Pol. J. Environ. Stud. Vol. 34, No. 5 (2025), 5999-6015
DOI: *10.15244/pjoes/192042* ONLINE PUBLICATION DATE: 2025-04-16

Review

Research Progress of Vegetation Response to Drought in Alpine Plateau Region

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Received: 30 May 2024
Accepted: 5 August 2024

Abstract

In the context of global climate change, droughts are expected to become more severe, persistent, and frequent. Drought is considered to be one of the main drivers of vegetation mortality, and the mechanism of vegetation response to drought has been the focus of global attention. This paper analyzes the research hotspots on vegetation response to drought at internal and international through bibliometric analysis, summarizes the progress of drought assessment in the alpine plateau region on this basis, and further analyzes the mechanism of vegetation response to drought from the perspectives of vegetation structure and physiological changes, vegetation water recharge, and ecosystem stability. The objective of this paper is to provide a comprehensive overview of the research conducted on the impact of drought on vegetation in the alpine plateau region. Additionally, the paper will discuss the existing challenges and limitations of this research, as well as offer insights into future directions and trends in this field. This paper aims to serve as a valuable reference for researchers, establish a foundation for further research and decision-making in the alpine plateau region, and contribute to the advancement of research in this field.

Keywords: Alpine plateau, vegetation, drought response, ecosystem stability

Introduction

According to the IPCC assessment, throughout the next 20 years, the rise in global temperature will reach or surpass 1.5ºC [1]. Droughts will grow increasingly severe, protracted, and frequent in the context of global climate change, which is principally defined by rising temperatures [2, 3], and their effects on ecosystems will worsen [4, 5]. Drought development is a complicated process that is frequently brought on by unusual weather patterns, including low precipitation and unusual temperature swings [6]. Unusually high temperatures

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may hasten the evaporation of water in the soil and increase plant transpiration, whereas below-average precipitation would result in a soil water deficit and wilt of the plants. Plants lose water more quickly when these two conditions combine, which is quite dangerous for the growth of vegetation [7]. Understanding the mechanism of interaction between drought and vegetation and determining the threshold of vegetation response to drought is critical for drought monitoring, drought adaptation, and ecological environment protection. Drought has been recognized as one of the main drivers of vegetation mortality, and understanding the coupling relationship between vegetation and drought has been the focus of global attention [8]. Global observations point to the rapid extinction of many dominant plants [9, 10], the widespread dieback events that are already taking place in many forests and woodlands [11-13], and the expectation of additional die-off events due to rising temperatures and droughts [11, 12, 14]. It is also important to acknowledge that the occurrence of extreme drought events is likely to increase. It has been demonstrated that the loss of Above Ground Net Primary Productivity (ANPP) is 60% higher at sites experiencing extreme droughts (A-hundred-year return period) than at those sites with average drought severity [15]. This indicates that the global impact of increased drought severity may be underestimated. Given that extreme drought events are historically rare, understanding how drought affects grassland ecosystem functioning is crucial for further investigation into how to cope with the impacts of extreme drought events on grassland ecosystems in the alpine zone.

Numerous factors, including the area temperature, the kind of vegetation, the intensity and length of the drought, and others, affect how vegetation responds to drought [16-19]. Despite the complexity of exploring this issue, research on it has made significant progress in recent years. Researchers have systematically studied the physiological and ecological characteristics, species diversity, and growth and development status of vegetation based on ground observation, remote sensing monitoring, and model simulation, revealing the changes in vegetation under drought stress and its impact on the ecosystem. These research findings offer a solid theoretical foundation for the investigation of the mechanisms by which vegetation responds to drought, amass a substantial body of information and case studies, and strongly suggest more in-depth research on this topic in the alpine plateau region. The climate in the alpine plateau region is complex and highly sensitive, strongly reflecting global temperature rise, making it the region with the greatest uncertainty in the impact of future climate change [20]. However, there is currently relatively little research on the response of vegetation to drought in high-altitude plateau areas, and the research content is scattered and lacks a systematic summary [21]. In order to better understand the ecological environment's vulnerability in the alpine plateau region and enhance the ecosystem's ability to adapt to drought, it is crucial to compile and organize pertinent research findings in this area and investigate the mechanisms by which vegetation in this region responds to drought.

This study employs bibliometric research methods to conduct a keyword co-occurrence analysis of international research on the interaction between vegetation and drought. Utilizing knowledge graphs, it examines the current state and focal points of research on this interaction. Building on this, it summarizes the progress in research on the alpine plateau region, delving into the mechanisms by which vegetation responds to drought through physiological changes, water replenishment, and ecosystem stability. The study explores the existing issues and challenges and anticipates future research trajectories and developmental trends. This article aims to provide a comprehensive review of the research on vegetation responses to drought in alpine plateau regions, offering valuable insights for researchers, establishing a solid foundation for further drought research and policy-making in these areas, and advancing the field's in-depth exploration and growth. The framework for the study of vegetation response to drought is shown in Fig. 1.

Bibliometric Analysis

Trend in the Number of Publications

Web of Science (WOS) is an international scientific citation index database, and China National Knowledge Infrastructure (CNKI) is a large academic database in China. Both databases are widely used and representational, with searches conducted on the themes of "drought" and "vegetation" over the past decade. The annual trends in publication volume for CNKI and WOS over the past decade are presented in Fig. 2. Both databases exhibit a growth trend, with CNKI's annual publications showing a fluctuating upward trajectory, with an average annual increase of 20 articles, while WOS's annual publications have seen more significant growth, with an annual increase of 104 articles over the past decade. However, the growth rate has decelerated since 2020. In summary, over the past decade, publications on themes of "drought" and "vegetation" have consistently increased. However, in 2021, there was a turning point where the trend began to slow down.

Analysis of National and Journal Trends

A clustering map of the publishing volume of drought and vegetation-related literature in different countries may be created by examining the country affiliation of articles in the WOS database and setting the frequency of keyword occurrences to be at least thirty times (Fig. 3). The graph illustrates how the publication volumes of the US and China significantly outpace those of other nations, with the US having the greatest volume at 3140 articles and China coming in second with 2944 articles.

