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OVERVIEW

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Droughts in forested ecoregions in cold and continental climates: A review of vulnerability concepts and factors in socio-hydrological systems

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Abstract

In a changing climate, drought risk and vulnerability assessments are becoming increasingly important. Following the global call for proactive drought risk management, drought vulnerability assessments are progressively taking their stage in the drought research community. As the manifestation of drought vulnerability is dependent on the social, ecological, and hydroclimatic context in which it occurs, identifying vulnerability factors relevant for specific climatological and ecological regions may improve the quality of vulnerability assessments. Meanwhile, a holistic overview of factors affecting vulnerability in polar and cold climates is currently lacking. These regions are home to large socio-hydrological systems including urban areas, energy systems, agricultural practices, and the boreal forest. By conducting an interdisciplinary systematic literature review, the manifestation and conceptualization of drought vulnerability were identified for forested ecoregions in the Köppen–Geiger D and E climates. Vulnerability factors, as described by several scientific disciplines, were identified and combined into a conceptual framework for drought vulnerability in the study region. The results demonstrate the wide range of conceptualizations that exist for assessing drought vulnerability, and the thematic differences between sectors such as forestry, water supply, and agriculture. The conceptual framework presented herein adopts a novel approach, categorizing vulnerability factors by their location in a socio-hydrological system, and their relation to blue or green water sources. This allowed for identification of systemic vulnerability patterns, providing new insights into regional differences in drought vulnerability and a base for stakeholders performing proactive drought risk assessments in the study region.

This article is categorized under:

- Human Water > Methods
- Science of Water > Water Extremes
- Water and Life > Conservation, Management, and Awareness
- Human Water > Water Governance

KEYWORDS
agriculture and forestry, drought risk assessment, socioeconomic and cultural systems, vulnerability factors, water resources and supply

1 | INTRODUCTION

During the period of 1995–2015, an estimated 1.1 billion people were affected by drought globally (Ward et al., 2020). It is one of the most complex and costliest hazards and disasters (Kim et al., 2015; Meza et al., 2020; van Loon, 2015) with the potential of affecting many parts of the socio-hydrological system, from the system as a whole down to the individuals. Often confused with water scarcity, drought occurs due to climatic variability that creates a regional water deficit compared with normal conditions. It is a recurrent slow-onset phenomenon that can occur in virtually all climatic zones (Wilhite, 1996). Even though droughts are often perceived primarily as an issue in arid or semi-arid regions, recent events have reminded us that it can also occur in colder and more humid climate zones, such as the 2018 drought affecting large parts of Europe including Scandinavia (Bakke et al., 2020; Teutschbein et al., 2022). Due to its complex nature and region-specific mechanisms (Hisdal & Tallaksen, 2003), a common categorization of the drought hazard is based on where in the hydrological system it occurs, differentiating it into four types: meteorological (precipitation deficit sometimes combined with evapotranspiration), soil moisture (soil moisture deficit), hydrological (negative anomalies in surface or groundwater), and socioeconomic drought (impacts on water as an economic good; Mishra & Singh, 2010; van Loon, 2015; Wilhite & Glantz, 1985). Nevertheless, due to the intricate nature of drought propagation, the four drought types are interconnected with both positive and negative feedback loops between them (van Loon, 2015).

The scale and cascading systemic impacts of a drought can be wide ranging, as it affects key sectors of society such as agriculture, forestry, water supply, or energy production, as well as provision of numerous ecosystem services (UNDRR, 2021). Moreover, drought impacts often evolve over long time periods as a combination of direct and indirect effects that can appear long after the drought event itself has ended, making it difficult to fully apprehend its effects. By analyzing drought risk, the understanding of how droughts propagate and impact our societies can be developed and system resilience can be improved. As several international initiatives have advocated the need for proactive risk management (EDC, 2013; UNCCD, 2018; UNDRR, 2021), an increasing amount of drought risk assessments are being produced (Hagenlocher et al., 2019; Mishra & Singh, 2011), often defining risk as the product of three components: hazard, exposure, and vulnerability (UNDRR, 2021). The three-component definition of risk recognizes not only the hazard component, but also the importance of the socio-economic contexts contributing to risk (Birkmann, 2013), and implies that for a hazardous event to turn into a disaster, there must be entities exposed and these entities must be vulnerable to the hazard (Meza et al., 2020; UNDRR, 2019).

While hazard assessments focus on parameters relating to the drought phenomenon itself, drought exposure and vulnerability assessments focus on the elements or systems affected by the hazards (UNDRR, 2021). According to IPCC AR5, exposure refers to the entities exposed to the hazard, for example, people, livestock, or crops (IPCC, 2014). Exposure and vulnerability are interlinked, with exposure traditionally being regarded as a sub-component of vulnerability (Adger, 2006; Turner et al., 2003), representing the characteristics of the hazard (i.e., magnitude, severity, duration). In recent years, a shift in perspective acknowledges the equal significance of both exposure and vulnerability as integral components of risk assessments (IPCC, 2014). Although vulnerability is a widely used concept in society, it has proven difficult to define and conceptualize (Fuchs & Thaler, 2018; Füssel, 2007). In its essence, vulnerability can be broadly described as the predisposition to be harmed by an external stressor (Füssel, 2007; Turner et al., 2003). However, how to describe and formulate this predisposition will depend on aspects such as the time-frame, the stressor (Adger, 2006), and the place (Turner et al., 2003). As a result, a common interdisciplinary understanding of vulnerability is lacking (Ciurean et al., 2013; Fuchs & Thaler, 2018), and its definitions often include other complex concepts such as resilience, susceptibility, sensitivity, or capacity to cope and/or adapt. One common definition of vulnerability within the disaster risk management (DRM) community is "*The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards*" (UNDRR, 2021). Another commonly adopted definition of vulnerability stems from the IPCC's (2007) fourth assessment report (AR4), defining vulnerability as a "*function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system.*" This definition was updated in the fifth assessment report (AR5) and is still used in the sixth assessment report (AR6), where the exposure component is replaced by the capacity to cope (IPCC, 2014, 2022), thereby stating that "*vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*". The choice of definition will affect how vulnerability is conceptualized and which components are assessed. As an example, the inclusion or exclusion of the exposure component will affect the operationalization of vulnerability in vulnerability assessments, where the former often implies inclusion of hazard components, thereby positioning the assessment closer to what the DRM community would describe as a risk assessment (Birkmann, 2013). As vulnerability is studied in many scientific disciplines, ranging from disaster research, economics, sociology to ecology as some examples (Fuchs & Thaler, 2018; Füssel, 2007), a wide range of conceptualizations exists, from human-centered vulnerability excluding biophysical systems to coupled human–environment systems (Adger, 2006). However, various fields such as disaster science, climate change, and sustainability research are progressively recognizing the significance of interdisciplinary research collaborations. Thus, understanding and communicating the conceptual differences, as well as clearly defined terminology across scientific disciplines is of high importance (Füssel, 2007).

The drought community also acknowledges the distinctions among drought vulnerability concepts, components, factors, and indicators (as outlined in Box 1). Despite the diverse vocabulary employed in discussions surrounding drought vulnerability, it is widely understood within the community that each of these three terms plays a crucial role in the understanding and assessment of drought vulnerability.

Measuring drought vulnerability is intricate. One of the traditionally most common methodologies is indicator- or index-based, combining one or more indicators describing different factors of vulnerability to form a representation of the vulnerability dynamics of a system. Depending on the study focus and scale, several indicators may be weighted, ranked, and combined into a composite index (Blauhut et al., 2016; Ciurean et al., 2013; Hagenlocher et al., 2019), often relying on expert knowledge, stakeholder involvement, and statistical analysis (Blauhut et al., 2016; Meza et al., 2020). Other quantitative approaches use past drought impacts or simulation models to measure and assess system vulnerability, whereas qualitative approaches often aim to describe and assess vulnerability using qualitative tools, for example, storylines or narratives (Hagenlocher et al., 2019).

In recent years, several index-based vulnerability assessments have been produced, examining vulnerability from a wide range of conceptual frameworks and ranging from global to local scale, system to sector, or social to hydrological perspectives (González Tánago et al., 2016; Hagenlocher et al., 2019; Zarafshani et al., 2016). However, the relative

BOX 1 Vulnerability terminology

A vulnerability ***concept*** is a generalized idea or abstract notion that represents a category of things, phenomena, components, factors, conditions, or relationships that contribute to vulnerability in the face of drought. In the context of drought vulnerability, it is a mental construct that helps us understand and organize information, and that encompasses multiple components and factors that collectively contribute to the overall vulnerability.

A vulnerability ***component*** refers to a specific aspect or attribute that contributes to the overall vulnerability to drought. These components represent distinct domains or properties of a system (e.g., susceptibility, coping capacity, or adaptive capacity) that are influenced by various factors and shape vulnerability. Each component represents a different facet of vulnerability that needs to be assessed and addressed.

Drought vulnerability ***factors***, on the other hand, pertain to individual elements or variables that contribute to or influence a particular phenomenon or outcome. These factors represent distinct causes or components within a larger system or process, for example, water stress. It is crucial to note that factors can be independent or dependent, and they are often identified through empirical research or analysis. By exploring these underlying factors, the complex dynamics associated with drought vulnerability can be better understood and effectively addressed. They can be measured and monitored using vulnerability indicators.

Drought vulnerability ***indicators*** are developed to monitor, measure, and quantify vulnerability factors. They can be subjected to statistical analysis to explain observed vulnerability patterns and drought impacts as well as identify potential vulnerability hotspots. Indicators can also be combined into forming indices. For example, the previous example of the vulnerability factor 'water stress' can be assessed using an index such as the Water Exploitation Index (WEI), which comprises indicators for water demand and long-term average freshwater resources.

importance of the vulnerability factors used depends on several aspects, such as historical hydrological conditions, management practices, and cultural context (Taylor et al., 2009). This would imply that particular vulnerability factors may be of differing importance depending on the on-site hydroclimatic and social settings of the region being considered (McEwen et al., 2021).

