understanding the natural and social context. *Drought and water crises: Science, technology, and management issues*, *3*, p.29.

Wilhite, D.A. and Glantz, M.H., 1985. Understanding: the drought phenomenon: the role of definitions. *Water international*, *10*(3), pp.111-120.

Wilhite, D.A. ed., 2012. *Drought assessment, management, and planning: theory and case studies: theory and case studies* (Vol. 2). Springer Science & Business Media.

Wilhite, D.A., Svoboda, M.D. and Hayes, M.J., 2007. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water resources management*, *21*, pp.763-774.

2. Barriers and opportunities for actionable knowledge production in drought risk management: embracing the frontiers of co-production

Sam Grainger, Conor Murphy, Sergio M. Vicente Serrano

2.1 Introduction

Drought risks pose serious threats to socio-ecological systems, built environments, livelihoods and human wellbeing. Managing these risks requires long-term collaboration between diverse groups with different values, interests and forms of knowledge. Funders, researchers and practitioners have increasingly advocated for collaborative models of knowledge production in which all participants recognise the multiple ways of understanding drought risk and strive to co-create knowledge for decision making. Such transdisciplinary research approaches aim to develop and sustain more equitable and meaningful interactions between scientific and societal actors, and have been shown to increase knowledge use and build resilience to climate variability. In practice, however, collaborations around drought remain largely science-driven and, as a result, can struggle to produce actionable knowledge necessary to better manage drought risk.

This article draws from drought studies and related transdisciplinary fields to highlight common barriers inhibiting actionable knowledge production across a broad range of drought risk management contexts. We also propose opportunities for improved knowledge production that can guide researchers, practitioners and funders seeking to engage in transdisciplinary work. Diverse understandings of drought risk have hindered widespread advances in knowledge production and resilience building. We argue for multi-disciplinary researchers to come together with stakeholders and focus on creating inclusive and context-driven environments. While not appropriate or cost-effective in all situations, co-production between researchers, practitioners and other stakeholder groups offers opportunities for

actionable management plans and policies that reflect the complex and contested problem framings and socio-ecological contexts in which droughts impact society.

Droughts are the result of complex interactions between physical, biological and social systems (Wilhite and Pulwarty, 2017). In this human-dominated era, prolonged droughts pose serious threats to economies, societies and the environment (Wilhite, 2012; Van Loon et al., 2016a). Their impacts are difficult to observe and quantify as they affect sectors in myriad ways (Van Loon et al., 2016b; Vicente-Serrano et al., 2020). Drought risks are a function of both the probability and severity of events (exposure) and underlying vulnerability of the exposed system, community or society (Vogt, 2018). Prolonged dry conditions can increase the risk of wildfires and water shortages which can have adverse effects on ecology, water supplies, public services, infrastructure, agriculture and industry. At an individual level, these impacts can affect people's recreational activities, livelihoods and ultimately their well-being. Historically, droughts have traditionally been managed using reactive, crisis-driven approaches (see Pulwarty and Sivakumar, 2014). In recent decades, numerous studies have argued for proactive approaches to managing drought risk based on long-term monitoring and multi-actor engagement (see Wilhite et al. 2014; Bachmair et al., 2016a; Finnessey et al., 2016).

Understanding where, when and how drought conditions evolve can give those affected time to prepare and act to minimise harm. In recent decades, there have been significant advances in drought monitoring and early warning, seasonal forecasting and data processing (Wilhite and Pulwarty, 2017; Hannaford et al., 2018). Monitoring and early warning systems (MEWS) have been developed to continuously track and, in some cases, forecast hydrometeorological variables at different scales (Wilhite, 2006; Hannaford et al., 2018). There have also been considerable efforts in repackaging these data in the form of drought indicators or indices (e.g. Hao and Singh, 2015). Several studies have assessed the links between different drought indicators (e.g. Vicente-Serrano and López-Moreno, 2005; Vicente-Serrano et al., 2012), and drought impacts in different sectors (Bachmair et al., 2016b).

However, while data-driven MEWS can characterise environmental conditions, they have limitations when it comes to connecting with how drought is locally experienced and recorded by impacted sectors and communities (Bachmair et al., 2016a; Ferguson et al., 2016). For example, drought is often scientifically defined, based on standardised indices that have little meaning for those impacted. Consequently, MEWS can struggle to produce

actionable knowledge necessary to reduce vulnerability and enhance long-term resilience (Kirchhoff et al., 2013). There remains a simplistic belief in some literature (see e.g. Finnessey et al., 2016) that producing and simply communicating scientific information can depoliticise complex and highly contested societal problems such as climate change, loss of biodiversity and drought. In reality, such top-down approaches can reinforce existing unequal relationships (Murphy et al., 2016) and the perception that science alone can produce and deliver the knowledge needed to address complex social problems (Pohl et al., 2010; Turnhout et al., 2020). For example, creating narrow definitions of drought that suit empirical scientists from meteorology, hydrology, engineering, economics or agricultural science automatically marginalises less technical sectors and types of knowledge. In response, a growing body of literature has emerged (see Cash and Borck, 2006; Kirchhoff et al., 2013; Lemos et al., 2018a), advocating instead for transdisciplinary research that seeks to create meaningful knowledge for decision makers, communities and organisations through inclusive and interactive approaches (see Norström et al., 2020).

Transdisciplinarity can be defined as a commitment by academics and non-academics to integrate multiple forms of knowledge and perspectives within a collaborative research process (Suldovsky et al., 2018). There is growing evidence, particularly in the context of addressing complex socio-ecological challenges, that transdisciplinary approaches (e.g. knowledge co-production, post-normal science, action research) increase the likelihood of producing actionable knowledge (i.e. knowledge that is perceived as sufficiently credible, salient and legitimate to be used in decision making) (Cash et al., 2003; Lemos et al., 2018b). As a result, funders, researchers and practitioners are turning to more collaborative models of knowledge production and management to build resilience to intractable climate-related hazards such as drought.

While drought literature on transdisciplinary knowledge production is limited, recent drought studies draw from social sciences to argue for improved understanding of transdisciplinary knowledge-making practices and for stakeholders to play a more prominent role in the development of open and transparent MEWS (Hannaford et al., 2018; Van Loon et al., 2016b). For example, while exploring drought impacts and MEWS development in Europe, North America, and Australia, the “DrIVER” project incorporated learnings from stakeholder workshops to develop collective insights into different perspectives of drought impacts and MEWS needs (Collins et al. 2016; Hannaford et al., 2018). In a Mediterranean context, Turco et al., (2019) developed a fire forecasting system that merged user relevant information with

seasonal climate forecasts to provide tailored outlooks for fire managers in Catalunya. Ferguson et al. (2016) collaborated with a Native American community in the U.S. Southwest on a drought information system that combined local observations and knowledge with scientific monitoring data. Experiences in sub-Saharan Africa have also shown that ignoring the cultural and power dynamics of different ways of knowing (traditional and scientific knowledge) can reinforce tensions within communities and enhance vulnerability to drought (Murphy et al., 2016). Such endeavours are pioneering integration of scientific tools and data with local understandings of drought impacts, towards shared or 'co-produced' definitions of drought. With drought research taking this turn and attempting to operate in a transdisciplinary space, it is important to reflect on some inherent challenges of knowledge production for drought risk management and how they can potentially be addressed.

In this focused review, we draw on drought specific and related literature from more mature transdisciplinary fields that share similar epistemic foundations and risk-based decision-making contexts (e.g. water governance, climate services, climate risk management and sustainability science). We also draw upon our own insights and practical experiences collaborating with societal actors on climate risk, drought and water resources decision making. Our objectives are to (i) identify common barriers to the production of actionable knowledge and (ii) propose opportunities for improved knowledge production that can guide researchers, practitioners and funders seeking to engage in transdisciplinary drought work across diverse drought contexts and scales (**Table 1**). We conclude by elaborating some of the benefits and potential pitfalls of co-production, discussing the important role of social science in drought research, and recommending some future research directions.