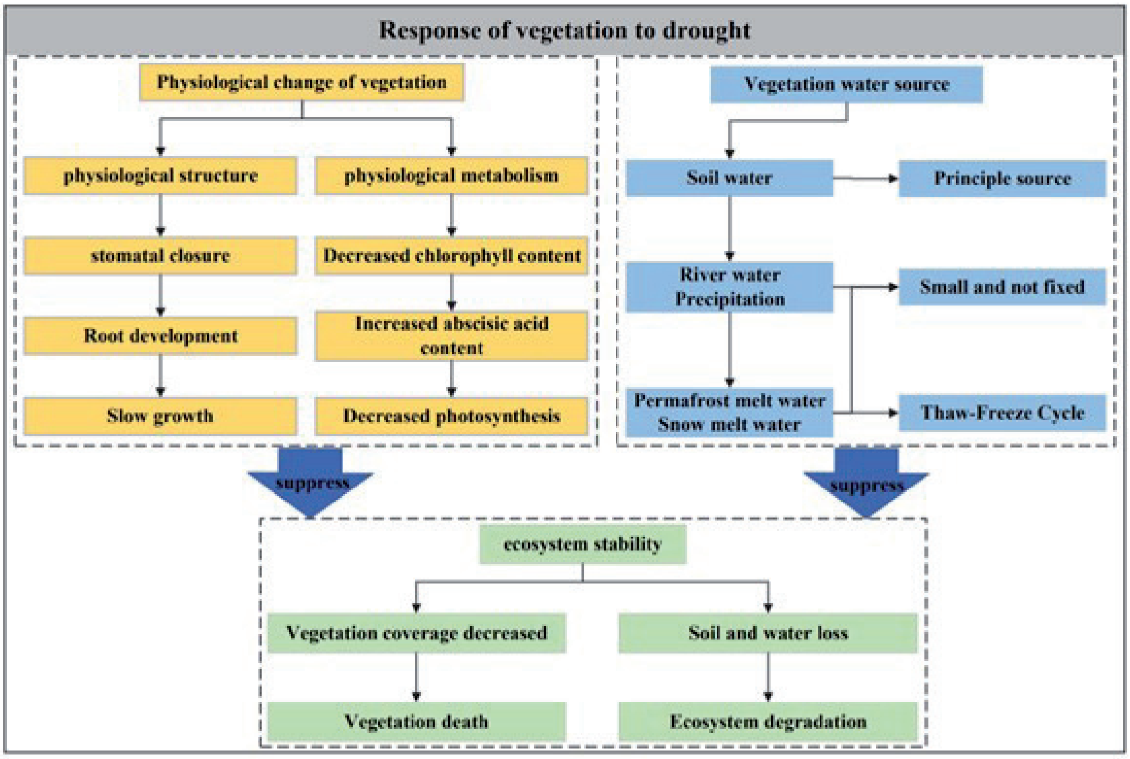

Fig. 1. Research framework of vegetation response to drought.

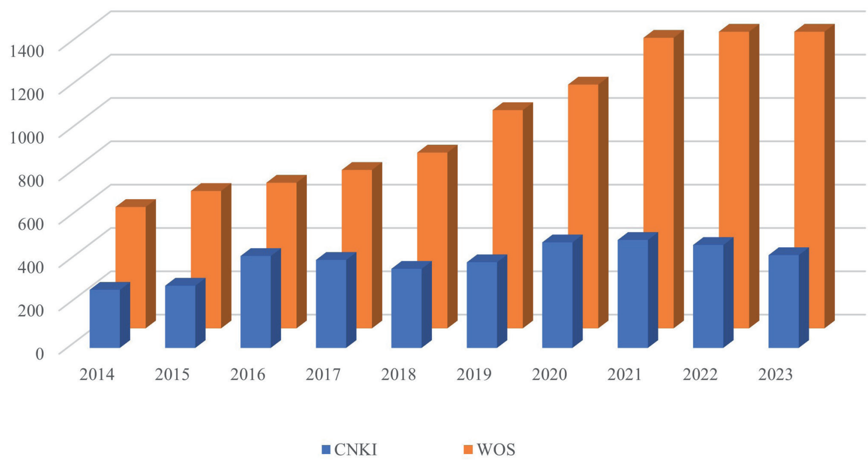

Fig. 2. Annual trend in the number of publications.

In the last ten years, the number of articles published in other nations has been less than 1000. Germany has published approximately 900 articles, followed by England, France, Australia, Spain, Brazil, and other countries with approximately 500 articles each. The remaining countries have had relatively low publication volume in the past 10 years.

A clustering diagram of the publication volume of various journals linked to drought and vegetation can be created by examining the publication frequency of articles in the WOS database and setting the keyword frequency to 70 or more times (Fig. 4). The top 10 journals are Remote Sensing, General Environmental Science, Agriculture and Forestry Meteorology, Global Change Biology, Forest Ecology and Management, Forests, Hydrology Journal, Environmental Remote Sensing, Ecological Indicators, and Environmental Research Newsletter.

Research Hotspot Analysis

Bibliometric analysis encompasses a vast amount of literature data, offering a comprehensive understanding of a field's research status and trends. Hence, we selected

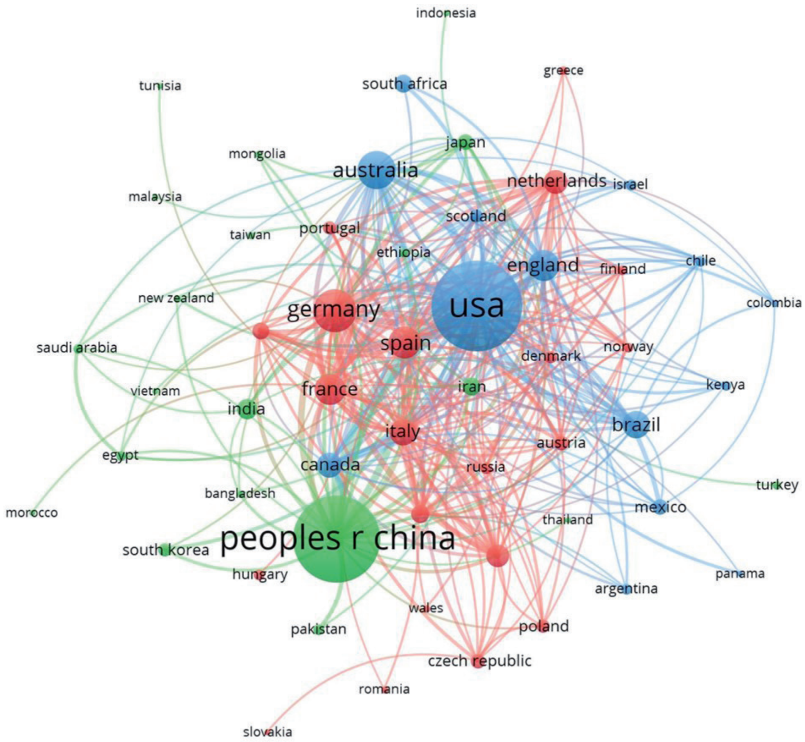

Fig. 3. Network visualization – WOS Country search.