Despite a presumed regional variation of vulnerability factors, the existing scientific literature focuses to a large extent on dry or tropical climates (Hagenlocher et al., 2019). While arid climate zones (group A) in the updated Köppen–Geiger climate classification system (Beck et al., 2018) are indeed the dominant class by land area (30%), cold/continental climate zones (group D) are the second most dominant climate types globally (25%), with the majority of the climate zone accounting as humid cold without a dry season (Df; Peel et al., 2007). Furthermore, in combination with polar climate zones (group E, 13%), the two climate zones cover more than a third of global landmass and are home to the majority of the world's boreal forests—the second-largest terrestrial biome (Keenan et al., 2015), which is of high socioeconomic and biophysical importance (Buermann et al., 2014). Consequently, other aspects, such as susceptibility of forest ecosystems or of sectors such as the paper and pulp industry, may play a crucial role in vulnerability assessments in these regions. Recent literature reviews on drought vulnerability have targeted human-centered sectors (González Tánago et al., 2016; Hagenlocher et al., 2019) such as agriculture or drinking water, so far excluding sectors linked to forests. A holistic overview of vulnerability factors that considers spatiotemporal scales, sectors, social, and hydrological aspects relevant for the ecological and climatological setting of traditionally cold climate regions (D and E) with a large share of forested areas is currently lacking.

To address this research gap, this article provides a systematic literature review focusing on cross-national, national, and subnational vulnerability studies and assessments in D- and E-climate zones in ecoregions classified as forest or tundra. The review is based on current understanding of drought vulnerability being dependent on hydroclimatic and cultural settings and highlights how vulnerability has, and is currently being conceptualized in the regions in question. The results aim to provide an overview of vulnerability factors currently used to describe or assess vulnerability in the study region. We also offer a conceptual framework to guide drought vulnerability assessments in these regions, and discuss current knowledge and future research needs.

2 | REVIEW OF SCIENTIFIC LITERATURE

To identify vulnerability factors relevant for forested countries in cold climate regions, we designed a systematic literature review to identify: (1) vulnerability factors described as and/or used for representing vulnerability dynamics in socio-hydrological systems in these regions, (2) conceptualizations of drought vulnerability, and (3) potential categories of drought vulnerability factors that are used in these regions.

The literature review focused on regions following the global climate classification by Köppen–Geiger for cold/continental and polar climate regions (group D and E) located in ecoregions classified as forest or tundra. Countries with a majority of their territory located in these regions were selected for the literature review.

2.1 | Search strategy

The literature review was conducted between December 2021 and March 2022 using the Scopus and Web of Science (WoS) databases. We only considered sources written in English and published in peer-reviewed scientific journals. With the purpose of identifying all articles addressing any component of drought vulnerability, broad search formats were selected and combined in a systematic order (Table 1). To narrow the search results to the desired climate regions, the search terms were combined with the country/region name (e.g., Latvia) and the corresponding adjective (e.g., Latvian) in each search. In Scopus, articles containing "drought" in the title or abstract were selected. In Web of Science, articles containing "drought" in the topic (i.e., title, abstract or keywords) were selected.

2.2 | Screening process and eligibility criteria

The search for relevant literature with the above search terms (Table 1) generated an initial list of 723 articles for the selected climate zones. The search return rate was high, with 80% of the country and region searches returning at least

TABLE 1 Search term combinations used in the systematic literature review.

Source	1st term	2nd term	3rd term
Scopus	TITLE-ABS (Drought)	TITLE-ABS-KEY (Vulnerability)	Austria*; Belarus OR Belarusian; Canada OR Canadian; Czech; Estonia*; Nordic OR *Scandinavia*; Finland OR Finnish; Germany OR German; Latvia*; Lithuania*; Norway OR Norwegian; Poland OR Polish; Russia*; Slovakia OR Slovak; Sweden OR Swedish; Switzerland OR Swiss; Ukraine OR Ukrainian; Romania*; Hungary OR Hungarian; *Boreal; Central Europe*;
WoS	Drought (Topic)	Vulnerability (Topic)	
Example	Scopus	TITLE-ABS (drought) AND TITLE-ABS-KEY (vulnerability) AND (Latvia OR Latvian) AND (LIMIT-TO (DOCTYPE," ar")) AND (LIMIT-TO (LANGUAGE," English"))	
	WoS	Drought (Topic) AND Vulnerability (Topic) AND (Latvia OR Latvian) (Topic) and Articles (Document Type) and English (Languages)	

Note: All possible combinations of search terms from each column were used to identify relevant articles in the Scopus and Web of Science databases. The asterisk (*) is used when country/region name and adjective include same word but have different beginnings/endings and to find all possible variations of a region name. For example, *Scandinavia* retrieves search results for both Fenno-scandinavia, Scandinavia, and Scandinavian.

one search result. Belarus, Iceland, Lithuania, and Latvia did not return any search results. The removal of duplicates within and across the two databases resulted in a list of 364 unique articles, which were subject to an initial assessment based on the title and abstract of the articles using the following set of criteria for inclusion or exclusion:

1. *Climate region*: Only articles within the selected climate- and ecoregions of this review (i.e., climate group D and E with forest and tundra biomes) were included.
2. *Spatial scale*: Only articles of local, national, and cross-national scale were included.
3. *Drought vulnerability*: Only articles with a clear focus on drought vulnerability or one of the commonly used components of drought vulnerability (i.e., susceptibility, capacity to adapt/cope, etc.) were considered. This implies that we excluded articles that (1) studied climate change broadly without specific focus on drought, (2) solely assessed vulnerability/risk of other hazards (wildfire, heat wave, flood, etc.), (3) focused on compound events without separately studying vulnerability to drought, (4) only studied drought as a hazard, or (5) studied mitigation measures and strategies during a drought event.
4. *Functional scale*: Only articles with a functional scale that allowed for cross-national generalization within the study region were included. Consequently, articles focusing specifically on drought vulnerability of local ecological systems or species without connection to a specific sector were excluded from the review.
5. *Language*: We only considered articles available in English.

Based on title and abstract, all 364 articles were broadly categorized into their overall thematic focus (agriculture, environment, water resources, holistic, socioeconomic, forestry and forest ecosystems (labeled: forestry), energy and industry, other/unspecified). Because of the disproportionally large number of articles categorized as forestry (29% of articles in this initial assessment), only articles related to *modeling and assessments* and *forest management* were included in this category, eligible for further assessment along with articles from the other categories.

The initial assessment of all 364 articles led to the identification of 194 potentially relevant articles that were open-access or available through university subscription and eligible for a subsequent in-depth assessment. These articles were evaluated against the same criteria above, this time based on the full contents of the articles. The in-depth assessment resulted in a final set of 55 relevant articles that were subsequently included in the review.

2.3 | Data synthesis and conceptualization of results

The final set of eligible articles was analyzed following a search protocol to ensure that all articles were evaluated against the same assessment criteria. These criteria included information on vulnerability definitions and conceptualizations, geospatial distribution and scale, thematic focus, methodological approach, time scale of study, identified vulnerability factors, and water consumption perspective. For the water consumption, all articles were categorized into focusing mainly on blue or green water (or both), following the conceptualization made by Falkenmark and Rockström (2006): blue water represents all water available in surface water and groundwater bodies (e.g., lakes, dams, aquifers, rivers), while green water refers to the water that has naturally infiltrated into the soils and is stored as soil moisture in the unsaturated zone. The latter can be taken up by vegetation and evapotranspired back into the atmosphere. All factors described or used as being related to vulnerability in the articles were recorded.

The resulting list of vulnerability factors was grouped and analyzed in relation to thematic focus or socio-hydrological processes (e.g., governance processes), as well as the connection to direct and indirect consumption of blue and green water sources. All factors were categorized as relating to either blue water, green water, or as being universal, that is, pertinent regardless of water type consumption (such as the existence of a drought management plan, monitoring, and forecasting schemes or risk management tools). The resulting list was condensed by aggregating factors with similar focus (but different phrasing) into a more general term, for example, factors expressed as indices in highly operational terms (e.g., water depletion index, water exploitation index or % area with high water stress) were re-categorized into the overarching factor they were meant to represent (e.g., water stress) as described in the articles from which they were derived.

The analysis of identified factors and their categorization resulted in a conceptualization of vulnerability from the perspective of water source and consumption in socio-hydrological systems located in forested countries in cold climates.

3 | SYNTHESIS OF RELEVANT DROUGHT STUDIES

3.1 | Study characteristics

3.1.1 | Publications over time

The earliest publication included in the review was published in 1997 and the most recent six articles were published in 2021. The articles included were distributed over time, with an average of 2.2 articles per year since 1997 (Figure 1). From 2011 and onward, the number of annually published articles relating to drought vulnerability in the study region increased, with an average of 4.5 articles published per year between 2011 and 2021.

