Ecological Indicators 178 (2025) 113979

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Unraveling the link between riparian vegetation health and drought severity

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A B S T R A C T

Riparian ecosystems are ecologically sensitive landscapes that are highly vulnerable to drought, yet the spatial and temporal dynamics of riparian vegetation response to drought severity remain poorly understood, especially in large, human-influenced river basins. This study examines how riparian vegetation in the Lower Mississippi River Basin (LMRB) responds to varying drought severity levels using a multi-method approach that integrates U.S. Drought Monitor classifications (D0–D4) with MODIS-derived NDVI indices for vegetation resistance and recovery. We combined regression models, spatial autocorrelation (Moran's I), hot spot analysis, and ANOVA to assess vegetation health across 2010–2014. Results reveal counterintuitive patterns: high-resistance areas corresponded to more weeks of moderate drought (D1), suggesting the influence of land management practices, while extreme drought (D4) was linked to low resistance. Recovery patterns varied by drought exposure, with paradoxical associations between higher recovery and moderate drought (D1–D2). Spatial clustering of vegetation responses diminished over time, highlighting potential legacy effects and homogenization. These findings underscore the need to consider spatial variability, drought history, and land use in managing drought impacts on riparian ecosystems, offering practical insights for resilience strategies in similar dynamic regions.

1. Introduction

Riparian ecosystems, located at the interface between terrestrial and aquatic environments, play a vital role in maintaining biodiversity, stabilizing riverbanks, regulating hydrological processes, and providing essential ecosystem services (Knopf et al., 1988; Rusnák et al., 2022). Due to their inherent exposure to climatic fluctuations, ecological sensitivity, and history of degradation, these ecosystems are particularly vulnerable to climate change impacts (Capon et al., 2013). Rising temperatures and increased evapotranspiration rates intensify drought conditions, leading to reduced soil moisture and prolonged water stress for riparian plant communities (Perry et al., 2012; Poff et al., 2012). More frequent and severe droughts can further weaken riparian vegetation by disrupting water uptake, limiting photosynthetic activity, and increasing mortality rates, particularly among water-dependent species (Garssen et al., 2014).

Despite these growing climate pressures, riparian vegetation also possesses notable resistance, resilience and recovery, shaped by its long evolutionary history of adaptation to dynamic hydrological and environmental conditions. The resistance is largely driven by physiological and morphological traits that enable survival during drought, including deep root systems for accessing groundwater, high stomatal plasticity for regulating water loss, and drought-deciduous behavior to minimize stress (Nimmo et al., 2016; Scott et al., 1999). Additionally, riparian ecosystems demonstrate resilience through their ability to recover following disturbances, particularly in regions where water availability remains sufficient to sustain critical ecological functions (Tolkkinen et al., 2020). However, the extent of this resilience depends on the severity and frequency of climatic disturbances, as well as the effectiveness of conservation and management strategies aimed at maintaining riparian connectivity and hydrological integrity. Moreover, there is a limited understanding of how these dynamics manifest specifically in large, managed river basins like the Lower Mississippi River Region (LMRB), where drought impacts can be highly variable across space and time.

Drought is one of the most significant climate-related stressors affecting riparian ecosystems, making it a crucial factor in assessing the impacts of climate change on riparian vegetation health (Albano et al., 2020; Portela et al., 2023). Unlike other disturbances, droughts can develop over extended periods and lead to prolonged water deficits, severely influencing vegetation structure, function, and survival (Chaulagain et al., 2023; Farooq et al., 2009). The severity of drought events, defined by duration, moisture loss, and affected area, directly impacts riparian plant communities, altering their physiology, growth,

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https://doi.org/10.1016/j.ecolind.2025.113979
Received 16 April 2025; Received in revised form 14 July 2025; Accepted 31 July 2025
Available online 2 August 2025

and ecosystem resilience (Brito et al., 2018). To systematically classify and monitor drought conditions, the National Oceanic and Atmospheric Administration (NOAA) and the National Integrated Drought Information System (NIDIS) have established a standardized drought severity classification system (i.e., D0, D1, D2, D3 and D4) based on multiple hydrological, meteorological, and ecological indicators in the United States, with increasing levels indicating more severe and prolonged drought conditions (Svoboda et al., 2002).

Many previous studies have employed these drought severity levels to assess the impact of drought on vegetation by linking them with remotely sensed vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (Karnieli et al., 2010; Vicente-Serrano et al., 2013; Wu et al., 2024). These studies typically analyze how vegetation greenness declines with increasing drought severity, providing valuable insights into vegetation stress and recovery patterns at regional and global scales. For example, existing research has examined vegetation dieback during extreme drought events in the Mississippi River Delta (Elsey-Quirk et al., 2024), and vegetation health deteriorated rapidly due to a flash drought in the Mississippi River Valley in 2012 (Otkin et al., 2016). However, while this approach effectively captures general trends in drought-induced vegetation decline, it often overlooks the complex, spatially heterogeneous responses of riparian ecosystems. Riparian vegetation may exhibit different levels of resistance and recovery depending on groundwater accessibility, river flow dynamics, and human regulations, factors that are not explicitly accounted for in broad-scale drought severity classifications (Portela et al., 2023; Stromberg et al., 2010). Additionally, most studies using NOAA's drought categories only focus on drought forecasting, early warning systems and drought pattern analysis, with fewer efforts directed at examining how riparian vegetation health spatially fluctuates across different drought severity levels and their quantitative relationships.