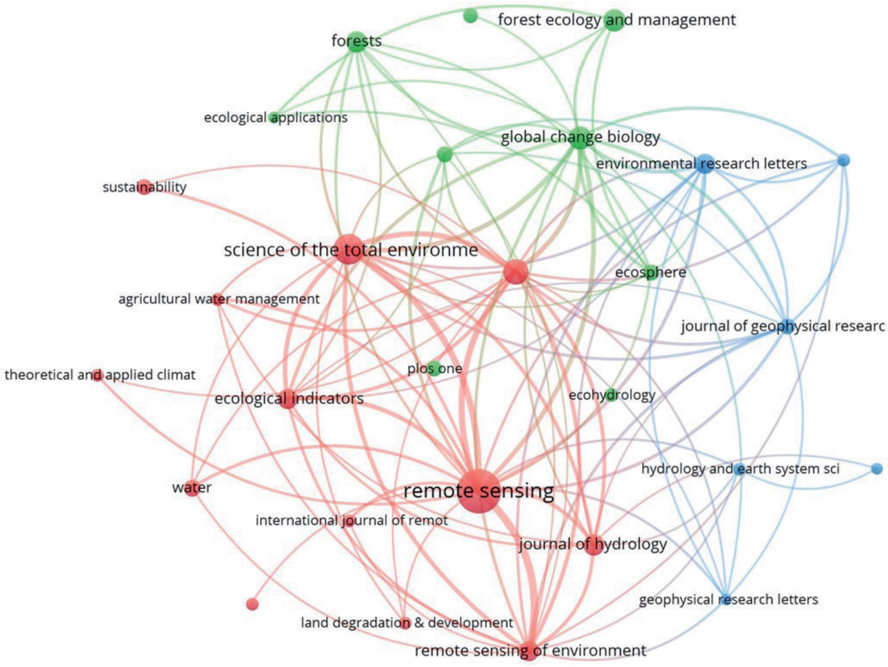

Fig. 4. Network visualization – WOS Journal search.

VOSviewer to analyze the recent research hotspots in this field. Initially, a literature search was conducted using keywords related to drought and vegetation, encompassing "drought" and "vegetation". Subsequently, the literature was filtered to include only those from the past decade to ensure the analysis of research trends is based on the most recent developments. We utilized VOSviewer to analyze the keywords within the selected literature. We set a minimum threshold of 20 occurrences for keywords in both WOS and CNKI and created keyword clustering charts (Fig. 5 and Fig. 6). Our primary focus is on the co-occurrence

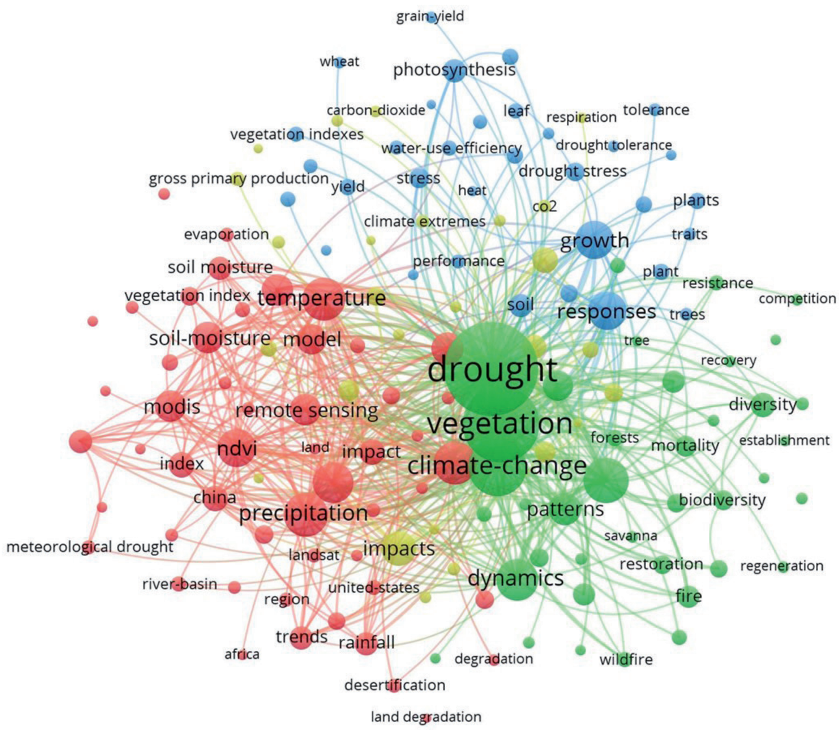

Fig. 5. Network visualization – WOS all keyword search.

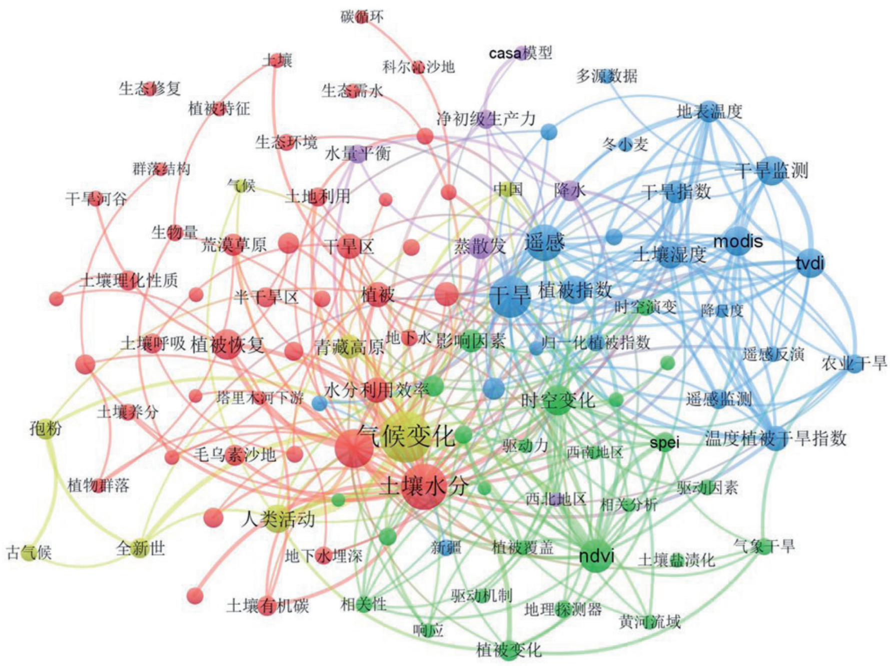

Fig. 6. Network visualization – CNKI all keyword search.

patterns and trends of "drought" and "vegetation". The findings of co-occurrence analysis indicate that, in recent years, there has been a notable increase in the frequency of "drought" and "vegetation" co-occurrences, with a rapid rise in the number of publications centered around these themes.