3.1.2 | Conceptual frameworks and definitions

Half of the articles neither defined vulnerability nor described how it was conceptualized (51%, see Figure 1). This was particularly frequent among forestry articles, of which 76% lacked a definition of vulnerability. The most commonly

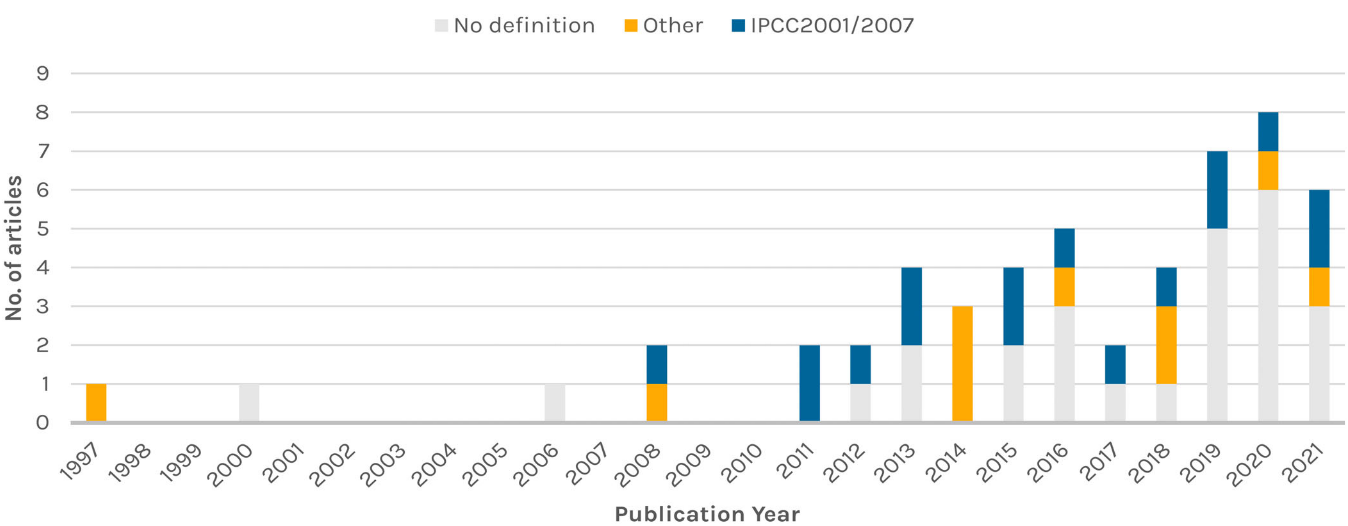

FIGURE 1 The number of articles published per year between the period 1997–2021 and the definitions used for vulnerability in the articles included in the overview.

adopted definition among the articles (31%) was provided by the IPCC AR3 and AR4 (IPCC, 2001, 2007). The latest definition for vulnerability used in IPCC AR5 and AR6 (IPCC, 2014, 2022) was not used in any of the reviewed articles, even though more than half of the articles were published after the AR5 release. The remaining articles (18%) adopted alternative definitions of vulnerability.

In addition, several approaches for measuring adaptive capacity, a subsidiary concept to vulnerability according to IPCC AR5 (IPCC, 2014), were seen in the literature. For instance, in their study of social capacities for proactive and reactive drought risk management in Switzerland, Kruse and Seidl (2013) linked adaptive capacity to the concept of social capacities, where adaptive capacity itself was divided into five categories (information and knowledge, technology and infrastructure, organization and management, economic resources, policies and institutions). Meanwhile, Hurlbert and Gupta (2017) performed a comparative assessment of adaptive capacity by using the adaptive capacity wheel (ACW), a qualitative assessment tool that incorporates six sub-categories to vulnerability (fair governance, variety, learning capacity, room for autonomous change, leadership, resources), each of which having three to six sub-categories themselves.

3.1.3 | Geographical and spatial distribution

Approximately 30% of the articles focused on drought vulnerability in Canada (Figure 2a) where most articles were performed at sub-national scale (56% of Canadian articles) covering a range of different climates, from humid cold (22%) to semi-arid or arid (33%). Some Canadian articles simply described their areas as water-rich (11%) or dry or drought-prone (33%). On the European continent, 40% of the articles looked at drought vulnerability in Central Europe (including Austria, Czech Republic, Germany, Hungary, Poland, Slovakia, and Switzerland). This region includes Germany and Hungary, the two European countries with the second and third most articles related to drought vulnerability (13% and 11% of reviewed articles, respectively). Five articles performed comparative cross-continental analyses, comparing vulnerability across several countries located both inside and outside our study region. For instance, Acosta and Galli (2013) and Alcamo et al. (2008) performed comparative drought vulnerability assessments for case studies in Portugal, India, and Russia. Hurlbert and Montana (2015) and Hurlbert and Gupta (2017) investigated categories of adaptive governance in Canada, Chile and Argentina, while Raikes et al. (2021) explored integration between disaster risk reduction

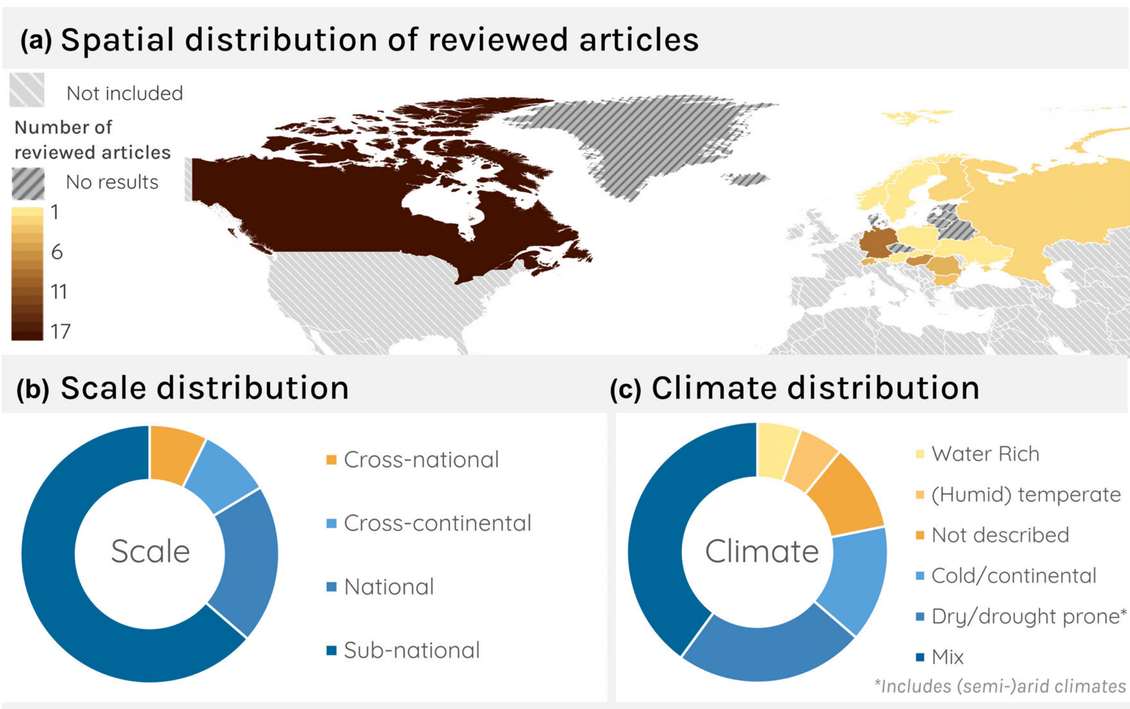

FIGURE 2 Overview of the study characteristics of all 55 reviewed articles: (a) distribution of articles per country, where darker shades imply a greater number of articles, (b) spatial scale, and (c) climate types.

and human development through semi-structured interviews and Delphi studies in Australia and Canada. Most studies were performed at sub-national scale (Figure 2b), with only 11 articles conducted at national and 5 on cross-national scale. National-scale assessments were conducted for Canada (4 articles), Switzerland (2), Hungary (2), Finland (1), Bulgaria (1), and Romania (1). Cross-national scale assessments were performed on the European continent, focusing either on vulnerability on a pan-European scale (Buras & Menzel, 2019; Olesen et al., 2011; Williges et al., 2017) or the Carpathians (Bosela, Tumajer, et al., 2021). Many articles included a mix of climate types (40%; Figure 2c), followed by a focus on dry or drought-prone climates within the countries (24%). Approximately 15% of the articles specifically described focusing on humid cold/continental climate regions or boreal climates, and 5% described the study region as being water abundant or water-rich. Around 11% of the articles did not describe the climate in the study region.

3.1.4 | Thematic coverage

Five different thematic foci were seen in the literature (Figure 3a), where most articles were related to forestry (31%), followed by agriculture (27%), holistic perspectives (15%) and water resources & supply (15%). Only 13% of the articles were categorized as focusing on socio-economic or -cultural systems. Central European countries followed by North American ones (particularly Canada) had the greatest number of forestry-related articles, whereas no forestry-related articles were identified for Eastern Europe (Figure 3b). Studies with a focus on agricultural vulnerability were found in all regions, where Central and Southern Europe stood out as having the most articles related to this topic. Among the forestry articles: pine (Pinus genus) was studied in 71% of all forestry articles (Figure 3c), followed by spruce (*Picea*, 65%) and beech (*Fagus*, 59%). Among the articles focusing on Europe, 41% centered on Scots Pine (*Pinus sylvestris*), 35% on Norway Spruce (*Picea abies*) and 47% on European Beech (*Fagus sylvatica*). Among the articles targeting