Table 1: Barriers to and opportunities for actionable knowledge production in drought risk management

Common barriers	Opportunities
Droughts have different meanings.	Deliberately co-produce.
Droughts can be perceptually challenging.	Understand stakeholder context and needs.
Droughts are context specific.	Explicitly recognise diverse drought meanings.
Droughts are difficult to predict.	Create enabling environments and be transparent about uncertainties.

2.2 Barriers to actionable knowledge production for drought risk management

Drought affects different parts of the hydrological cycle, environment and society in ways that are highly subjective, pervasive and difficult to quantify (Bachmair et al., 2016a). The complexity of drought as a hazard, and contestation over how drought impacts society prevents more nuanced understandings of drought and knowledge exchange (Wilhite and Glantz, 1985; Redmond, 2002; Kallis, 2008; Ferguson et al., 2016). This section identifies some of the fundamental barriers inhibiting actionable knowledge production for drought risk management.

Droughts have different meanings

At their most abstract, droughts are periods characterised by adverse effects from insufficient water. Drought impacts are often framed from an agricultural, economic or ecological perspective. Farmers may associate reduced yield or loss of harvest or livestock with dry conditions; economists may only consider conditions to be drought-like when demand for water exceeds supply; ecologists may focus on the impact of dry conditions on ecological health and water quality (Wilhite and Glantz, 1985; Mishra and Singh, 2010). Drought can also be defined in operational terms based on agreed criteria that help planners decide when to declare an event and activate response plans (Estrela and Vargas, 2012; Bachmair et al.,

2016a; Maia and Vicente-Serrano, 2017). However, there can be no universal definition that relates to how droughts impact social systems (Lloyd-Hughes, 2014; Kohl and Knox, 2016). Drought and its impacts mean different things to different people depending on their specific interests, experiences and context. Moreover, thresholds and descriptions of event severity (moderate vs severe) often differ depending on how drought impacts are framed by dominant voices, emphasising the importance of facilitating integrative assessments and perspectives that draw on diverse experiences. How we define drought can draw out pre-conditioned biases and a priori alienate or empower different stakeholders, indicating which impacts, sectors and types of knowledge have greater legitimacy in a policy or decision-making process.

Droughts can be perceptually challenging

Droughts are typically associated with drier than normal weather (meteorological drought). Reductions in precipitation can drive soil moisture deficits (agricultural drought) and in time lower surface and sub-surface water levels in a catchment (hydrological drought). However, drought evolution depends on the magnitude, timing and duration of the precipitation anomaly, the type of soil and land cover, dominant runoff pathways, geology and increasingly engineering and management interventions.

Drought impacts can propagate slowly without being immediately seen or experienced (Wilhite, 2012). As a result, impacts on public services, businesses and communities may also not immediately be attributed to drought conditions. Purely conceptual or scientific characterisations of drought have limited relevance for many stakeholders, particularly when the spatial and temporal resolution of the information provided does not match with their context (Ferguson et al., 2016). Drought planning is a particular challenge where recent societal and institutional experiences of drought may not be reflective of actual risk due to long-term climate variability (Murphy et al., 2017). Rivers or reservoirs in a region may appear to be at normal levels due to careful management, but low soil moisture may be impacting rain-fed agricultural production. In fact, hydrological droughts can persist even after heavy rainfall or flooding.

Droughts are context specific

A particular socio-ecological and historical context will influence drought risk perception (Gil et al., 2000). Seven days without rainfall might be considered a meteorological drought in traditional agricultural societies that rely on precipitation on almost a daily basis during the

rainy season. However, in desert societies where rainfall is scarce, such occurrences would be unremarkable.

How people perceive and respond to drought is strongly related to past experiences and memories (Taylor et al., 1988). Throughout history, drought-prone societies have developed culturally embedded rules of thumb or heuristics derived from experiential knowledge and mental models of their local environment (Courkamp et al., 2019). In some places, increases in extreme climate events are likely to have an effect on risk perception and on how people and societies understand seasons and climate variability in the future. Recent attention has been drawn to 'flash drought' events in humid regions, characterised by their sudden onset, rapid intensification and severe impacts (Pendergrass et al., 2020).

At a societal level, droughts may be downgraded or 'forgotten' entirely if they occur around the same time as a heat wave or prior to a significant flood event (Ciais et al. 2005; Marsh et al., 2013; Shepherd et al., 2018). It can be difficult to communicate drought risk in cultures with a perennially wet climate, associated with green landscapes (Weitkamp et al., 2019). In northern European countries, droughts are usually associated with hot weather which, in turn, evokes positive memories of being outdoors and enjoying the sunshine (Bruine De Bruin et al., 2016). As a result, droughts are not always seen as major hazards that require long-term planning. Perceptions of drought risk can also change as a function of socio-economic conditions and dynamic policy landscapes (Gil et al., 2000). For example, in the mid twentieth century, Spanish society moved from a focus on meteorological droughts to hydrological droughts as their economy became less reliant on rainfed agriculture.

Droughts are difficult to predict

It is difficult to develop confident meteorological forecasts of drought more than two weeks in advance. With the exception of some tropical and subtropical regions in which climate variability is strongly determined by sea surface temperature variability (Vicente-Serrano et al., 2011), in the majority of the world regions the skill of seasonal forecasting is still very low to be effective in developing accurate seasonal drought forecasts (Bechtold et al., 2008; Dutra et al., 2013). Such capacity would be very useful to anticipate possible impacts and to allow preparedness of economic sectors to associated losses, hydrological managers to improve dam operation and optimization of available water resources and environmental managers to prepare for possible hazards (e.g. fire risk) and to reduce soil erosion and land degradation (e.g. with better management planning of livestock). While recent studies have

suggested some improvement in skill (e.g. Davili and D'Andrea, 2020; Smith et al., 2020), current drought forecasting systems (e.g. https://www.drought.gov/drought/data-maps-tools/outlooks-forecasts) are still subject to large uncertainties.

2.3 Opportunities for actionable knowledge production for drought risk management

There are a number of opportunities for researchers, practitioners and funders seeking to overcome these barriers. These are neither comprehensive nor prescriptive but offer insights from drought and related literature that can inform a pragmatic approach to producing actionable knowledge in a range of drought-sensitive decision-making contexts.

Focus on co-producing rather than translating knowledge

Public-facing drought information systems tend to focus on translating scientific knowledge for a wide range of stakeholders (Hannaford et al., 2018). Integration of scientific and non-scientific knowledge remains rare (Giordano et al., 2013; Solano-Hernandez et al., 2020), with some exceptions (e.g. Estrela and Vargas, 2012). This centralised, technocratic model of knowledge production is ineffective because it creates a disconnect between monitoring networks, scientists and sector-specific drought planning (Hannaford et al., 2018).

Collaborative knowledge production (commonly referred to as 'co-production') can be defined in normative terms, as a learning process that deliberately brings together diverse perspectives to co-create actionable knowledge and new practices (Bremer and Meisch 2017; Lemos et al., 2018b). Co-production should be interactive, iterative, context-driven, problem-focused and involve deep engagement with non-scientific knowledge systems (Norström et al., 2020). Co-produced knowledge is more likely to be perceived as credible, salient and legitimate (Cash et al., 2003). While systematic assessments are rare (Mach et al., 2019; Arnott et al., 2020; Jagannathan et al., 2020), co-production has been shown to increase the likelihood of knowledge use in decision-making (Lemos et al., 2018b).

However, assembling a sufficiently broad group of actors, while keeping the process practically and strategically manageable requires considerable time, resources and expertise (Page and Dilling, 2019; Norström et al., 2020). Potential participants may not have sufficient capacity or motivation to engage in co-productive processes (Page and Dilling, 2019). Many academics are still primarily incentivised to conduct disciplinary science that cannot directly address societal challenges (Dilling and Lemos 2011). Conversely, practitioners and other

stakeholders may work within professional contexts that do not reward iterative learning, innovation and critical reflection (Norström et al., 2020).