The graph indicates that the hot keywords in the WOS database are drought, vegetation, climate change, temperature, precipitation, and NDVI. Similarly, the hot keywords in the CNKI database are climate change, soil moisture, drought, vegetation index, remote sensing, and NDVI. Furthermore, the connection between

Table 1. The evolution process of major drought indices.

		Meteorological Drought	Hydrological drought	Agricultural Drought	Ecological Drought	Generalized Drought
Emerging period	Before 1950s	Munger Index				
		Kincer Index				
		Marcovitch Index				
		Blumenstock Index				
	1950s	Previous Precipitation Index		Moisture Adequacy Index		
		Moisture Index(MI)		Soil Moisture(SM)		
Growth period	1960s	Palmer Drought Severity Index(PDSI)	Aggregate Dryness Index(ADI)	Soil Moisture Index(SMI)		
		precipitation Anomaly(PA)	Run Theory	Crop Moisture Index		
		Standard Deviation				
		Keetch-Byrum Drought Index				
	1970s	Vapor pressure difference (VPD)			Soil thermal inertia model	
					National Daylight Velocity Index (NDVI)	
	1980s	BMDI Drought Index	Hydrological Drought Intensity	crop water deficit index (CWDI)	Solar-Induced chlorophyll Fluorescence (SIF)	
		Area Drought and Flood Index	Surface Water Supply Index(SWSI)			
		Positive and Negative Anomaly				
Developmental period	1990s	Aridity index (AI)		Soil Water Deficit Index (SWDI)	Vegetation Health Index (VHI)	
		Standardized Precipitation Index(SPI) Standardized Precipitation Evapotranspiration Index (SPEI)		Water Supply-Demand Index	Enhanced Vegetation Index (EVI)	
		Self-calibrating Palmer Drought Severity Index(SC-PDSI)			Evaporation Factor Index (EFI)	

Developmental period	21st century	Z Index	GRACE-based terrestrial water storage anomalies	Relative Soil Index(RSI)	Vegetation Temperature Status	Generalized Drought Assessment Index (GDAI)
		Composite Drought Index (CI) Meteorological Drought Index (DI)	Standardized Water-Level Index(SWI)		Temperature-vegetation Drought Index(TVDI)	
		Meteorological Drought Composite Index (MCI)	Standardized Streamflow Index (SSI)			
			Streamflow Drought Index(SDI)			
			Standardized Meltdown and Rainfall Index (SMRI)			
			Standardized Reservoirs Supply Index(SRSI)			

drought and vegetation is particularly close, intense, and extensive. Consequently, recent research has shifted from focusing solely on "drought" or "vegetation" to examining the interactive feedback between the two factors.

In conclusion, the literature publication and research hotspots in the field of "drought" and "vegetation" have demonstrated a notable increase over the past decade. The United States and China have emerged as the primary contributors to this field of study, with the majority of relevant studies published in a select group of journals. The research focus has shifted gradually towards the examination of the mutual feedback between drought and vegetation. This means the investigation of how drought affects the growth of vegetation and the adaptation of vegetation growth to drought or extreme drought events.

Research Progress in Drought Assessment

Research Progress on Drought Assessment Index

Drought assessment is essential for accurately understanding drought dynamics, assessing regional drought conditions, and informing future drought mitigation strategies. It remains a primary focus of drought research. This field has been developing since the early 20th century, leading to the emergence of various drought assessment indices. Based on the impact of different elements in the water cycle, concepts such as meteorological drought, hydrological drought, agricultural drought, ecological drought, and generalized drought. Historically, research on drought assessment indices has evolved through three stages: emerging period, growth period, and developmental period (Table 1).

(1) During the initial phase, drought assessment was predominantly meteorological, with indices characterized by single or dual factors such as the Munger Index and Kincer Index for precipitation and temperature, respectively [22]. The Moisture Adequacy Index considering evapotranspiration; and the Soil Moisture (SM) that incorporates both precipitation and evapotranspiration [23].

(2) The growth stage index predominantly utilizes multiple factors, taking into account water cycle elements and processes, with a physical basis such as the Palmer Drought Severity Index (PDSI) [24]. Additionally, due to meteorological factors leading to the depletion of surface and groundwater resources and related hydrological systems, hydrological drought indices have been developed, such as the Aggregate Dryness Index （ADI） and Run Theory [25, 26]. Other drought assessment indexes are based on runoff, including the hydrological drought intensity index and the Surface Water Supply Index (SWSI) [27, 28], etc.

(3) Since the 1990s, drought assessment research has progressed into a developmental phase. The rise

of computers and hydrological models has facilitated the development of diverse comprehensive drought assessment indices and evaluations, incorporating multiple characterization factors and indices, with more refined spatiotemporal scales. Examples include the land water storage anomalies, the Standardized Water-Level Index (SWI), and the Standardized Meltdown and Rainfall Index (SMRI) derived from GRACE-based terrestrial water storage anomalies [29-31]. There is also the Generalized Drought Assessment Index (GDAI) that takes all four factors into account that are widely used [32]. The drought indices based on remote sensing data have also diversified, with the introduction of the Vegetation Health Index (VHI), the Enhanced Vegetation Index (EVI) and the Temperature-Vegetation Drought Index (TVDI) [33-35], etc.

It is important to note that these drought indices cannot be used to fully characterize the role of ecosystems in the evolution of drought. While they do reflect the hydrometeorological elements that affect ecosystems, they do not fully capture the nuances of drought's impact on ecosystems [36]. The evapotranspiration rates of different vegetation types are influenced by the same water-scarce environment to varying degrees [37, 38]. Consequently, the response of different cover types in an ecosystem to the same intensity of drought is also variable. Park et al. [39] proposed that ecological drought should be quantified from an ecosystem perspective, with separate assessments for aquatic and terrestrial ecosystems. In response, an ecological drought index was gradually developed that can better characterize the effects of drought on vegetation in ecological terms. Although the concept of ecological drought was first introduced by the Science of Nature and Humanity Partnership (SNAPP) in 2016, there is still no widely accepted indicator for monitoring ecological drought [36]. Previous studies have typically employed remote sensing-based vegetation indices to characterize the response of terrestrial ecosystems to drought. These indices indirectly reflect the impact of drought on vegetation and vegetation water consumption. However, they do not generally reflect the dynamics of the balance between ecological water depletion and water demand in the process of drought evolution [40]. In addition to reflecting the imbalance between ecological water use and water demand, a suitable ecological drought index should be able to determine the duration of droughts and should detect anomalies in the energy balance at the land-air interface caused by changes in meteorological and hydrological conditions [36].