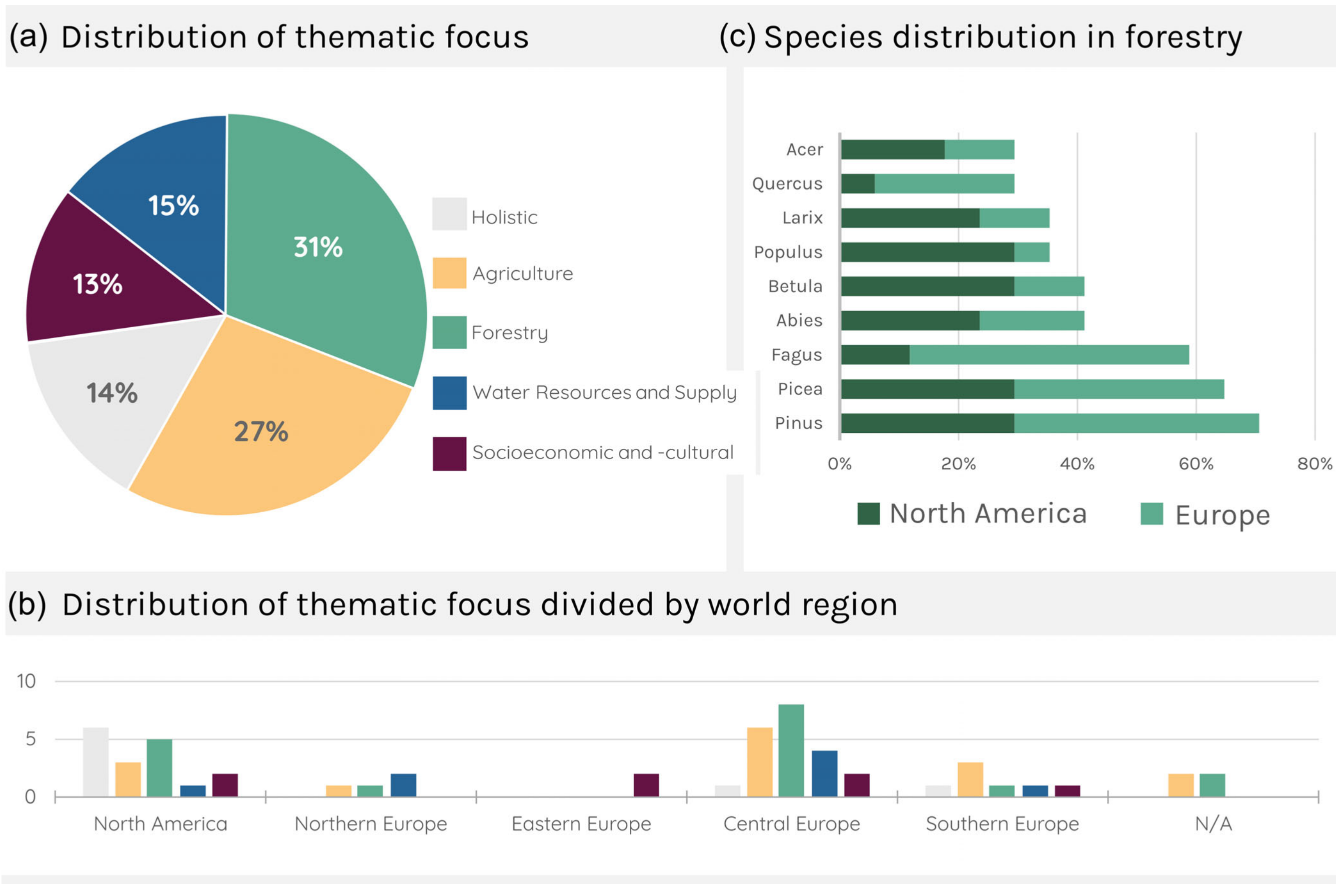

FIGURE 3 Thematic distribution of articles: (a) distribution of thematic foci for all 55 articles included in review, (b) thematic foci distribution among articles, divided by world region, N/A relates to cross-national articles on the European continent. (c) Species foci of articles specifically studying forest vulnerability.

North America, 29% addressed Jack Pine (*Pinus banksiana*), 29% Black spruce (*Picea mariana*), and 12% American Beech (*Fagus grandifolia*). Other tree species commonly studied in North America were Balsam poplar (*Populus balsamifera*), Trembling Aspen (*Populus tremuloides*), and Paper Birch (*Betula papyrifera*).

3.2 | Commonly used methods, timescale, and vulnerability factors

3.2.1 | Methodological approaches

The reviewed literature had different objectives when studying vulnerability. Most articles' main goal was either to assess vulnerability for a specific system (49%) or to better understand factors that influence vulnerability, including the performance of different measures (45%). The remaining articles specifically focused on the development of a vulnerability index or framework (5%; Figure 4). To achieve these objectives, several different methods were used. The most common methodologies were index-based approaches (31% of articles, Figure 4) which were used for studying vulnerability in all sectors identified in the review (Table 2).

Forestry stood out compared with most other sectors, as only 3 out of 17 articles related to forestry were considered to be solely index-based (Table 2). Instead, articles focusing on forestry mainly used simulation models (47% of forestry papers, 27% of all articles) such as growth or forest simulation models. The models often incorporated several site-specific input parameters such as climate variables and climate scenarios, soil properties or elevation, but managerial approaches and treatments were also studied by looking at their modeled effect on drought impacts. Brecka et al. (2020), for example, evaluated Canadian forest vulnerability over a 200-year period, comparing future scenarios for high versus low-intensity clear-cutting treatments, whereas Albert et al. (2015) compared three silvicultural management strategies in relation to forest vulnerability to drought stress in current and future climate. Several studies highlighted the need for long temporal scales to provide decision support for management practices due to the typically long rotation periods in forest stands (Albert et al., 2015; Buras & Menzel, 2019).

Across the reviewed articles, simulation models were only used in articles studying vulnerability relating to forestry (47% of forestry papers), agriculture (33%), and water resources and supply (29%). Some of these models did, however, incorporate different forms of vulnerability indices such as drought resistance indices (Zamora-Pereira et al., 2021), drought resilience indices (Sidor et al., 2019; Zamora-Pereira et al., 2021), and different forms of drought threshold values (Boucher et al., 2020; Lochhead et al., 2019) for forestry, or the water depletion index (Ahopelto et al., 2019) for assessing vulnerability to water supply. Other articles using simulation models focused instead on the modeled impacts based on different model parameters (e.g., Albert et al., 2015; Bloch et al., 2015). Qualitative approaches (16% of all articles)

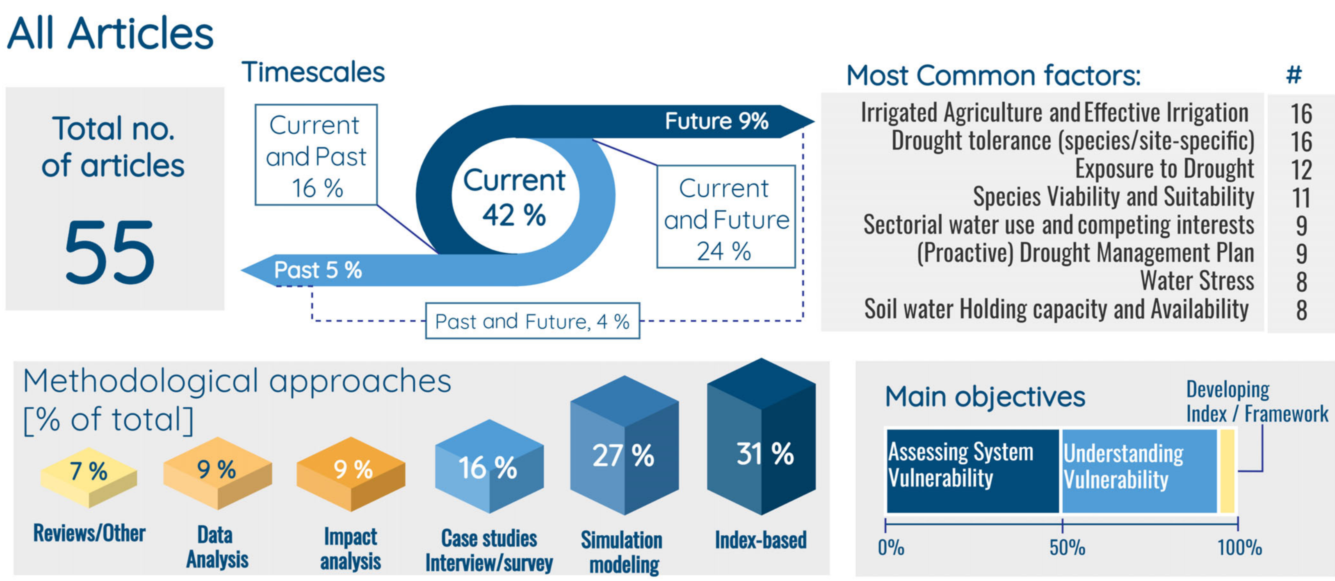

FIGURE 4 Overview of methodological approaches and most common vulnerability factors mentioned in articles for all reviewed articles (with additional information on article objectives and temporal scales).

TABLE 2 Overview of methodological approaches for each of the five thematic foci identified in the review.

	Agriculture	Forestry	Holistic	Socioeconomic and cultural	Water resources and supply
Index-based	6	3	2	3	3
Simulation modeling	5	8	0	0	2
Case study, interview/surveys	2	0	4	3	0
Impact analysis	1	3	0	1	0
Data analysis	1	1	1	0	2
Review	0	2	1	0	0
Other	0	0	0	0	0
Total no. of articles	15	17	8	7	7

were also used by incorporating stakeholder knowledge and opinions through interviews (Disch et al., 2012; Hurlbert & Montana, 2015), surveys (e.g., Kruse & Seidl, 2013; Olesen et al., 2011), workshops (Hill et al., 2014; Kruse & Seidl, 2013), or focus groups (McMartin et al., 2018). Five articles looked at vulnerability in connection to impact analyses using other approaches than simulation models (Bosela, Stefancik, et al., 2021; Bosela, Tumajer, et al., 2021; Buras et al., 2018; Erfurt et al., 2019; Xu et al., 2012).

Among the reviewed literature, temporal resolution ranged from past events to future projections (Figure 4). The most common approach was to look at current conditions (42%) followed by combinations of current conditions and future projections (24%) or current conditions and past events (16%). Nine percent of the literature was solely focusing on future projections, compared with 5% studying past events. Current and/or future projections were most common in articles focusing on agriculture (53% of agricultural articles) or forestry (47%) vulnerability.

3.2.2 | Vulnerability factors in literature

A large number of vulnerability factors were identified in the review. While many factors only occurred in a single article, some vulnerability factors frequently appeared in relation to drought vulnerability (Figure 4). The most frequently used factors were related to irrigated agriculture and effective irrigation (30%), species- and/or site-specific drought tolerance (30%) and exposure to drought (22%). Irrigation was mentioned in articles with a sole focus on agricultural systems, as well as in articles with a holistic or socioeconomic or -cultural perspective (Figure 5), where the articles stressed the importance of both having irrigation systems in place (Buzasi et al., 2021; Hurlbert & Montana, 2015; Pappné Vancsó et al., 2016) and having effective irrigation systems (De Stefano et al., 2015; Gan, 2000). Drought tolerance was a recurrent factor in articles looking at agricultural systems or forestry.