Successful co-production is predicated on including a plurality of perspectives, which often requires the disruption of established roles and routines (Vincent et al., 2018; Turnhout et al., 2020). Deep rooted power imbalances can prevent engagement, reproduce knowledge hierarchies and, consequently, undermine the co-production process (Mobjork, 2010; Reed et al., 2014; Brandt et al., 2018). To avoid such pitfalls, it is important that all actors involved in the co-productive processes are committed to achieving a common goal and able to regularly and systematically reflect on and discuss the extent to which their understandings and values are being represented (Reed et al., 2014; Norström et al, 2020).

Iteratively analyse stakeholder needs and context

Given the complex and multi-sectoral nature of drought it is vital that a thorough analysis of potential stakeholders and their decision-making contexts is conducted prior to and throughout collaborations. Top-down, 'loading dock' approaches that focus solely on information provision often fail to consider the complexity and dynamism of local cultural sensitivities around the legitimacy of different types of knowledge systems (Cash and Borck, 2006). This can create friction between local stakeholders and ultimately result in mal-adaptative decision making (Murphy et al., 2016). Uncritical mapping and selection of potential stakeholders (e.g. just targeting water managers) can reinforce existing narrow perceptions and power structures. It is important to know whether stakeholders are already used to dealing with hydrological variability or other climate-related hazards such as flooding. Businesses may also have to prioritise other stressors/threats above drought preparedness (e.g. the COVID-19 pandemic) when making decisions.

Contextual analysis and participatory design approaches can inform the development of tailored communications and interactions (Grainger et al., 2020; Hannaford et al., 2018). Some stakeholders may require technical information (SPI, severities, probabilities), others might just want high-level information about the general hydrological trend. A recent appraisal of the release of the 2019 UK Climate Projections (UKCP09) highlighted that scientists often assume that users will be highly numerate and able to handle technical information (Porter and Dessai, 2017). This often leads to parachuting default or familiar approaches when interacting with stakeholders. Our experiences would suggest that, despite the inclusion of stakeholder analysis and engagement within some drought projects,

researchers from the social and behavioral sciences are rarely involved in framing, planning and designing these interactions. Funders and natural scientists should acknowledge how valuable their contribution could be to knowledge production and reach out to these disciplines as early as possible in the project creation process.

Explicitly recognise diverse understandings of drought

It is crucial to recognise that plurality of perspectives make drought an inherently complex and context-differentiated hazard (Collins and Ison, 2009; Lange et al. 2017; Hannaford et al., 2018). As a result, no single perspective can presume superiority over another, and claim to have a definitive understanding of drought and potential solutions. The inclusion of multiple forms of knowledge has the potential to enhance knowledge use and build trust between researchers and drought-sensitive sectors.

Any characterisation of drought that strives for societal relevance must consider what makes drought socially relevant in that particular context (Ferguson et al., 2016). We would therefore encourage researchers to support drought sensitive decision makers to develop their own drought definition tailored to their own context. This can be achieved through collaborative ground-truthing of drought indicators with stakeholder knowledge (Bachmair et al., 2016a) and with an understanding of their specific needs (Estrela and Vargas, 2012).

Create enabling institutional environments

Effective knowledge production requires collaboration between different sectors and knowledge systems operating at various spatial and temporal scales. Currently, links between community, national and global-scale drought management are weak (Pulwarty and Sivakumar, 2014). This fragmented management context is exacerbated by science and institutional systems that are grounded in top-down modes of knowledge production and mobilization. Drought researchers and planners might benefit from working through organisations operating at the interface between science and policy (known as boundary organisations (Guston, 2001)) to help connect different sectoral drought plans and knowledge systems (e.g. water supply and agricultural sector) (Hannaford et al., 2018). Page and Dilling (2019) suggest taking advantage of existing intra-sectoral communities of practices or local ‘champions’ that may be influential within broader stakeholder groups (e.g. water managers / farmers).

The use of climate information and related services within drought risk management has been promoted by several key international initiatives including the United Nations’ Global

Framework for Climate Services and Integrated Drought Management Programme (Finnessey et al., 2016). However, Turnhout et al. (2020) show that these types of science-led initiatives are often dominated by depoliticisation dynamics that reinforce rather than mitigate existing uneven post-colonial politics. It is, therefore, vital that the drought research community reflect upon important institutional questions around who should instigate and drive collaborations (Hannaford et al., 2018).

Openly discuss and characterise uncertainty

Drought management is beset by scientific and socio-economic uncertainties that require joint knowledge and problem solving by researchers, practitioners and other societal actors. Decision makers should have awareness of the uncertainty associated with different forms of knowledge and knowledge production processes (Fischhoff and Davis, 2014). However, this can be problematic, particularly when dealing with inherently uncertain processes in risk averse cultural contexts driven by institutional expectations for precision and accuracy (Taylor et al., in press). Overlooking uncertainty in response to these expectations may result in a false sense of certainty, potentially leading to mal-adaptive decision making and loss of trust in scientific partners (Macintosh, 2013, LeClerc and Joslyn, 2015). It is therefore important to manage expectations carefully, and characterise uncertainties in a manner that is transparent, relevant and understandable to all stakeholders. Expert elicitation is one method that could help drought planners to interpret and apply uncertain model information. When engaging with broader and non-scientific audiences, storylines or narrative approaches can help connect with people's innate understanding of future uncertainty and reveal important points of commonality (Shepherd et al., 2018; Jack et al., 2020).

2.4 Conclusion

Despite decades observing and quantifying changes in hydrological extremes, drought remains intractable in clear scientific terms and as a risk for societies to manage. Recent drought research has taken the first steps towards connecting with, and making actionable knowledge for, those communities and sectors impacted by drought impacts. In this focused review, we have reflected on this progress by highlighting some key barriers to knowledge production and proposing potential opportunities for strengthening drought knowledge.

Drought perceptions are strongly differentiated among scientific disciplines, stakeholders and economic sectors, and are subject to change as a function of hazard severity, socioeconomic and environmental conditions. Context is crucial, with drought having very different

meanings and experiences in time and space - from humid and semi-arid regions to local differences within the same catchment. These scientific, perceptual and contextual challenges have made it difficult to engage with different sectors on anything other than a reactive basis (Wilhite, 2012).

To overcome these barriers, we urge those involved in drought risk management to embrace co-production as a model of engagement and knowledge production. This will require that researchers become partners in knowledge creation rather than solely producers of knowledge and to recognise multiple ways of understanding drought risk. In the right collaborative environment, explicit interaction with different knowledge systems can help to build trust, develop shared understandings and enrich knowledge outcomes (Tobias et al., 2019). Creating an enabling environment that accommodates a diverse understanding of drought is far from straightforward, requiring skills not typically required in natural science.

As we have stated earlier, drought literature on co-production is limited. Further exploration of the challenges raised in this article require future research into current knowledge production practices and use in specific drought risk management contexts to better understand the implications of 'silo-ed' knowledge on decision making. The social sciences and humanities need to play a more prominent role in co-produced drought research not only as facilitators but also as action researchers so that we can better understand the cultural, political and institutional dimensions that influence drought understandings and risk management processes.

We should expect individual, disciplinary and organisational resistance to new ways of working as power dynamics and knowledge hierarchies are slowly revealed and dismantled. There are inevitable trade-offs between the time and resources required to co-produce research and the expectation on researchers to publish and advance in their careers. Transdisciplinary research will not be appropriate in all drought contexts and all parties will need to carefully consider whether the costs outweigh the expected benefits. Success criteria for co-production will differ greatly and evaluations will need to reflect the complexity of stakeholder expectations, motivation and capacities (Wall et al., 2017). Funders, researchers and practitioners have unique ways of assessing whether to use a co-production approach and collaborators need to explicitly acknowledge differences in motivations early in the process. However, a common goal running through transdisciplinary research should be the emergence of a shared purpose and learning in groups (or social learning), both collectively

and individually. Proactive approaches to monitoring and evaluation, adaptive project programming and participant flexibility are also critical within co-production processes (Vincent et al., 2018). While collaborative efforts may not immediately provide solutions, mutual exchange of experiences, ideas and values can, in the long-term, facilitate collective action and develop the vital capacities, networks and social capital needed to manage drought risk.