Scientists have predicted that the frequency of ecological droughts will increase globally as temperatures rise and precipitation patterns become more unpredictable [41]. The current research on ecological drought is still in its infancy, and the future development of ecological drought indices has a long way to go [42, 43]. In the future, comprehensive ecological drought indices can be constructed based on multi-source remote sensing inversion data for meteorological, hydrological, ecological vegetation, and other multivariate variables. Moreover, the adaptability of these eco-drought indices to the alpine plateau region also requires further investigation. Consequently, the new eco-drought indices may be developed or existing indices may be modified for the specific areas within the alpine plateau region.

Research Progress on Drought Assessment Methods

The process of drought assessment involves the identification of drought events through the application of computational drought indicators, followed by the calculation of drought characteristics, including drought severity, duration, affected area, frequency of occurrence, and the analysis of the statistical patterns presented by these characteristics [44]. The analysis will apply a series of mathematical statistics, modeling, remote sensing, or machine learning methods to construct a drought assessment system, build a drought assessment model, and realize the qualitative or quantitative assessment of drought.

Initially, drought assessment methods are limited to station data through the drought index, which is used to calculate and analyze the drought intensity of each station at a certain moment. This is achieved through techniques such as time series analysis, multiple regression analysis, fuzzy mathematical methods, gray cluster analysis, and so on. By the beginning of the 21st century, the concept of drought assessment had evolved to incorporate additional characteristics, such as drought intensity, duration, area covered, and frequency. This led to the development of more complex assessment systems and methods for evaluating drought [44]. For instance, the Model Order Reduction (MOR) [45], Principal Component Analysis (PCA) [46], Analytic Hierarchy Process (AHP) [47], Entropy Weighting Method (EWM) [48] and a variety of improved modified Copula functions applicable to the region may be employed.

Furthermore, some hydrological models are capable of providing comprehensive data support for drought assessment based on hydrological response units from a watershed perspective. This has led to the formation of a school of methods based on water cycle theory [49]. For instance, in 2012, Zhang et al. [50] and others integrated the Variable Infiltration Capacity (VIC) model with the Palmer Drought Severity Index (PDSI) to create the VIC-PDSI model, which assesses drought based on hydrological processes. This model has been shown to improve the accuracy of drought assessments [50].

The advent of remote sensing technology has facilitated the development of spatial analysis methods based on 3S technology, including the spatial interpolation method and superposition analysis method, among others. These methods have enabled the assessment of drought to progress from site assessment to regional assessment, thereby facilitating the dynamic monitoring and assessment of drought. In addition to being employed directly to invert soil moisture to assess drought, remote sensing data can also be utilized to construct remote sensing drought monitoring indices or models [51]. The most commonly utilized remote sensing drought assessment indices include the Temperature Vegetation Drought Index (TVDI) and the Vegetation Water Supply Index (VSWI), among others.

In recent years, data-driven methods such as machine learning and artificial intelligence have also been applied to drought assessment with the objective of improving the accuracy and efficiency of assessment by analyzing massive data sets in order to identify drought characteristics and trends. Deep learning models, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), are employed to identify vegetation conditions and soil moisture, and even predict precipitation, thereby enabling the assessment of the extent of drought [52]. Seonyoung Park employed three machine learning methods, namely random forests, augmented regression trees, and Cubist, to model the relationship between 16 remotely sensed drought factors based on remote sensing and in-situ reference data. The objective was to predict drought changes [53]. Omid et al. [54] utilized six machine learning methods, including CART, BRT, RF, MARS, FDA, and SVM, to predict the spatial pattern of agricultural drought. Furthermore, optimization algorithms are employed in drought assessment methodologies, including the Chaos Optimization Algorithm [55], the Extreme Learning Machine Model (ELM) [56], the Sparrow Search Algorithm (SSA) [57], the Bee Colony Algorithm (ABC) [58], the Bat Algorithm (BA) [58], the Genetic Algorithm (GA) [59] and the particle swarm optimization algorithm (PSO) [60].

In conclusion, the field of drought assessment has witnessed significant advancements in recent years. The current drought indicator systems are distinguished by their regional specificity, with a notable tendency towards the selection of comprehensive indicators. In employing the extant drought indicators, it is imperative to give due consideration to their applicability. As a result of social and economic development and scientific and technological progress, numerical simulation technology, hydrological models, remote sensing technology, machine learning, and other continuous improvements and developments, drought assessment methods have become increasingly diverse and have made significant advances in terms of accuracy and efficiency. The content of drought research has gradually evolved from an initial emphasis on precipitation to a more comprehensive approach that integrates climate change, the ecological environment, and social and economic development. The progress made in drought assessment research is of great significance to the study of vegetation response mechanisms to drought. Drought assessment can help to determine the growth and survival capacity of vegetation under drought conditions, thus facilitating a more detailed understanding of the response strategies and mechanisms of vegetation to drought.

The Response of Vegetation in High-Altitude Plateau Areas to Drought

Vegetation's Response to Water Supply in Drought

Water is a significant factor influencing plant growth and distribution [61]. It has been demonstrated that anomalies in vegetation activity are positively correlated with water balance status. Furthermore, grassland vegetation in arid areas responds more rapidly to water deficit. In the context of moderate, severe, and extreme drought conditions, the effects of increased water deficit on vegetation activity were found to be 77.27%, 83.83%, and 88.35%, respectively [62]. This study quantified the effect of water deficit on vegetation under different drought conditions, demonstrating that the greater the degree of drought, the greater the negative impact of water deficit on the vegetation. In ecologically fragile areas such as the alpine zone, the composition, growth status, and distribution patterns of plant species are directly influenced by the availability of water [63]. The alpine zone is typically characterized by a diversity of subsurface types, including glaciers, snow, tundra, and grassland. The sources of plant water are inherently complex in this environment. In general, the water that plants can absorb and utilize primarily originates from the soil. Consequently, the multiplicity and complexity of soil water recharge sources determine the diversity of plant water sources. The current research on water source resolution employs two principal methods: the reverse resolution method, which is based on the use of tracer elements, and the forward resolution method, which is based on hydrologic modeling [64]. The following two perspectives are the primary focus of research on plant water source resolution:

The first is to quantify the percentage contribution of various water sources to plant recharge water. In a typical study, Liu et al. [65] employed stable isotope tracer techniques to analyze different types of plant water sources in the Yangtze River source area. The Yangtze River source area was selected as the study area. The results indicated that different types of plant recharge water originated directly from soil water, which was predominantly groundwater at varying depths, with a contribution of 50% to 60%. The indirect sources of plant recharge water included river water, seasonal permafrost meltwater, snow and ice meltwater, precipitation, and subsurface ice meltwater. These sources collectively contributed less than 10% to the total plant recharge water sources [65]. In a study conducted by Gonzalo et al. [66], a model was employed to simulate water source contributions at the landscape scale. The findings revealed that plants situated in high terrain utilized a greater proportion of shallow soil water, while those in low terrain relied more heavily on groundwater from high terrain, with both water sources being utilized for 18-29% of the year and 36-47% of the dry season [66]. From this, it can be concluded that subsurface soil moisture recharge