Forestry-centered articles evaluated drought tolerance using a variety of indicators, for example, drought threshold values (Lochhead et al., 2019; Salamon-Albert et al., 2016) and response ranges (Salamon-Albert et al., 2016), as well as indices measuring recovery (Zamora-Pereira et al., 2021), resilience (Sidor et al., 2019; Zamora-Pereira et al., 2021), resistance (Bosela, Tumajer, et al., 2021; Zamora-Pereira et al., 2021), sensitivity (Aubin et al., 2018; Boisvert-Marsh et al., 2020), and drought-induced mortality rates (Zamora-Pereira et al., 2021). Many of these indices were related to drought impacts. For example, three of the articles using the aforementioned indices incorporated indicators of growth rate such as basal area increments or mean annual increments for assessing the site-specific drought tolerance (Bosela, Tumajer, et al., 2021; Sidor et al., 2019; Zamora-Pereira et al., 2021).

The third most commonly used vulnerability factor in the reviewed literature was exposure to drought (Figure 5), repeatedly measured using drought hazard indices such as the Standardized Precipitation Index (Popova et al., 2014; Xu et al., 2012), Standardized Groundwater Drought Index (Minea et al., 2020), the Palfai Drought Index (Buzasi, 2021; Buzasi et al., 2021), and the Climate Moisture Index for forest vulnerability (e.g., Aubin et al., 2018; Brecka et al., 2020).

Among articles focusing on water resources and supply (Figure 5), as well as articles having a holistic perspective, factors concerning water availability were among the most frequently used. For instance, water stress was included in six out of eight articles looking at vulnerability in water resources and supply systems, where most expressed it by using indices such as water depletion indices (Ahopelto et al., 2019), water stress indices (Milano et al., 2016), or groundwater

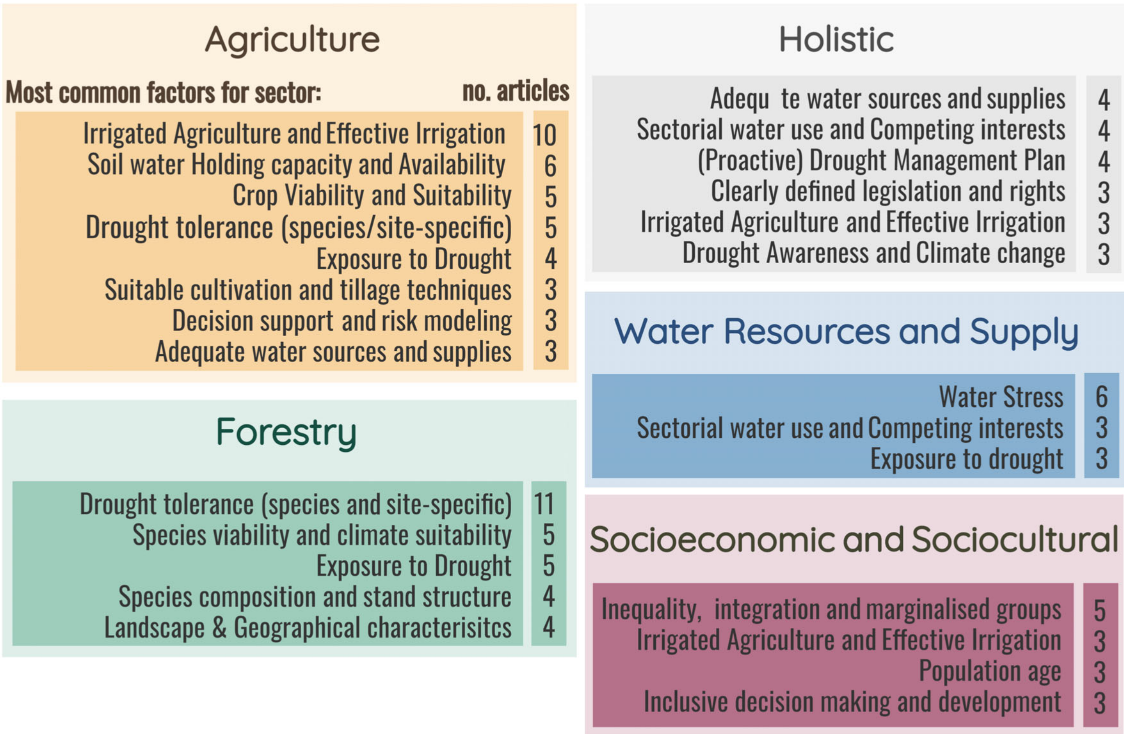

FIGURE 5 Overview of the most common vulnerability factors mentioned in articles for each of the five thematic foci identified in the review: Agriculture (orange), Forestry (green), Holistic (Gray), Water Resources and Supply (Blue), and Socioeconomic and Sociocultural (purple).

exploitation indices (Gurwin, 2014; Minea et al., 2020; Schumann, 1997). This factor was also mentioned in connection to other sectors. For example, Popova et al. (2015) looked at the impact of drought-induced water stress on crop yields and Acosta and Galli (2013) incorporated water stress when assessing societal vulnerability using crisis probability curves. To some extent, this factor is connected to another commonly occurring factor among articles with a holistic perspective, namely the availability of adequate water resources and supplies (De Stefano et al., 2015; Disch et al., 2012; Gan, 2000; Wittrock et al., 2011). Five out of seven articles studying vulnerability in connection to socioeconomic- or cultural systems described aspects concerning inequality (Hurlbert & Gupta, 2017), low social integration (Alcamo et al., 2008; Erfurt et al., 2019; Hurlbert & Montana, 2015) or marginalized groups (Dumitrascu et al., 2018) as factors influencing vulnerability.

4 | CONCEPTUAL FRAMEWORK OF DROUGHT VULNERABILITY

Based on the literature review and the subsequent analysis of identified factors that influence vulnerability, vulnerability factors can be structured into a simplified conceptual framework of drought vulnerability (Figure 6) that can facilitate design and selection of factors for a vulnerability or risk assessment in the study region. The literature review revealed three distinct categories of vulnerability factors, linked to the characteristics of (1) direct water consumers (DWC), that is, sectors or groups using water directly (e.g., for drinking water, watering crops, etc.), (2) indirect water consumers (IWC), that is, sectors or groups that use water indirectly through consumption of goods that need water for production (e.g., food, energy, etc.), or (3) governance processes and plans (GPP), such as policies and plans concerning drought, financial ability to adapt or respond to drought, and so on. In the conceptual model, vulnerability factors are therefore divided into these three categories, together forming a vulnerability triangle where each corner represents the three main categories of vulnerability factors. Each category is further divided into subcategories reflecting different attributes contributing to vulnerability within their category. The conceptual model follows IPCC AR6's (IPCC, 2022) definition of vulnerability, where susceptibility or sensitivity is defined as "*The degree to which a system or species is affected, either adversely or beneficially*" by drought, adaptive capacity is "*The ability of systems, institutions, humans, and*

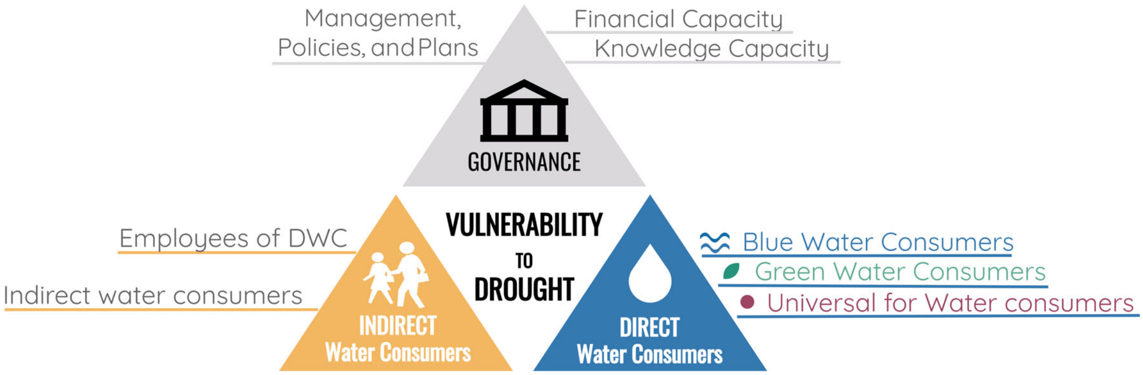

FIGURE 6 Overview of the conceptual framework based on three categories of vulnerability factors. The three categories of vulnerability factors are related to the direct consumers of blue/green water, that is, DWC, consumers of products produced by the DWC and its employees, that is, IWC, and strategies relating to governance, that is, GPP. The three categories may affect each other through positive and negative feedback loops.

other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences" and coping capacity is "*The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources and opportunities, to address, manage and overcome adverse conditions in the short to medium term*" (IPCC, 2022). In the following sections, the factors within the three main categories (DWC, IWC, and GPP) are therefore separated by their relation to these three components of vulnerability.

4.1 | Vulnerability factors for DWC

The DWC category is related to water-dependent sectors that need blue or green water supply (Figure 7) for maintaining function, and include sectors such as agriculture, municipal or private water supply, forestry, energy, and industry. This sector also includes the environment as a water-dependent sector for provision of ecosystem services. The sectors categorized as DWC may be affected by different vulnerability factors depending on the sectoral structure as well as the type of water resource they are dependent on. For example, *Agriculture* may be vulnerable to several drought types (affecting the provision of blue or green water resources) whereas the water supply sector is primarily considered to be affected by droughts affecting the supply of blue water resources such as groundwater or surface water supply. There are, however, factors that can be considered to be universal for most, or all, DWC regardless of water type. Universal factors include the existence of a drought management plan, availability, and use of risk assessment tools, drought monitoring, and forecasting as well as early warning systems. Such factors may reduce the drought vulnerability, regardless of the water resource that the sector depends on.