References

Arnott, J. C., Kirchhoff, C. J., Meyer, R. M., Meadow, A. M., and Bednarek, A. T. (2020). Sponsoring actionable science: what public science funders can do to advance sustainability and the social contract for science. *Current Opinion in Environmental Sustainability*, *42*, 38–44. https://doi.org/10.1016/j.cosust.2020.01.006

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., Knutson, C., Smith, K. H., Wall, N., Fuchs, B., Crossman, N. D., and Overton, I. C. (2016a). Drought indicators revisited: the need for a wider consideration of environment and society. *Wiley Interdisciplinary Reviews: Water*, 3(4), 516–536. https://doi.org/10.1002/wat2.1154

Bachmair, S., Svensson, C., Hannaford, J., Barker, L. J., and Stahl, K. (2016b). A quantitative analysis to objectively appraise drought indicators and model drought impacts. *Hydrology and Earth System Sciences*, 20(7), 2589–2609. https://doi.org/10.5194/hess-20-2589-2016

Bechtold, P., Koehler, M., Jung, T., Doblas-Reyes, F., Leutbecher, M., Rodwell, M.J., Vitart, F. and Balsamo, G. (2008). Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, *134*(634), 1337-1351.

Brandt, F., Josefsson, J. and Spierenburg, M. (2018). Power and politics in stakeholder engagement: farm dweller (in)visibility and conversions to game farming in South Africa. *Ecol. Soc*. 23, 32.

Bremer, S., and Meisch, S. (2017). Co-production in climate change research: reviewing different perspectives. *Wiley Interdisciplinary Reviews: Climate Change*, 8(6), 1–22. https://doi.org/10.1002/wcc.482

Bruine de Bruin, W., Lefevre, C. E., Taylor, A. L., Dessai, S., Fischhoff, B., and Kovats, S. (2016). Promoting protection against a threat that evokes positive affect: The case of heat waves in the United Kingdom. *Journal of Experimental Psychology: Applied*, *22*(3), 261–271. https://doi.org/10.1037/xap0000083

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., (2003) Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci.* U.S.A. https://doi.org/10.1073/pnas.1231332100.

Cash, D.W., and Borck, J. C. (2006). Countering the Loading-Dock Approach to Comparative Analysis of El Niño / Southern Oscillation (ENSO) Forecasting Systems. *Science, Technology, and Human Values*, 31(4), 465–494. https://doi.org/10.1177/0162243906287547

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A. and Chevallier, F. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, *437*(7058), 529-533.

Collins, K., and Ison, R. (2009). Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. *Environmental Policy and Governance*, *19*(6), 358-373.

Collins, K., Hannaford, J., Svoboda, M., Knutson, C., Wall, N., Bernadt, T., Crossman, N., Overton, I., Acreman, M., Bachmair, S., and Stahl, K. (2016). Stakeholder coinquiries on drought impacts, monitoring, and early warning systems. *Bulletin of the American Meteorological Society*, *97*(11), ES217–ES220. https://doi.org/10.1175/BAMS-D-16-0185.1

Courkamp, J. S., Knapp, C. N., Allen, B. (2019). Immersive Co-production to Inform Ranch Management in Gunnison, Colorado, USA. *Rangelands*, *41*(4), 178–184. https://doi.org/10.1016/j.rala.2019.05.002

Dutra, E., Magnusson, L., Wetterhall, F., Cloke, H. L., Balsamo, G., Boussetta, S., and Pappenberger, F. (2013). The 2010–2011 drought in the Horn of Africa in ECMWF reanalysis and seasonal forecast products. *International Journal of Climatology*, *33*(7), 1720-1729.

Davini, P., and D'Andrea, F. (2020). From CMIP-3 to CMIP-6: Northern Hemisphere atmospheric blocking simulation in present and future climate. *Journal of Climate*, 1-50.

Dilling, L., and Lemos, M. C. (2011). Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change*, *21*(2), 680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006

Estrela, T. and Vargas, E. (2012). Drought Management Plans in the European Union. The Case of Spain *Water Resour. Manag.* 26 1537–53 Online: http://link.springer.com/10.1007/s11269-011-9971-2

Ferguson, D. B., Masayesva, A., Meadow, A. M., and Crimmins, M. A. (2016). Rain gauges to range conditions: Collaborative development of a drought information system to support local decision-making. *Weather, Climate, and Society*, *8*(4), 345–359. https://doi.org/10.1175/WCAS-D-15-0060.1

Finnessey, T., Hayes, M., Lukas, J., and Svoboda, M. (2016). Using climate information for drought planning. *Climate Research.* 70(2–3), 251–263. https://doi.org/10.3354/cr01406

Fischhoff, B., and Davis, A. L. (2014). Communicating scientific uncertainty. *Proceedings of the National Academy of Sciences*, *111*(Supplement_4), 13664–13671. https://doi.org/10.1073/pnas.1317504111

Gil, A. M., Cantos, J. O., and Amorós, A. M. R. (2000). Diferentes percepciones de la sequía en España: adaptación, catastrofismo e intentos de corrección. *Investigaciones Geográficas*, (23), 5-46.

Giordano, R., Preziosi, E., Romano, E. (2013). Integration of local and scientific knowledge to support drought impact monitoring: some hints from an Italian case study. *Nat. Hazards* 69 (1), 523–544.

Grainger, S., Ochoa-Tocachi, B. F., Antiporta, J., Dewulf, A., and Buytaert, W. (2020). Tailoring Infographics on Water Resources Through Iterative, User-Centered Design: A Case Study in the Peruvian Andes. *Water Resources Research*, *56*(2), 1–16. https://doi.org/10.1029/2019WR026694

Guston, D.H. (2001) Boundary organizations in environmental policy and science: An introduction. *Sci Technol Human Values* 26:399–408

Hannaford, J., Collins, K., Haines, S., and Barker, L. J. (2018). Enhancing Drought Monitoring and Early Warning for the United Kingdom through Stakeholder Coinquiries. *Weather, Climate, and Society*, *11*(1), 49–63. https://doi.org/10.1175/wcas-d-18-0042.1

Jack, C. D., Jones, R., Burgin, L., and Daron, J. (2020). Climate risk narratives: An iterative reflective process for co-producing and integrating climate knowledge. *Climate Risk Management*, *29*(May). https://doi.org/10.1016/j.crm.2020.100239

Jagannathan, K., Arnott, J. C., Wyborn, C., Klenk, N., Mach, K. J., Moss, R. H., and Sjostrom, K. D. (2020). Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. *Current Opinion in Environmental Sustainability*, 42, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010

Kallis, G. (2008). Droughts. *Annual Review of Environment and Resources*, *33*, 85–118. https://doi.org/10.1146/annurev.environ.33.081307.123117

Kirchhoff, C. J., Lemos, M. C., and Dessai, S. (2013). Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. *Annual Review of Environment and Resources*, 38(1), 393–414. https://doi.org/10.1146/annurev-environ-022112-112828

Kohl, E., and Knox, J. A. (2016). My Drought is Different from Your Drought: A Case Study of the Policy Implications of Multiple Ways of Knowing Drought. *Weather, Climate, and Society*, *8*(4), 373–388. https://doi.org/10.1175/wcas-d-15-0062.1

LeClerc J, Joslyn, S. (2015) The cry wolf effect and weather-related decision making. *Risk Anal.* 35, 385–395. (doi:10.1111/risa.12336)

Lemos, M. C., Eakin, H., Dilling, L., and Worl, J. (2018a). Social Sciences, Weather, and Climate Change. *Meteorological Monographs*, *59*, 26.1-26.25. https://doi.org/10.1175/amsmonographs-d-18-0011.1