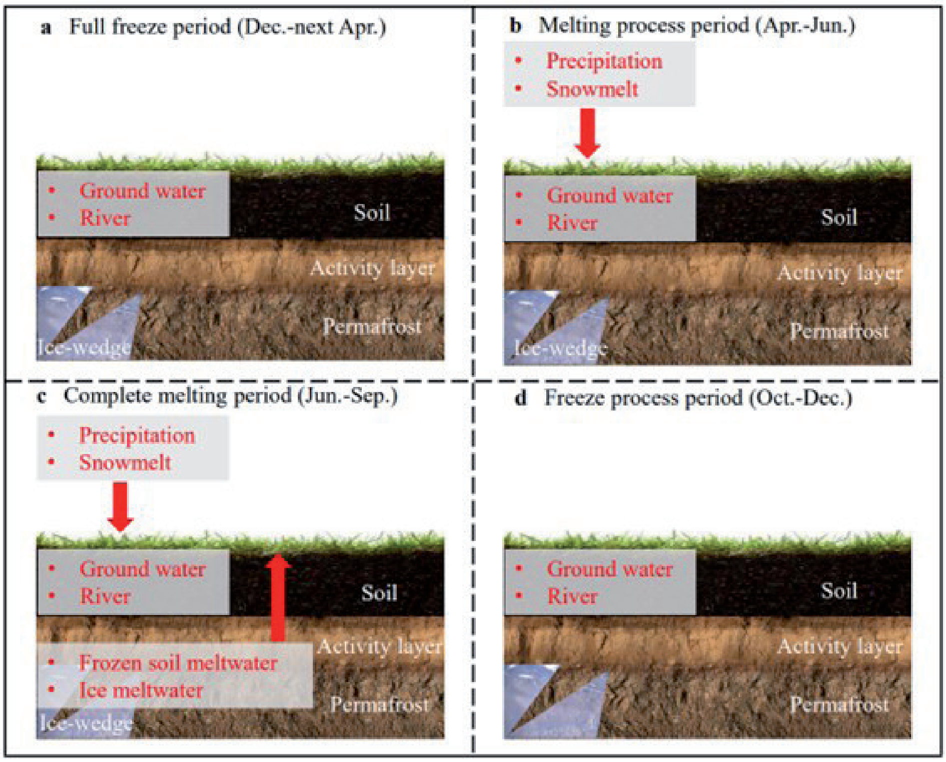

Fig. 7. Analysis diagram of vegetation replenishment water source.

represents a significant limiting factor for vegetation growth [67]. Consequently, the identification of the sources of soil water recharge represents a pivotal step in the investigation of the limiting factors for vegetation growth.

The second is the impact of freeze-thaw cycles in the alpine zone on the transformation of water source types. The alpine plateau region is subject to freeze-thaw cycles, which result in a constant change in the composition of soil water. As early as 2019, Dong et al. [68] addressed this cutting-edge issue and employed isotope experiments for water source resolution in the alpine zone, thereby elucidating the sources of water during different freeze-thaw processes in alpine watersheds. The preceding studies demonstrate that the water source of runoff and soil water in the alpine plateau region is not fixed by the freeze-thaw cycle[68]. This is not only related to topographic differences but also to the freeze-thaw cycle time. A schematic diagram (Fig. 7) of water supply during four freeze-thaw periods in the alpine plateau region, which well illustrates the above conclusions. Freeze-thaw cycling represents the most significant environmental factor influencing the growth and survival of vegetation in alpine regions [69, 70]. This process not only affects the transformation of soil water types but also impairs cellular activity and may even result in the demise of plant root cells. Conversely, an increase in the frequency of freeze-thaw cycles can accelerate the loss of soil nutrients, reduce the soil water-holding capacity and soil moisture, and impede the growth of the root system [70].

In recent decades, isotopes have been employed extensively for the delineation of plant water sources. This is due to the ability to distinguish between different water sources and the enhanced measurement capabilities afforded by laser spectroscopy techniques. Nevertheless, the resolution of plant water sources remains subject to significant uncertainty with regard to the selection of tracers, correction methods, and the choice of mixing models [71]. Furthermore, the paucity of attention devoted to plant water sources in the alpine region of China constrains the precision of forecasting future ecological alterations in the cold region. Consequently, further in-depth studies pertaining to the alpine zone are required in the future. It is of paramount importance to further investigate the uncertainty of plant water sources and the optimization of methods.

Physiological Response of Vegetation to Drought

The function of vegetation is influenced by its structure and physiology. These two components may respond differently to environmental stresses, which necessitates a comprehensive characterization of the associated structural and physiological changes when examining the large-scale vegetation response to drought [72]. The physiological response of vegetation to climate change is largely determined by drought and influenced by unusual hydrometeorological conditions and vegetation type [72]. Consequently, the isolation and quantification of the physiological response of vegetation to drought can facilitate a more

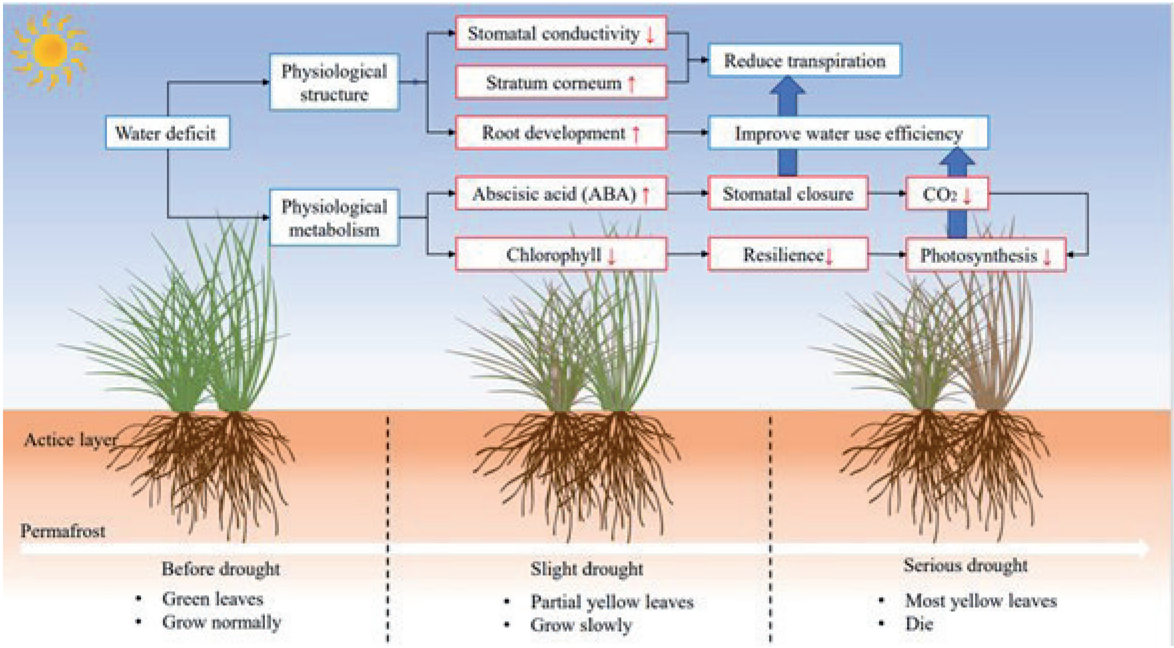

Fig. 8. Block diagram of physiological response analysis of vegetation to drought.