Vulnerability factors concerning blue or green water sources within the DWC category mainly revolve around access and availability of water or the tolerance to lack of water. In this context, the most frequently used vulnerability factor found in the literature review, "Irrigated Agriculture & Effective Irrigation", arises as an interesting factor with opposing effects on vulnerability depending on the water source that is examined. For instance, access to irrigation is regularly used as a factor decreasing drought vulnerability in agriculture (e.g., Buzasi et al., 2021; Wittrock et al., 2011). Meanwhile, in articles assessing drought vulnerability using indices related to water stress and competing interests, irrigation is sometimes included as a factor that increases vulnerability by adding pressure on water sources used by several competing interests (Milano et al., 2016). Furthermore, as irrigation requirements during drought can exceed water availability (Ahopelto et al., 2019; Wheaton et al., 2008) or water allocation permits (Hurlbert & Montana, 2015; Neilsen et al., 2018), the potential of its performance as a factor lowering vulnerability may be dependent on surrounding circumstances as well. This exemplifies the complexity of drought vulnerability, where a vulnerability factor can have both positive and negative effects, depending on the water type or sectors that is subject to the assessment.

Both forestry and agriculture involve several factors targeting vulnerability to lack of green water availability in the biophysical realm, such as the use of drought-tolerant species (Bosela, Tumajer, et al., 2021) or the site-specific drought tolerance of a species (Albert et al., 2015). Such tolerance can be affected by soil (e.g., Albert et al., 2015; Felton et al., 2020), elevation (Bosela, Stefancik, et al., 2021; Bosela, Tumajer, et al., 2021), and climate characteristics (Salamon-Albert

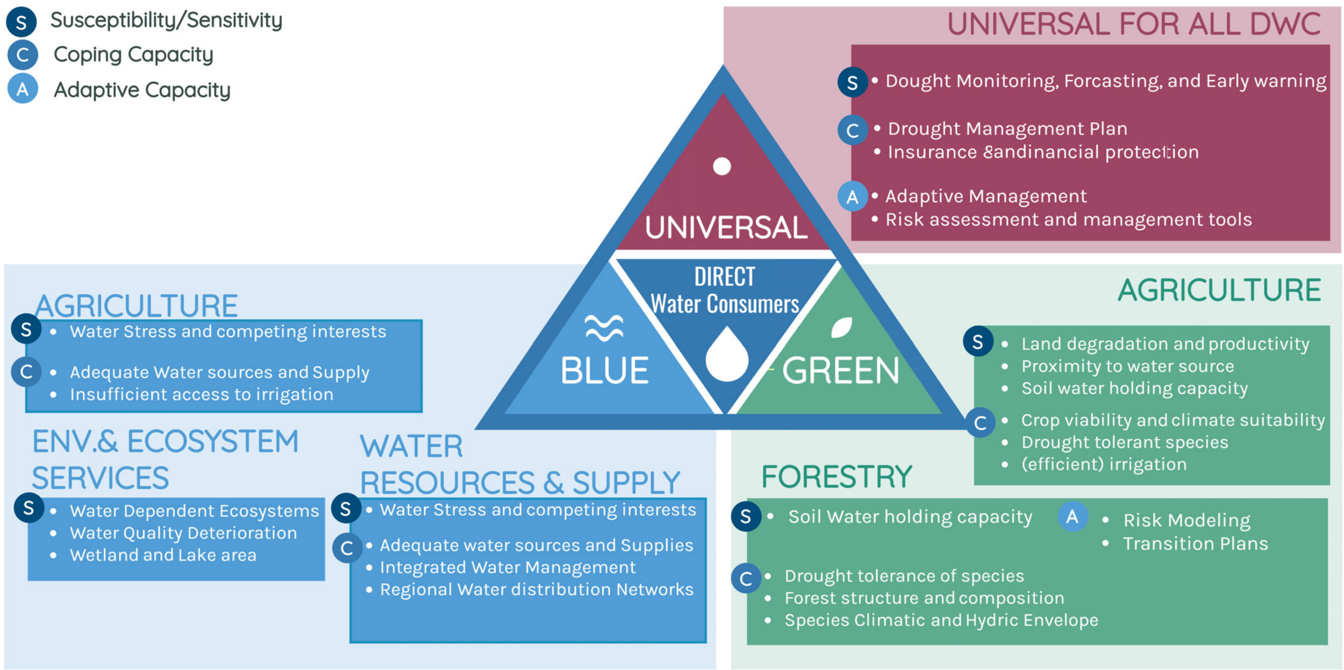

FIGURE 7 Examples of factors relevant for vulnerability concerning DWC and its subcategories: universal factors independent of water source (purple), factors concerning green water sources (green), and factors concerning blue water sources (blue), labeled according to the three vulnerability components Susceptibility (S), Coping Capacity (C), and Adaptive Capacity (A).

et al., 2016; Thrippleton et al., 2020). The role of forest structure and composition (e.g., Buras et al., 2018; Thrippleton et al., 2020) as well as the size and growth rate of trees (Bosela, Stefancik, et al., 2021; Bosela, Tumajer, et al., 2021) were also described. Drought tolerance can also be linked to management treatments such as thinning, whose positive (van der Maaten, 2013) or negative (Bosela, Stefancik, et al., 2021) impacts on forest vulnerability were debated in the reviewed articles.

The literature review found seven factors concerning vulnerability of the environment and its provision of ecosystem services (mentioned in five of the reviewed articles), which were included as a sector within the DWC in the conceptual model (Figure 6a). De Stefano et al. (2015) identified and described three of the seven factors for environmental vulnerability, namely water-dependent ecosystems, water quality deterioration, and controlled water network, while Kvaerner and Klove (2006) advocated for the importance of wetlands and lakes for baseline streamflow during drought periods and Dumitrascu et al. (2018) used water, pond and forest vegetation land cover as a factor decreasing vulnerability in their assessment of socio-economic vulnerability in Romania. Hurlbert and Gupta (2017) described deteriorating ecosystems, and Cosmulescu and Gruia (2016) discussed the influence of land degradation on drought impacts of fruit orchards.

Additionally, De Stefano et al. (2015) provided vulnerability factors for energy production, stating that the distribution and age of hydropower plants as well as the lack of strategic reserves play a role for its vulnerability. Ahopelto et al. (2019) included industrial water use when assessing water stress during drought and compared the locations of water-intensive industries, such as paper and pulp industries, cooling water, and aquaculture, with areas with increased risk of water stress during drought.

4.2 | Vulnerability factors for IWC

The second category of the conceptual model, IWC, relates to the socio-economic and socio-cultural characteristics that may affect societal vulnerability (Figure 8). These factors primarily concern vulnerability to indirect effects of drought on the population, when viewed as consumers of products produced by sectors within the DWC category (i.e., water, food, energy, etc.), and when viewed as employees within sectors included in the DWC category (Figure 8).

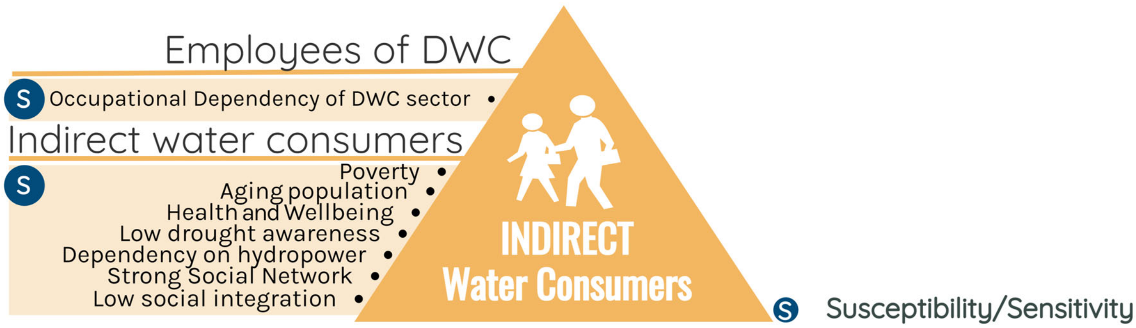

FIGURE 8 Examples of factors relevant for vulnerability concerning IWC divided into two sub-categories: Employees of DWC and IWC, labeled according to the three vulnerability components Susceptibility (S), Coping Capacity (C), and Adaptive Capacity (A).

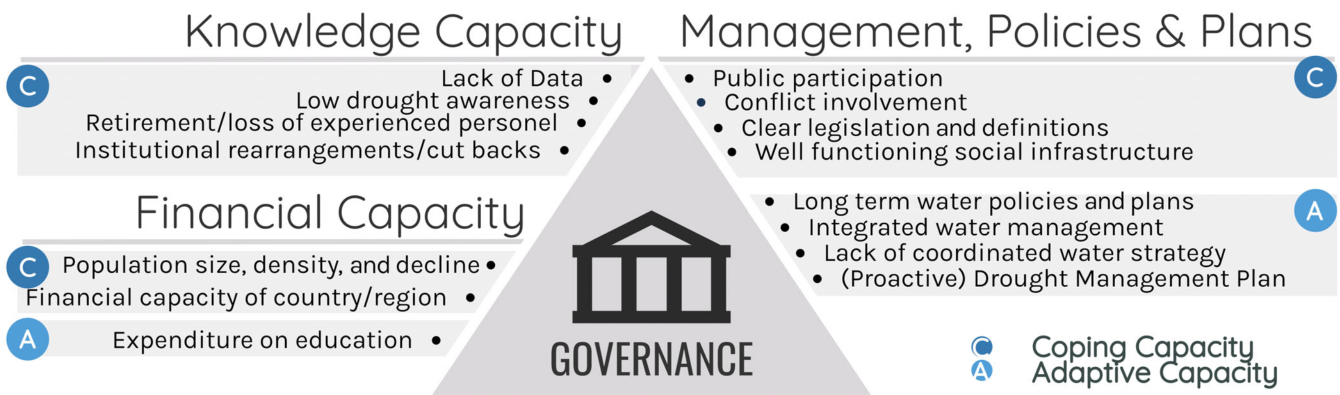

FIGURE 9 Examples of factors relevant for vulnerability concerning governance processes and plans (GPP) and its three sub-categories: knowledge capacity, financial capacity, management, policies and plans, labeled according to the three vulnerability components Susceptibility (S), Coping capacity (C), and Adaptive Capacity (A).