Lemos, M. C., Arnott, J. C., Ardoin, N. M., Baja, K., Bednarek, A. T., Dewulf, A., Fieseler, C., Goodrich, K. A., Jagannathan, K., Klenk, N., Mach, K. J., Meadow, A. M., Meyer, R., Moss, R., Nichols, L., Sjostrom, K. D., Stults, M., Turnhout, E., Vaughan, C., Wong-Parodi, G. and Wyborn, C. (2018b). To co-produce or not to co-produce. *Nature Sustainability,* 1(12), 722–724. https://doi.org/10.1038/s41893-018-0191-0

Lloyd-Hughes, B. (2014). The impracticality of a universal drought definition. *Theoretical and Applied Climatology*, 117(3–4), 607–611. https://doi.org/10.1007/s00704-013-1025-7

Mach, K. J., Lemos, M. C., Meadow, A. M., Wyborn, C., Klenk, N., Arnott, J. C., Ardoin, N. M., Fieseler, C., Moss, R. H., Nichols, L., Stults, M., Vaughan, C., and Wong-Parodi, G. (2019). Actionable knowledge and the art of engagement. *Current Opinion in Environmental Sustainability*, 42, Under Review. https://doi.org/10.1016/j.cosust.2020.01.002

Macintosh, A. (2013). Coastal climate hazards and urban planning: how planning responses can lead to maladaptation. *Mitigation and Adaptation Strategies for Global Change*, *18*(7), 1035-1055.

Maia R and Vicente-Serrano, S. M. (2017). "Drought Planning and Management in the Iberian Peninsula." in Drought and water crises: integrating science, management, and policy, eds. D. Wilhite and R.S. Pulwarty (CRC Press), pp 481-506.

Marsh, T., Parry, S., Kendon, M., & Hannaford, J. (2013). The 2010-12 drought and subsequent extensive flooding: a remarkable hydrological transformation. NERC/Centre for Ecology & Hydrology.

Mishra, A. K., and Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1–2), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mobjörk, M. (2010). Consulting versus participatory transdisciplinarity: A refined classification of transdisciplinary research. *Futures*, *42*(8), 866-873.

Murphy, C., Tembo, M., Phiri, A., Yerokun, O., & Grummell, B. (2016). Adapting to climate change in shifting landscapes of belief. Climatic Change, 134(1–2), 101–114. https://doi.org/10.1007/s10584-015-1498-8

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

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., Bednarek, A. T., Bennett, E. M., Biggs, R., de Bremond, A., Campbell, B. M., Canadell, J. G., Carpenter, S. R., Folke, C., Fulton, E. A., Gaffney, O., Gelcich, S., Jouffray, J. B., Leach, M., … Österblom, H. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, *3*(3), 182–190. https://doi.org/10.1038/s41893-019-0448-2

Page, R., and Dilling, L. (2019). The critical role of communities of practice and peer learning in scaling hydroclimatic information adoption. *Weather, Climate, and Society*, *11*(4), 851–862. https://doi.org/10.1175/WCAS-D-18-0130.1

Pendergrass, A.G., Meehl, G.A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., Bonfils, C.J., Gallant, A.J., Hoerling, M., Hoffmann, D. and Kaatz, L. (2020). Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nat. Clim. Chang.* 10, 191–199. https://doi.org/10.1038/s41558-020-0709-0

Pohl, C., Rist, S., Zimmermann, A., Fry, P., Gurung, G. S., Schneider, F., Speranza, C. I., Kiteme, B., Boillat, S., Serrano, E., Hadorn, G. H., and Urs, W. (2010). Researchers' roles in knowledge co-production: Experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. *Science and Public Policy*, 37(4), 267–281. https://doi.org/10.3152/030234210X496628

Porter, J. J., and Dessai, S. (2017). Mini-me: Why do climate scientists' misunderstand users and their needs? *Environmental Science and Policy*, *77*(June), 9–14. https://doi.org/10.1016/j.envsci.2017.07.004

Pulwarty, R. S., and Sivakumar, M. V. K. (2014). Information systems in a changing climate: Early warnings and drought risk management. *Weather and Climate Extremes,* 3, 14–21. https://doi.org/10.1016/j.wace.2014.03.005

Redmond, K. T. (2002) The depiction of drought Bull. *Am. Meteorol. Soc*. 83 1143–7.

Reed, M. S., Stringer, L. C., Fazey, I., Evely, A. C. and Kruijsen, J. H. J. Five principles for the practice of knowledge exchange in environmental management. *J. Environ. Manag*. 146, 337–345 (2014).

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N. W., Wilby, R. L., and Zenghelis, D. A. (2018). Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*. https://doi.org/10.1007/s10584-018-2317-9

Smith, D. M., Scaife, A. A., Eade, R., Athanasiadis, P., Bellucci, A., Bethke, I., ... and Danabasoglu, G. (2020). North Atlantic climate far more predictable than models imply. *Nature*, *583*(7818), 796-800.

Solano-Hernandez, A., Bruzzone, O., Groot, J., Laborda, L., Martínez, A., Tittonell, P., and Easdale, M. H. (2020). Convergence between satellite information and farmers' perception of drought in rangelands of North-West Patagonia, Argentina. *Land Use Policy*, *97*(April). https://doi.org/10.1016/j.landusepol.2020.104726

Suldovsky, B., McGreavy, B., & Lindenfeld, L. (2018). Evaluating Epistemic Commitments and Science Communication Practice in Transdisciplinary Research. Science Communication, 40(4), 499–523. https://doi.org/10.1177/1075547018786566

Taylor, J. G., Stewart, T. R., and Downton, M. (1988). Perceptions of drought in the Ogallala Aquifer region. *Environment and Behavior,* 20(2), 150-175.

Taylor, A.L., Grainger, S., Dessai, S., Siu Y.L., Bruno Soares, M. (in press) Communicating Uncertainty in Climate Information for China: Recommendations and Lessons Learned for Climate Services. *Journal of Meteorological Research.*

Tobias, S., Ströbele, M. F. and Buser, T. (2019). How transdisciplinary projects influence participants' ways of thinking: a case study on future landscape development. *Sustain. Sci.* 14, 405–419.

Turnhout, E., Metze, T., Wyborn, C., Klenk, N., and Louder, E. (2020). The politics of co-production: participation, power, and transformation. *Current Opinion in Environmental Sustainability*, 42(2018), 15–21. https://doi.org/10.1016/j.cosust.2019.11.009

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and Van Lanen, H. A. J. (2016a). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91. https://doi.org/10.1038/ngeo2646

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., and Van Lanen, H. A. J. (2016b). Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences,* 20(9), 3631–3650. https://doi.org/10.5194/hess-20-3631-2016

Vincent, K., Daly, M., Scannell, C., and Leathes, B. (2018). What can climate services learn from theory and practice of co-production? *Climate Services*. 12(December), 48–58. https://doi.org/10.1016/j.cliser.2018.11.001

Vicente-Serrano, S. M., and López-Moreno, J. I. (2005). Hydrological response to different time scales of climatological drought: an evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. *HESS*, *9*(5), 523-533.

Vicente-Serrano, S.M., López-Moreno, J.I., Gimeno, L., Nieto, R., Morán-Tejeda, E., Lorenzo-Lacruz, J., Beguería, S. and Azorin-Molina, C., (2011). A multiscalar global

evaluation of the impact of ENSO on droughts. *Journal of Geophysical Research: Atmospheres*, *116*(D20).

Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., ... and Sanchez-Lorenzo, A. (2012). Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, *16*(10), 1-27.

Vicente-Serrano, S. M., Quiring, S. M., Peña-Gallardo, M., Yuan, S., and Domínguez-Castro, F. (2020). A review of environmental droughts: Increased risk under global warming? *Earth-Science Reviews*, 201, 102953.

Vogt, J.V., Naumann, G., Masante, D., Spinoni, J., Cammalleri, C., Erian, W., Pischke, F., Pulwarty, R. and Barbosa, P., (2018). *Drought Risk Assessment. A Conceptual Framework. EUR 29464 EN. Publications Office of the European Union*. Luxembourg 978-92-79-97469-4 2018.(doi: 10.2760/057223, JRC113937).