comprehensive understanding of the role of ecosystems in regulating climate change. The specific structural and physiological response processes are excellently represented in a logistic relationship diagram (Fig. 8), which includes two main aspects:

The first is the level of plant physiological structure. In response to drought stress, plants typically close their stomata to reduce water transpiration, thereby increasing transient water utilization [73]. This effectively protects plants from drought. The opening and closing of stomata affects the uptake of CO_2, which results in a significant slowing of plant growth during this period [74]. Chen et al. [75] observed that the stomatal size of Qilian cypress is inversely proportional to the altitude, while the number of stomata is positively proportional to the change in altitude [75]. This adaptation allows the plant to thrive in the high-altitude arid environment. Furthermore, in the event that the root system encounters an uneven distribution of water in the soil, lateral roots will tend to grow towards the soil with a higher water content. This process is regulated by the action of growth hormones [74]. One of the most significant drought tolerance strategies employed by alpine plants is the morphological and structural modification of their stem, leaf, and root systems. In their study, Li et al. [76] identified two primary mechanisms by which alpine plants adapt to their environment. The first involves strengthening the leaf surface, reducing the leaf surface area that is susceptible to evaporation, and thickening the cuticle [76]. The second involves altering the internal structural organization to form well-developed aeration tissues and generally possessing large and deep root systems [77].

The second is the level of plant physiology and metabolism. When soil moisture is reduced, plants typically limit water and nutrient uptake, exhibiting symptoms of elemental deficiencies. This leads to a weakening of photosynthesis, which in turn causes the leaves of vegetation to wither and a reduction in photosynthetic products [72]. This is corroborated by experimental measurements of photosynthesis rate and chlorophyll content, which typically demonstrate a decline in chlorophyll content and a yellow-brown color. Consequently, plants with a high chlorophyll content are generally more drought-resistant. This phenomenon has been observed in the alpine plateau region [78]. Furthermore, the ABA (Abscisic Acid) content in leaves increases, thereby regulating the opening and closing of stomata to enhance the efficacy of water utilization [74]. It has been demonstrated that the physiological response of vegetation to stress is typically more rapid than its structural appearance, and provides a more accurate reflection of the response of vegetation to drought [79-81]. A patch of yellowish grass is readily apparent as being subject to drought, whereas a tree with a normal structural appearance may in fact have undergone physiological alterations resulting from severe drought. The type of vegetation in an ecosystem is therefore of critical importance in terms of its ability to withstand drought. Different species have different strategies for adapting to drought, with some plants being more resistant to drought and others being more inclined to avoid periods of drought.

The majority of plant response strategies to drought focus on fine-tuning stomatal conductance and manipulating the ABA signaling through stomatal-specific promoters. Consequently, a significant proportion of the decline in vegetation function is attributable to the downregulation of vegetation physiology, with the downregulation being most pronounced in areas with limited water resources. The response of vegetation to drought at the physiological and metabolic level is a complex system that, in addition to regulating phytohormone levels and adjusting nutrient partitioning, increases antioxidant synthesis and other behaviors to maintain basic life activities and adapt to arid environments [82, 83]. Recent studies have demonstrated that plant growth in increasingly arid environments typically exhibits a nonlinear response. When aridity reaches or exceeds a specific drought threshold, the condition of the vegetation is known to decline significantly. Moreover, there are notable discrepancies in the drought thresholds of different vegetation types across diverse geographical regions. In the case of the alpine zone, further investigation is required to ascertain the influence of its distinctive environmental characteristics [84].

Response of Vegetation to Ecosystem Stability in Drought

The functioning of Earth's ecosystem is largely determined by the composition and physical structure of vegetation [85-87]. However, climate change may result in the disruption of ecosystem services and the loss of biodiversity due to changes in vegetation composition and structure [88, 89]. It is anticipated that the severity and frequency of droughts will increase in the future due to a combination of factors, including global warming-driven decreases in regional precipitation, increases in temperature, and evaporation rates [2, 90]. Previous studies have demonstrated that moisture conditions play a pivotal role in the productivity of alpine meadow ecosystems [91, 92]. Consequently, the resilience of alpine meadow ecosystems to drought conditions determines their capacity to adapt to global climate change. The study of the ecosystem stability response mechanism of vegetation to drought is of great significance for the protection of the ecological barrier function in alpine plateau regions and coping with global climate change.

The response of ecosystem stability to drought is reflected in the following five aspects:

(1) Climate modification. Under extreme arid climatic conditions, extreme droughts are likely to greatly slow down the rate of carbon sequestration in grasslands and shrublands, making the ecosystem response to short-term extreme droughts from highly drought-resistant to highly vulnerable [93].

(2) Soil and water conservation. Arid climates can cause soil moisture deficits, and plants maintain soil stability and reduce erosion through their root systems during periods of drought. Severe drought stress will exacerbate soil water loss, reduce soil water-holding capacity, and lead to soil erosion, which in turn affects the living conditions of vegetation and even grassland degradation and desertification, threatening ecosystem stability [94].

(3) Vegetation resilience. Drought directly leads to a slowdown in vegetation growth, and above-ground biomass and vegetation cover can decrease, resulting in a rapid decline in ecosystem productivity and stability [95]. The greater the severity of the ecological drought, the longer the time required for vegetation resilience. Regions with a high frequency of drought events exhibit higher resilience, while forested grasslands exhibit higher resilience and lower resistance [96]. In addition to environmental factors and vegetation types [97-99], phenology has also been found to affect ecosystem stability [100]. Scholars such as T. Zhang et al. [95], who used alpine meadow ecosystems as the object of their research, have demonstrated that the timing of droughts plays a significant role in determining whether or not they inhibit ecosystems [95]. Alpine meadow ecosystems are most susceptible to drought at the beginning of the growing season and in the middle of the peak growing season when they exhibit the weakest water sensitivity and the strongest drought stability [95].