From the consumer side, these factors include demographic characteristics that can affect an individual's ability to handle price increases, acquire information, or maintain health during droughts. For example, Alcamo et al. (2008) used inference modeling to investigate drought vulnerability from several different social science disciplines (psychology, political science, and socio-economic) and described how factors such as low social integration, poverty, or low health and well-being of a population will affect the social susceptibility of a society to drought. This was also exemplified by Hurlbert and Montana (2015), who mentioned the tendency to increased vulnerability of First Nation communities as a result of prevailing circumstances for integration of indigenous populations in Canada. In contrast, a strong social network is described by Wittrock et al. (2011) as decreasing the vulnerability of an individual or a community.

From the employee's perspective, the vulnerability factor is related to occupational dependency, as well as employed knowledge capacity within a sector. For example, if a large share of a population is occupationally dependent on agricultural income (Alcamo et al., 2008) or without alternative income sources (Wittrock et al., 2011), the population may be more vulnerable to drought than populations with diversified incomes from less water-dependent sectors.

4.3 | Vulnerability factors relating to GPP

The third category of drought vulnerability is linked to the process of governance (Figure 9). The factors included in this category will primarily affect the other two categories by increasing or decreasing a system's ability to adapt and cope with a drought event through its management, policies and plans, financial capacity, or available knowledge (Figure 9). From a management perspective, several articles stress the availability of a drought management plan before drought events as important for lowering drought vulnerability. However, as described by Disch et al. (2012), the characteristics and design of such management plans are of importance for them to be effectively applied if a drought occurs. Another factor described in the literature as affecting the vulnerability of an area is public participation in water policies and plans (Alcamo et al., 2008; Disch et al., 2012; Hurlbert & Montana, 2015; Raikes et al., 2021), thereby facilitating its implementation at different drought stages.

Public participation can also be linked to knowledge capacities such as drought awareness. Raikes et al. (2021), for example, revealed that 100% consensus was reached for Canadian study participants on the importance of community awareness relating to droughts, with many participants advocating the importance of public participation for fostering household risk awareness. Drought awareness was also included in Buzasi et al.'s (2021) assessment of drought vulnerability in Hungary that used the existence of drought-awareness-raising measures as an evaluation criterion when assessing drought-related policy performance at county level. Moreover, knowledge capacity is related to both human resources and data availability. For instance, Hurlbert and Montana (2015) described how loss of knowledge due to retirement of experienced personnel, institutional rearrangements, as well as a lack of data are factors influencing vulnerability. Additionally, Neilsen et al. (2018) raised the value of incorporating local knowledge from First Nations for collaborative decision-making and, when studying the impacts of the 2001–2002 Canadian drought, Wheaton et al. (2008) found that adaptation measures were hindered by the lack of knowledge on water needs versus supplies and management.

Finally, the financial capacity category incorporates vulnerability factors that affect the capacity of a region to respond to droughts and support its population. Alcamo et al. (2008) described several of these factors, expressing relative state capacity to respond to crisis as being dependent on tax revenue and societal economic susceptibility as being connected to its dependency on hydropower and domestic agriculture production. Dependency on domestic agricultural production was also used by Buzasi et al. (2021) as a factor for adaptive capacity in their vulnerability assessment in Hungary. However, by adopting the latest definition of IPCC AR5 (IPCC, 2022), dependency on water-dependent sectors is categorized as affecting the adaptive capacity in our conceptual model. The financial capacity of a region or country was likewise described as affecting the vulnerability of a region by Acosta and Galli (2013) where high financial resources lower the vulnerability of a region.

5 | THE FUTURE OF DROUGHT VULNERABILITY ASSESSMENTS IN FORESTED ECOREGIONS IN COLD AND CONTINENTAL CLIMATES

The number of studies relating to drought vulnerability in forested countries with cold or continental climates has increased in recent years. A shift in the number of articles published concerning this subject can be seen since 2011 (Figure 1), likely in response to recent calls for proactive risk management and an increasing attention to vulnerability as has been seen in publications from IPCC (2007), Hyogo Framework for Action 2005–2015 (HFA, 2007), and the Sendai Framework (UNDRR, 2015). These trends are in line with results from global-scale literature reviews on drought risk assessments (Hagenlocher et al., 2019) and can be expected to continue in the future due to the continuing call for systemic drought risk assessments (UNDRR, 2021). In line with these developments, in this study we provide a holistic overview of conceptual approaches and methodologies for assessing drought vulnerability and discuss related challenges and research needs. By gathering a wide range of factors that are currently being used for vulnerability assessments, and synthesizing them in a comprehensive conceptual framework, we offer guidance for future drought vulnerability assessments in these regions. The following sections provide an overview of identified challenges and needs for drought vulnerability research in cold or continental climates.

5.1 | Challenges with vulnerability conceptualizations and definitions

Just as has been described by Ciurean et al. (2013) and Birkmann (2013), our review revealed that there is a large spread in the definition and conceptualization of vulnerability used in the literature, where the most commonly used definition of vulnerability is based on the IPCC AR4 (IPCC, 2007). The results of the literature review revealed that not a single article adopted the current definition of vulnerability as defined by the IPCC AR5 and AR 6 (IPCC, 2014, 2022). These results confirm the findings by Ishtiaque et al. (2022), who argued that the climate-change vulnerability research community tends to continue using the IPCC AR4 definition (IPCC, 2007), in part due to the unclear role of exposure when performing vulnerability assessments. Meanwhile, the significance of the choice of definition for system conceptualization clearly emerged during the construction of our conceptual model, due to the differences in adopting the definitions described in IPCC AR4 (IPCC, 2007) versus AR6 (IPCC, 2022). In articles adopting IPCC AR4's vulnerability definition, factors that would now be considered as coping capacity, were sometimes tagged as adaptive capacity. This could potentially be explained by the previous lack of the coping capacity term in the vulnerability definition. Additionally, some factors could debatably be considered as connected to both adaptive capacity and coping capacity. An example is the existence of a drought management plan. Such plans can increase a system's coping capacity in case a drought event occurs, simultaneously, a drought management plan can increase a system's adaptive capacity by pinpointing potential areas for adaptation. Further work is needed, to establish guidelines for consistent categorization of vulnerability factors that are frequently used in vulnerability assessments.

Furthermore, due to the wide range of conceptualizations of vulnerability, comparisons between these different assessments are difficult, which complicates achieving an overall understanding of vulnerability from an interdisciplinary point of view. At the same time, the scientific knowledge incorporated in each conceptual model provides valuable information on the many components of vulnerability, how it can be manifested and assessed. Here, a better understanding of how different conceptualizations of vulnerability are related and potentially combined is needed. An interdisciplinary collaboration to find an overarching conceptualization of vulnerability that can be applied to all scientific disciplines involved in drought vulnerability research could provide a useful way forward.

Nevertheless, the lack of a clear definition and conceptualization increases the risk of misinterpretations and misunderstandings, as there is no uniform and generalized understanding of what the terms vulnerability or drought vulnerability refer to. This transfers a large responsibility to the reader in identifying what exactly vulnerability means in each article, which consequently produces a barrier between the drought vulnerability research community and its intended audience. A first step in minimizing these risks would be to clearly state how drought vulnerability is defined and used in all future publications, and how it relates to other conceptualizations used within the drought community, as well as in the disaster-science and climate-change communities. This would create a stepping stone for the reader to better understand the premises for each assessment and the drought-vulnerability concept as a whole.

5.2 | The impact of scale

Vulnerability is highly dependent on scale: spatial, temporal, and functional (Meza et al., 2019, 2020). Within the study region, drought vulnerability is studied and assessed on several different spatiotemporal and functional scales, with a large focus on contemporary agriculture and forestry assessments on sub-national scale. As has been exemplified in previous sections, differences in methodological approaches and the choice of, as well as the role of, vulnerability factors are seen between the different functional scales, potentially showing a conceptual divide among different scientific disciplines. The same can be seen when analyzing temporal scales. Long temporal scales are of value when assessing drought risk and vulnerability in forestry, while many other sectoral assessments look at vulnerability by use of historic or present values as their prerequisites. In this sense, some of the forestry-focused articles offer an alternative perspective to vulnerability assessments, moving away from the static nature of many indicator- or index-based vulnerability assessments by combining vulnerability indicators with dynamic models. Whether or not this could be applied in a more holistic manner, incorporating other sectors of society or vulnerability categories, is unclear and needs to be explored. Future research should investigate appropriate time scales for different sectors, to perform vulnerability assessments with scales appropriate for its intended audience, thereby improving its use as decision support.

5.3 | Vulnerability factors—Emerging factors and vulnerability patterns

Similarly to the global literature review on drought vulnerability performed by González Tánago et al. (2016), irrigation was found to be one of the most frequently used vulnerability factors applied, even in forested cold or continental climate regions, which may seem surprising. One explanation could potentially be that irrigation is commonly used in vulnerability research from a global perspective because having access to irrigation in semi-arid or arid climates is of high importance. As some of the reviewed literature on sub-national scales focused on agriculture in semi-arid climates, access to irrigation as a factor in assessments of vulnerability is further explained. At the same time, as was exemplified by Milano et al. (2016), irrigation can be seen as a factor that may lower vulnerability in agriculture, while irrigation water needs can raise the vulnerability of water resources to water stress. Therefore, when using irrigation as a factor for assessing drought vulnerability, it is important to clearly establish the focus of the study, or to acknowledge the paradoxal nature of irrigation in the vulnerability analysis. The conceptual framework presented in this study offers a practical way to help guide in such ambiguous situations, by clearly delimiting the scope of the study from a thematic, as well as a water consumption perspective. Regardless, these results serve as an indication of the relatively large role that irrigation is given in drought vulnerability assessments for agricultural systems, even in forested cold or continental climates. The importance of irrigation systems is expected to further increase in a changing future climate, when shifts in seasonal hydroclimatic patterns and temporal redistributions of water availability increase the irrigation need (Grusson et al., 2021).