Weitkamp, E. McEwen, L., Ramirez, P. (2019) Communicating the hidden": drought risk, water shortage and communities. DRY (Drought Risk and You) Project Report.

Wilhite, D. A. (2006). Drought monitoring and early warning: Concepts, progress and future challenges. *World Meteorological Organization. WMO*, *1006*.

Wilhite, D. A. (2012). Breaking the hydro-illogical cycle: Changing the paradigm for drought management. *Earth*, 57(7), 70–71.

Wilhite, D. A., and Glantz, M. H. (1985). Understanding: The drought phenomenon: The role of definitions. *Water International*, *10*(3), 111–120. https://doi.org/10.1080/02508068508686328

Wilhite, D., and Pulwarty, R. S. (2017). “Drought as Hazard: Understanding the Natural and Social Context” in Drought and water crises: integrating science, management, and policy, eds. D. Wilhite and R.S. Pulwarty (CRC Press), 3-22.

Wilhite, D. A., Sivakumar, M. V. K., and Pulwarty, R. (2014). Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, 3(March 2013), 4–13. https://doi.org/10.1016/j.wace.2014.01.002

3. 2022 Stakeholder Engagement and Capacity Building Events

3.1 Seminar: Advancing Moldova's National Climate Change Adaptation Planning, November 2022

On 25th November 2022 a national conference was organized under the auspices of her excellency the President of the Republic of Moldova Maia Sandu titled “Advancing Moldova's National Climate Change Adaptation Planning”. A report was presented at the conference by Prof. Boris Boincean entitled "Sustainable and climate-smart management of Chernozem soils in Moldova". Simultaneously a brochure was prepared under the title: "Nature-based solutions in adaptation to climate change" Prof. Boincean was nominated as the national consultant for the development of knowledge products in agriculture management and ecosystem services. Participants discussed the issues related to potential decrease in crop yields and adaptation to climate change, in particular to more frequent droughts. The crucial role of soil health was emphasized in providing ecosystem and social services. The causes of soil health deterioration were evaluated and the "Soil Resolution" was offered as the policy document to be promoted by the Parliament of the Republic of Moldova.

3.2 Moldovan engagement with media on climate change impacts and adaptation for crops: Sept 2022

On 8 September 2022, correspondents from 8 TV and Radio companies from Moldova and the European Community met at Selectia Research Institute of Field Crops to discuss the scientific achievements of the institute in decreasing the negative influence of drought and global warming. Prof. Boris Boincean discussed the importance of using non-GMO locally

produced seeds and breed varieties and hybrids for different field crops. The importance of sustainable and resilient soil management systems were emphasized, which reduce the negative impact of global warming and soil erosion from extreme weather conditions.

3.3 Farm Visits in Moldova June 2022

Visits to farmers in different districts of Moldova discussing the problems of soil health and resilience to droughts were undertaken in June. Engagements highlighted that there are good possibilities to see real measures and results in promoting conservation agriculture systems. Guests from the USA, from Colorado State University could also see the real opportunities for improving soil quality, allowing the transition to a more sustainable farming system. During this and other visits to farms we have demonstrated the advantages of no-till sowing of winter cereal crops in reducing production expenses together with improving the quality of the environment and resilience to drought.

4. 2021 Stakeholder Engagement and Capacity Building Events

4.1 Livestream of panel discussion with stakeholders on climate change impacts for agriculture in Germany: November 2021

On the 30th November, Tobias Conradt of PIK was invited by a Bavarian producer of agricultural soil cultivation machinery (Horsch Maschinen GmbH, Schwandorf) to a panel discussion about future yield expectations and climate change related pressures on agricultural production. The German-language talk was video-streamed live on the Internet and covered the emerging findings from CROSSDRO ensuring adaptation plans were informed by research coming from the project.

4.2 Climate change impacts on drought and agriculture in Germany: October 2021

On 21 October Tobias Conradt represented CROSSDRO in an expert hearing about high end climate change (i.e. end of-century conditions under the pessimistic RCP 8.5 emission scenario) consequences for Germany. This was a four-hours virtual meeting with 20 participants from German research institutions and ministries, organized by the Berlin-based Adelphi company and PIK, with a break-out group focusing on drought effects in agriculture and forestry.

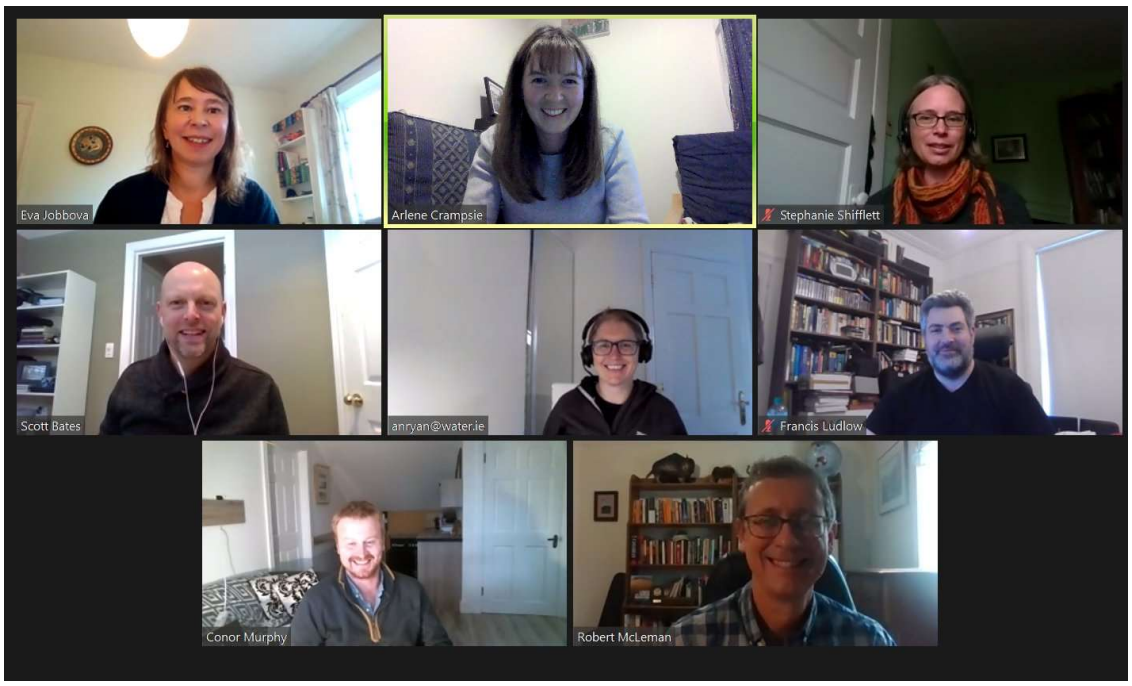
4.3 National Workshop on Drought in Ireland: October 2021

Lessons and insights from the project were disseminated nationally in Ireland via an invited presentation to a technical workshop on droughts organised by the Irish group of the International Association of Hydrogeologists (IAH). At the event Prof. Murphy outlined findings from the European and national scale from CROSSDRO to inform current and future thinking about drought on the island. He also provided an overview of drought impacts in the Boyne catchment using newspaper records and how such impacts can be used to better tailor drought metrics for monitoring and managing droughts in the catchment and across the island.

4.4 National Drought Planning Ireland: July 2021

Prof. Murphy has also had the opportunity to discuss drought and management plans with Irish Water, the national water management agency to ensure that results from the project clearly communicated to this important stakeholder and that their needs for more effective drought management are taken onboard by the project.In 2021, as part of its National Water Resources Plan, Irish Water published a twenty-three page technical appendix outlining activities to be undertaken in conjunction with other agencies (e.g. Met Éireann,

Environmental Protection Agency (EPA), Office of Public Works (OPW), Electricity Supply Board (ESB), Waterways Ireland, Inland Fisheries Ireland (IFI)) to monitor for emergent droughts and communicate risks to the public, and to coordinate conservation measures for water supplies during droughts (Irish Water 2021). Many of the actions described in this drought plan emerged from experience during the 2018 drought crisis and have been undergoing a process of continued refinement in subsequent years. Over two online meetings, lasting 3 hours each, Prof. Murphy and senior managers in Irish Water discussed critical gaps in knowledge, lessons from historical drought for use in drought planning and how climate change is likely to impact on droughts in Ireland.