(4) Biodiversity. Drought stress results in a reduction in species richness within ecosystems, particularly for species that exhibit low drought tolerance [101]. The resilience of alpine ecosystems to drought varies significantly among different grassland types. This includes alpine meadows, desert vegetation, and alpine vegetation. Some studies have confirmed that alpine grasslands and alpine meadows located in the Tibetan Plateau region are the most drought-resistant, the least resilient, and have the longest recovery time to drought, while typical meadows and grasslands located in the Inner Mongolia region are the least drought-resistant, the most resilient, and have the shortest recovery time.

(5) Ecosystem function. Droughts have been shown to reduce vegetation productivity, which affects global carbon flux [82, 102-104]. Additionally, droughts have been linked to a decrease in regional water conservation [105], which in turn weakens ecosystem services in the alpine region. Previous studies have demonstrated that the productivity of grassland ecosystems is sensitive to water effectiveness and is often dominated by water conditions [106]. As a result, it is frequently employed as an effective indicator of ecosystem drought sensitivity and drought tolerance [97, 98]. The identification of quantitative drought thresholds can assist in the prediction of the characteristics of carbon sinks or sources under global climate change [104].

The alpine plateau region is experiencing a number of ecological challenges as a result of climate change and human activities. These challenges threaten the stability of the ecosystem and require the implementation of effective conservation and management measures to maintain its ecological balance and functional integrity. The alpine plateau region's geography is profoundly shaped by climatic conditions, rendering the ecosystem inherently vulnerable. Consequently, targeted soil and water conservation and restoration measures must be implemented for different vegetation types. For instance, degraded grasslands should be restored through the implementation of enclosure and grazing bans. Utilized rangelands should be managed through the reduction of grazing intensity to maintain grassland biodiversity. Desert vegetation can be stabilized through the implementation of artificial planting and protection measures. In light of the aforementioned considerations, it is recommended that more grassland-type nature reserves be established for the long-term restoration and management of grassland ecosystems. Furthermore, the management level of the nature reserves can be enhanced by focusing on the protection of key ecosystem functional areas, such as water conservation areas and important biodiversity distribution areas. Concurrently, it is imperative to enhance public awareness and education regarding environmental protection in the alpine plateau region.

In conclusion, the response mechanism of drought to vegetation in the alpine zone encompasses three key aspects: vegetation water supply, vegetation changes in structure and physiology, and ecosystem stability.

(1) In the alpine plateau region, the direct source of vegetation water recharge is soil water at different depths, while the indirect sources are river water, water from the permafrost layer, snow and ice melt, precipitation, and underground ice meltwater. Furthermore, the source of vegetation water recharge is not fixed under the influence of the freeze-thaw cycle. In addition to being affected by spatial heterogeneity, it is also closely related to the time of the freeze-thaw cycle.

(2) When vegetation is subjected to drought stress, it will undergo changes at the physiological level, including alterations in structure and metabolism. Additionally, it will adapt its physiological processes in response to environmental cues in order to enhance its resilience. Furthermore, plant growth in response to increasing drought typically exhibits a non-linear pattern. The occurrence of ecological drought is contingent upon the attainment of a critical threshold.

(3) In order to fully comprehend the response mechanism of vegetation to drought in the alpine plateau region, it is essential to consider not only the water replenishment and physiological response at the micro-plot scale but also the role of vegetation in climate regulation, soil and water conservation, vegetation resilience, biodiversity, and ecosystem function at the macro-regional scale.

Conclusions and Perspectives

Over the past decade, research in the fields of drought and vegetation has primarily focused on elucidating the relationship between drought and vegetation feedback. Currently, the drought indicator system is distinguished by its regional characteristics, with a notable shift towards comprehensive indicators. The evolution of drought assessment methods has progressed from traditional mathematical statistics, numerical simulation, and hydrological modeling to 3S technology and machine learning, which have significantly enhanced the precision and efficiency of these techniques. The response of vegetation to drought is a mutual feedback mechanism. Therefore, the key point of study in this mechanism is plant water deficit. Insufficient precipitation may result in soil water deficit, which may in turn affect plant growth. Furthermore, the amount of water lost by transpiration may exceed the amount of water absorbed by the plant itself, which may also lead to plant water deficit. Alternatively, plant roots may be unable to absorb water effectively due to alterations in the surrounding environment, such as soil salinization, low temperatures, and extreme drought and flood events. The alpine plateau region is characterized by a distinct set of environmental and climatic conditions, which give rise to a unique response mechanism in plants to drought. To illustrate, (1) Recharge from permafrost or glacier meltwater occurs when vegetation in the alpine plateau region is under drought stress; (2) Solar radiation intensity in the alpine plateau region is greater than in other regions, which leads to an increase in transpiration; (3) the topography and geomorphology of the plateau region facilitate the accumulation of water in low-lying areas, which elevates the groundwater table and consequently raises the soil salinity as the water table rises. Salts in the soil accumulate as the water table rises, which causes soil salinization. (4) The alpine plateau region is typically highly susceptible to climate change, with grassland ecosystems in the region demonstrating heightened sensitivity to environmental shifts and extreme events. This contributes to the region's overall capacity for drought adaptation.

The advancement of drought assessment research has furnished a crucial foundation for the investigation of vegetation response mechanisms to drought and has also established the groundwork for further enhancement of drought assessment methods tailored to alpine regions. However, the current drought assessment methodology places greater emphasis on meteorological conditions, agricultural indicators, hydrological indicators, and disaster impacts, while the development process of drought and the impacts of human activities receive comparatively less attention. Furthermore, significant discrepancies exist in the established drought thresholds for various vegetation types across different regions. With respect to the alpine zone, there is a clear need for further investigation into the influence of its distinctive environmental characteristics. The response of vegetation to drought is a mutual feedback mechanism. Drought alters the vegetation, and the vegetation continuously and actively adapts to drought. However, there is always a limit to the natural regulation. The response mechanism of vegetation to drought should not be confined to the microscopic scale; it should also be considered at the macroscopic level. The current state of research on the response of vegetation to drought in the alpine plateau region is still limited, and the mechanisms by which vegetation responds to drought remain unclear.

In the future, it would be beneficial to further explore the development of a more suitable ecological drought index for the alpine plateau region, with the aim of assessing and providing targeted guidance for ecological restoration and protection.

Acknowledgments

This research was supported by the National Key Research and Development Project (Grant No. 2022YFC3201702), the National Science Fund Project (Grant No. 52130907 and 52342905), the Natural Science Foundation of Hebei Province (Fund No. E2024402117) and the Major Science and Technology Project of the Ministry of Water Resources of the People's Republic of China (SKS-2022033).

Conflict of Interest

The authors declare no conflict of interest.

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