Another factor that was revealed in the review, was the role of indigenous groups in two studies performed in Canada (Hurlbert & Montana, 2015; Neilsen et al., 2018). These articles describe aspects of integration and cooperation from two perspectives, on the one hand, identifying how marginalization can increase the vulnerability of First Nations, on the other hand, the importance of incorporating indigenous knowledge in collaborative decision-making. These findings are potentially also relevant for indigenous groups in several other countries within the study regions, such as the Sámi people of Norway, Sweden, Finland, and Russia. But further research is needed to identify how their local knowledge can be integrated into regional strategies for reducing drought vulnerability, and to understand their vulnerability to droughts given their interaction with nature and their dependence on reindeer herding (Valkonen & Valkonen, 2014).

However, some vulnerability factors found in global scale assessments (González Tánago et al., 2016; Meza et al., 2020) seem less critical in the cold or continental climate regions. For example, aspects concerning gender inequality and poverty are rare in the studied literature for forested cold or continental regions and only included in the vulnerability assessments performed by Alcamo et al. (2008). In their assessment, vulnerability is studied in and compared between Russia, India, and Portugal where such factors may possibly be of higher importance than in the rest of the study region. Finally, factors such as undernourishment, access to improved water sources, access to basic sanitation services and life expectancy were not found in the studied literature. This is not surprising, as the focus was on the global North, where some factors that are important for the global South are not of relevance. These results illustrate the importance of using site-specific vulnerability factors, and difficulties that could arise when using general vulnerability factors common in some climate regions to study and compare vulnerability for other climate zones.

5.4 | Vulnerability factors—Challenges and research gaps

There was a limited number of factors for environmental vulnerability and the delivery of ecosystem services in vulnerability assessments, beyond plot or ecosystem scales included in the studied assessments. Some factors were identified in the reviewed literature, but articles addressing such factors are few. As ecosystem services are crucial for maintaining societal function (Cardinale et al., 2012; Costanza et al., 1997), more focus should be put into understanding how terrestrial and aquatic ecosystems in forested ecoregions in cold or continental climates may be vulnerable to drought, how it can impact the services they provide to societies, and how to best incorporate such vulnerability in future socio-hydrological vulnerability assessments at different spatiotemporal and functional scales. Similar challenges exist for drought vulnerability assessments concerning the energy and industry sector. Several countries included in this review rely on hydropower and other water-intensive energy sources, meanwhile no articles specifically aimed at understanding vulnerability of the energy system were identified. While some articles included energy and/or industry in their assessments, no studies on a sector scale were found. This could potentially indicate a lesser need for vulnerability assessments for these sectors in the study region. However, such assumptions should be verified by further analysis.

Specific challenges concerning generic vulnerability factors for forestry relate to the complexity of forest ecosystems. A general consensus on the increased drought vulnerability of Norway Spruce could be seen in the reviewed articles (Bosela, Tumajer, et al., 2021; Felton et al., 2020). However, that does not necessarily translate to an overall factor where forest stands with Norway Spruce are always a sign of increased vulnerability, as this is affected by site characteristics of the stand location that it applies to. This implies that forest vulnerability is dependent on a combination of tree species and stand composition in relation to site characteristics and climate, but also on the management practices that are applied. However, it can be argued that similar site-specificities and dependencies exist for all five thematic foci seen in the literature. For example, agricultural systems involving crop production, are dependent on-site characteristics such as soil properties and landscape characteristics. Likewise, water supply is affected by complex hydrogeological processes. However, these complex site-specific interactions were in some forestry-centered articles (Albert et al., 2015; Thrippleton et al., 2020) assessed using complex simulation models with several input parameters that can influence overall vulnerability, such as soil properties, aspect, and elevation of the studied stand. Using such input parameters, these articles studied vulnerability by assessing the impacts that droughts would have, based on the modeled results. Vulnerability was described or assessed by, for example, growth rate, mortality rate, or standing or harvestable volumes which are rather measures of modeled impacts used to better understand and identify locations more vulnerable to drought, even if the vulnerability itself is, in fact, a combination of the aforementioned characteristics combined. Further research is needed to analyze and study the importance of the different model parameters to overall vulnerability, and, if possible, to identify potential vulnerability factors that can be used for assessing forest vulnerability as a standalone analysis as well as for including it in holistic vulnerability assessments involving several sectors. To include forestry in future applied vulnerability assessments, general factors that are somewhat independent of location are needed. If such factors are possible to create, they should be co-created with relevant stakeholder and sector-specific expertise. The same can be argued for sectors commonly using factors, such as irrigation, that can have opposing effects for vulnerability at different functional scales yet are highly used in the literature. If such factors are included in holistic vulnerability assessments, the contextual dependencies between different functional scales need to be examined or potentially replaced by less dependent factors.

5.5 | A conceptual framework for designing regional drought vulnerability assessments

The conceptual framework developed in this study provides a simplified framework for designing vulnerability assessments and selecting vulnerability factors relevant for the study region. The framework is designed to distinguish between different categories of vulnerability factors, such as factors connected to governance processes, IWC and DWC. This categorization draws attention to the many ways in which vulnerability may be manifested. It also highlights the connection between vulnerability and the different drought types that exist, where certain vulnerability factors are of importance depending on both the exposed objects and on what type of drought hazard they are exposed to (e.g., irrigation for crops during soil moisture drought), while others are applicable regardless of drought type (e.g., the presence of a drought management plan). As an example, the vulnerability of the same sector can and may need to be assessed using different factors depending on the drought type. The framework can therefore help facilitate discussion on why some vulnerability factors are suitable in certain vulnerability assessments but not in others, help communicate the chosen design for a vulnerability assessment, as well as interpret vulnerability assessments performed by other actors. Even if the conceptual framework can readily be used to provide a base framework in the design of a vulnerability assessment, the selection of factors, as well as their relative weights, need to be adapted to the local conditions and time frame for each study conducted. This could be done through, for example, expert judgment or principal component analysis.

5.6 | Limitations and research needs

To better understand how the term vulnerability is conceptualized in forested ecoregions in cold or continental climates, the search protocol in WoS and Scopus were primarily focused around the search term vulnerability and not on the individual components as defined by IPCC (2007) or IPCC (2014). By the design of the literature review, articles solely focusing on susceptibility, adaptive capacity, or coping capacity were only identified and reviewed if they were used in connection to vulnerability in their respective articles. Hence, some articles relevant for this review may have not appeared in the searches, even though they may be of relevance for the scope of this article.

The selected inclusion and exclusion criteria further affected the resulting list of included articles in this review. Compared with other global review articles on drought vulnerability, this review took a broad perspective as to what articles to include, thereby allowing articles from several different scientific disciplines to be included. Such inclusion provides opportunities to improve the understanding of drought vulnerability from a wide range of perspectives, adding new knowledge to how drought vulnerability may manifest itself in the socio-hydrological systems. Concurrently, analysis on in-depth vulnerability assessment from different scientific disciplines must be made with caution to minimize the risk of misinterpretation. Here, more knowledge on how to combine and rank vulnerability factors from different sectors must be applied through expert knowledge and/or statistical analysis to ensure the relative importance of each factor is included. With regard to forestry, plot scale assessments on plant traits and provenance were excluded from the review. However, these aspects play a role in species vulnerability at different locations and are of importance for the understanding of forest vulnerability as well as for the simulation modeling of forest vulnerability (Aubin et al., 2018). Thus, efforts to synthesize the results of these plot scale assessments would provide further information on the vulnerability of forest biomes and the impacts of droughts, as well as climate change that can already be seen in some locations. Such work has been initiated by, for example, Aubin et al. (2018) and Boisvert-Marsh et al. (2020), and more research on this topic is anticipated within the coming years.

6 | CONCLUSION

The study region is experiencing an increase in studies analyzing drought vulnerability from several different thematic foci, where vulnerability is currently being examined in the agricultural, forestry, and water supply sector as well as from socio-economic and -cultural perspectives. The articles included in this overview had different objectives, where most articles were either using different approaches to assess system vulnerability or to further the understanding of what influences vulnerability.

Drawing on the results of this literature review, a first attempt of conceptualizing drought vulnerability in forested countries with cold or continental climate was made. The conceptualization draws on the different effects a drought can have on green and blue water sources. By taking this approach, contradicting vulnerability factors, such as the role of irrigation, could be identified and understood, thereby adding to the overall understanding of vulnerability from a system perspective, including several functional scales. This provides several opportunities to analyze vulnerability to drought no matter where in the hydrological or socio-hydrological system it occurs, by highlighting potential vulnerability pathways within and across several scales. By including sectors such as forestry, the understanding of the vulnerability pathways in regions with a large share of forested area is further deepened, and drought vulnerability can be assessed across the whole socio-hydrological system. However, the conceptual framework must be tested and validated to evaluate its ability to capture drought vulnerability. This should be done using expert judgment and stakeholder engagement so that vulnerability factors can be identified and ranked for different scales.

The comprehensive list of vulnerability factors currently adopted in cold or continental climates, which was compiled in this study, provides a stepping stone to developing appropriate indicators and composite indices to capture these factors when performing future vulnerability assessments. For some of the identified vulnerability factors, one or several indicators have already been developed and adopted in literature, as is the case for, for example, factors such as water stress and access to irrigation. In relation to other factors, there is a need for further work in constructing suitable indicators or indices for future vulnerability assessments. By further developing this novel framework, and constructing applicable indices for the vulnerability factors identified, vulnerability assessments for forested cold or continental climates can be further improved. More work is, however, needed to extend the conceptual framework to better capture the vulnerability of sectors that have not yet been fully studied in the region and to deepen the understanding of the relative importance of particular factors, as compared with others.

AUTHOR CONTRIBUTIONS

Elin Stenfors: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (supporting); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Malgorzata Blicharska:** Supervision (supporting); visualization (supporting); writing – review and editing (supporting). **Thomas Grabs:** Conceptualization (supporting); methodology (supporting); supervision (supporting); visualization (supporting); writing – review and editing (supporting). **Claudia Teutschbein:** Conceptualization (supporting); funding acquisition (lead); methodology (supporting); project administration (lead); supervision (lead); visualization (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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