4.5 Outreach and engagement by Selectia Research Institute: 2021

During 2021 24 seminars with agricultural producers in different districts of Moldova and 6 scientific-practical conferences with the national and international participation were held. Simultaneously the work of the institute was reflected in 22 reports on the national radio and 23 reports on national TV. Field trials with different varieties of winter wheat, winter barley, peas, soybeans have been visited by farmers of Moldova. Long-term field experiments with different crop rotations, systems of soil tillage and soil fertilization have been visited by both local producers as well as official representatives from the Government of Moldova. The director of Selectia Research Institute of Field Crops has participated in two public lectures at the Academy of Sciences of Moldova on topics related to sustainable management of

Chernozem soils in the conditions of global warming and the restoration of seed production in Moldova. These topics are very important especially in the pandemic situation for providing food security of the country.

5. 2020 Stakeholder Engagement and Capacity Building Events

5.1 Stakeholder workshops in Aragón, Spain February 2020

Two workshops were attended by representatives from the agricultural, livestock and forestry sector, the local and regional administration, the field of research, environmental associations and civil society. We introduced the project and noted the wide range of stakeholder perspectives and concerns around the impact of drought on water resources, agriculture, fisheries, forests, ecology and indirectly on tourism and the economy in the region. The project team suggested that tailored early warning systems based on in-depth studies in the region may help them anticipate and prepare for drought events. Participants also highlighted the role of insurance and importance of effective communication when trying to engage with local politicians and the general public.

5.2 National Drought Planning Meeting Ireland: June 2020

Prof Conor Murphy met with national stakeholders regarding the objectives and early output from the project. These included the Irish Environmental Protection Agency, state-run water utility, Meteorological Agency, Geological Agency, Water Forum and the Federation for community managed water supply. Arising from the exceptionally dry spring experienced in Ireland this year and concerns about drought, this high-level group was convened to discuss the communication of drought impacts and warnings. Insight from the project was provided in terms of cross sectoral drought impacts and insights derived from initial engagement with stakeholders.

5.3 Business dialogues in Germany

The project team at the Potsdam Institute for Climate Impact Research took the opportunity to connect CROSSDRO with their business dialogue activities utilizing several meetings and ongoing cooperation with – i.e., Stadtwerke Potsdam (the Potsdam water works), Nordzucker (Germany's second largest sugar producer), Deutsche Bahn (the German national railways), and Vattenfall (Sweden's state-owned electricity provider which operates some of Berlin's thermal power plants).

5.4 *Meeting with Prime Minister of Moldova: July 2020*

The Prime Minister of Moldova visited partner institution, Selectia Research Institute of Field Crops in Balti city. They discussed lessons to be learned by farmers from the very severe drought in 2020 and potential measures that can be undertaken in order to revitalize the seed production for field crops, mainly for local varieties which have proven highly resilient to drought. Meeting participants agreed that challenges faced by modern agriculture, including global warming, can be overcome through the implementation of a new strategy for agriculture intensification based on the principles of agroecology.

6. Special Issue Frontiers in Earth Sciences: Advances in Drought Analytical Tools for Better Understanding of Current and Future Climate Change

Prof. Sergio Vicente Serrano and Prof. Conor Murphy co-edited a special issue of the journal Frontiers in Earth Sciences. This special issue sought to engage with the wider academic community in sharing advances in analytical tools for better understanding current and future droughts. The special issue is now published and contains 11 contributions from across the globe, including an editorial co-authored by CROSSDRO members. The special issue is available at https://www.frontiersin.org/research-topics/21782/advances-in-drought-analytical-tools-for-better-understanding-of-current-and-future-climate-change and has been viewed >18k times with >2.5k downloads. Below we provide an overview of the special issue and the papers published.

6.1 Overview of Special Issue

Drought is one of the most destructive natural disasters in terms of social, economic, and environmental implications, impacting a wide range of hydroclimatic zones worldwide. Droughts are caused by a variety of causes, and their effects can be seen in a variety of socioeconomic sectors and ecological systems, including irrigated agriculture, crop yield, biodiversity, aquatic and riparian habitat quality, water quality, urban and industrial water supply, hydropower generation, etc. These negative consequences are a major issue in the sense of climate change and increased human exposure to water shortages, especially with rapid population growth and urbanization. As such, an improved understanding and accurately and timely forecasting of drought have been seen as a central topic in hydroclimatic research. With access to high-resolution satellite data and high-performance computing resources, modelling approaches, new tools and advanced methodologies can be presented for more effective monitoring, attribution, forecasting, and reliable projections of drought and its impacts at various spatial and temporal scales. This Research Topic addresses advanced techniques and methods in understanding drought processes from local-to-global scales and how these developments can advance current plans and strategies for mitigating drought risks and impacts.

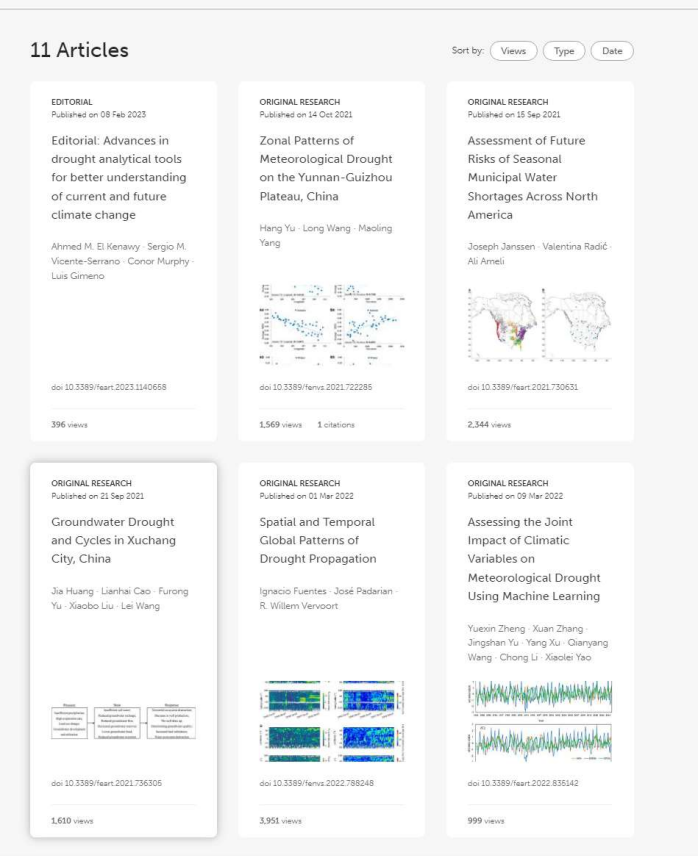
Objectives:

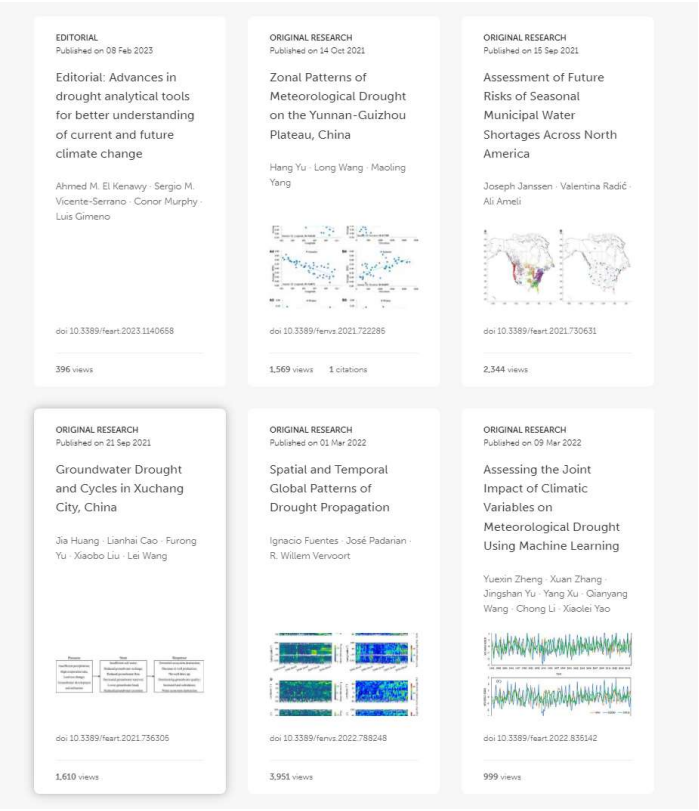
- To examine advanced methods and techniques promoting drought understanding and quantification;
- To highlight changes in different aspects of drought (e.g. meteorlogical, hydrological, and agricultural) across different climatic zones worldwide;
- To know techniques of drought attribution;
- To propose new approaches to determine physical drivers of drought (including atmospheric dynamic);
- To assess possible implications of Earth Observation in advancing drought research;
- To assess uncertainties in drought simulations and projections, including drought forecasting.

This Research Topic may cover, but is not limited to, the following aspects:

- The use of machine learning and artificial intelligence to aid drought monitoring and preparedness;
- Statistical techniques for drought quantification based on different drought metrics (including Earth System Models);
- Methods for drought attribution;
- Earth Observation (EO) for drought assessment and mitigation;
- Integrated data fusion and mining approaches for drought assessment;
- Assessing the performance of different downscaling approaches for drought assessment;
- Future drought risks under different climate scenarios and model configurations;
- Predicting drought on seasonal to decadal scales;
- Challenges, opportunities, and progress in drought quantification in arid and semi-arid regions;
- New paradigms and techniques to assess drought mechanisms related to atmospheric dynamic;
- Exploring the links between drought and other natural hazards (e.g. forest fires, heatwaves, vegetation browning, etc);
- Developments in assessing the impacts of environmental and socioeconomic impacts of drought;
- Strategies to adapt effectively to current and future changes in drought severity;
- Local-to-global drought monitoring system

6.2 Papers published



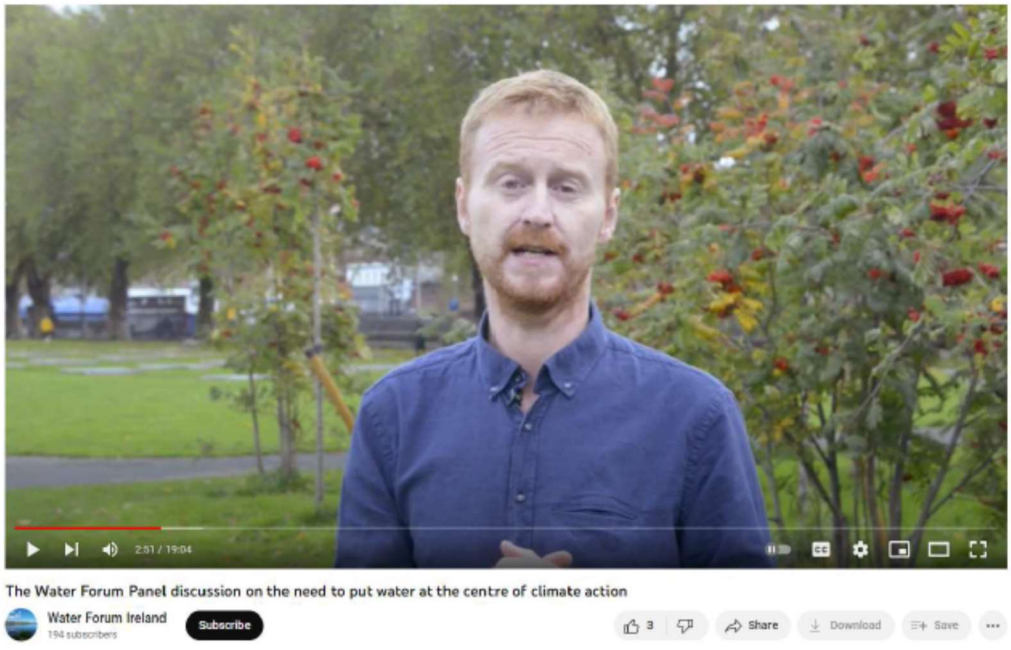


7. Sample Media Engagements from CROSSDRO

Prof. Vicente-Serrano on CNN Chile to discuss drought

https://www.youtube.com/watch?v=47f8RFfqIHo

Prof. Conor Murphy highlights the need to put water at the centre of climate action as part of Ireland's national Science Week.



https://www.youtube.com/watch?v=kSmZUs_Z8ig

The lack of rain and the decrease of reservoir water increase the fear of drought in Spain
https://www.lavanguardia.com/vida/20220208/8040323/temperatura-enero-consolidatendencia-inviernos-vez-mas-calidos.html

In Spain it does not rain less, but the temperatures are getting warmer
https://www.csic.es/es/actualidad-del-csic/sergio-vicente-en-espana-no-llueve-menos-perolas-

temperaturas-son-cada-vez-mas

Is it possible to predict a drought? These Spanish scientists try

https://www.elconfidencial.com/tecnologia/ciencia/2022-02-25/prevision-sequia-espana-faltalluvias_3379047/

La Niña hits half the world and fuels drought in Spain
https://www.abc.es/sociedad/abci-nina-golpea-medio-mundo-y-alimenta-sequia-espana-202202280024_noticia.html?ref=https%3A%2F%2Fwww.abc.es%2Fsociedad%2Fabci-nina-golpeamedio-
mundo-y-alimenta-sequia-espana-202202280024_noticia.html

What will happen if we continue without rain and the drought continues?
https://www.ondacero.es/programas/julia-en-la-onda/audios-podcast/entrevistas/que-sucederaseguimos-lluvias-continua-sequia_20220301621e578de2af800001dc75d9.html

A lethal avalanche and a historic drought: climate change hits northern Italy
https://elpais.com/clima-y-medio-ambiente/2022-07-06/un-alud-letal-y-una-historica-sequia-elcambio-
climatico-castiga-al-norte-de-italia.html

Reduce water in the city? It will be one of the largest droughts in a hundred years.
https://www.diariodepontevedra.es/articulo/pontevedra/reducir-agua-ciudad-sera-sequias-masgrandes-
cien-anos/20220801123407121235 1.html

The priority is always to maintain the urban water supply
https://www.laverdad.es/sociedad/prioridad-siempre-mantener-20220812135815-ntrc.html

A CSIC researcher reveals how water will be distributed in the droughts of the future
https://www.cope.es/programas/la-linterna/noticias/investigador-del-csic-desvela-como-repartiraagua-
las-sequias-del-futuro-20221005_2327653

"The prospects for the future are not very good": a CSIC expert explains what we can do to alleviate the effects of drought
https://cadenaser.com/nacional/2022/11/22/las-perspectivas-para-el-futuro-no-son-muy-buenas-unexperto-del-csic-explica-que-podemos-hacer-para-paliar-los-efectos-de-la-sequia-cadena-ser/

Podcast: Drought and its cycles
https://programaagroconciencia.blogspot.com/2022/11/sequia-ciclos.html

Is this winter our fault?
https://www.elcorreo.com/sociedad/invierno-culpa-20230108100701-ntrc.html

What does climate change mean for Irish rivers?

https://www.rte.ie/brainstorm/2022/0519/1299872-irish-rivers-climate-change/

The subtle danger climate change poses to 'highly vulnerable' Ireland
https://www.irishtimes.com/environment/climate-crisis/2022/11/10/the-subtle-danger-climatechange-
poses-to-ireland/

Royal Irish Academy Blog Series: Drought: a risk being overlooked in Ireland?

https://www.ria.ie/news/science-committees-climate-change-and-environmental-sciences-committee-climate-change-blog-1