Given these gaps, a more detailed investigation is needed to assess how riparian vegetation quantitatively responds to drought severity at a finer spatial resolution. This research uses the LMRB as a study area and aims to bridge the gap by leveraging NOAA's drought classification system (D0 – D4) alongside NDVI-based vegetation analysis to examine riparian vegetation health in response to drought events of varying intensity. By incorporating spatial variability and distinguishing between resistance and recovery across different severity levels, this study will provide a more nuanced understanding of the drought-vegetation relationship in riparian ecosystems. Using the LMRB as a case study, this research addresses three key questions: 1) How does riparian vegetation respond to varying drought severity levels during drought events? 2) What is the relationship between riparian vegetation resistance and recovery and different drought severity levels? 3) How is the spatial distribution of riparian vegetation response to drought characterized across the region? With a deep understanding of their relationships over space, we will be able to refine existing drought impact models and contribute to improved conservation through NOAA's drought classification system for riparian areas facing increasing climate stress.

2. Materials and methods

2.1. Study area

The LMRB spans approximately 220,000 square miles, covering portions of several states, including Missouri, Illinois, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana (Fig. 1). It owns a humid subtropical climate, with hot, wet summers and mild winters, and annual precipitation ranging from 45 to 60 in.. The region is characterized by flat floodplains and alluvial soils that support seasonal flooding. Water is used extensively for irrigation, navigation, flood control, and municipal supply.

As one of the largest and most hydrologically significant river basins in North America, the LMRB plays a crucial role in regional water

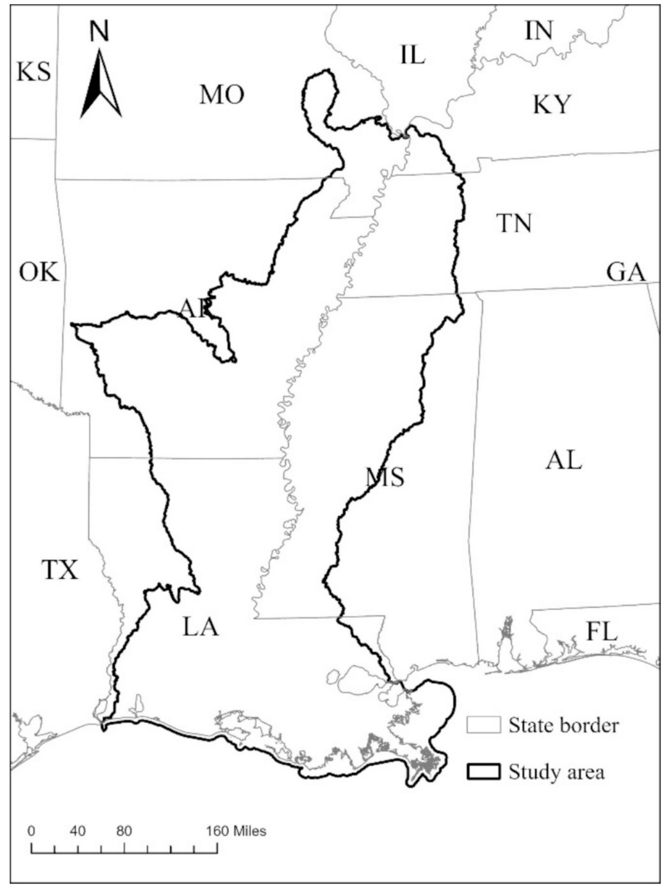

Fig. 1. Study area of the LMRB. (KS: Kansas, MO: Missouri, IL: Illinois, IN: Indiana, KY: Kentucky, TN: Tennessee, GA: Georgia, AL: Alabama, FL: Florida, MS: Mississippi, LA: Louisiana, AR: Arkansas, OK: Oklahoma, TX: Texas).

resources, supporting agriculture, fisheries, navigation, and biodiversity (Niebling et al., 2014; Reba et al., 2017). In the context of the LMRB, the riparian systems include floodplains, wetlands, and bottomland hardwood forests, which are ecologically distinct and highly responsive to drought and flooding dynamics. Understanding climate dynamics in the LMRB is particularly important due to the region's high vulnerability to hydrological extremes, including both floods and droughts. While the Mississippi River and its tributaries provide a buffer against short-term water deficits, prolonged droughts can significantly impact riparian vegetation, soil moisture levels, and overall ecosystem health (Elsey-Quirk et al., 2024; Steinbach & Zhuang, 2025).

The region's high agricultural dependence further amplifies the consequences of drought, as reduced water availability affects irrigation, crop yields, and economic stability. Additionally, the interaction between natural and anthropogenic influences, including river engineering projects and groundwater withdrawals, makes it critical to assess how riparian ecosystems respond to drought stress over time. The large spatial extent, diverse land cover, and combination of natural and human-modified landscapes make it an ideal area for examining how riparian vegetation responds to drought severity across different ecological and management contexts. Insights gained from the LMRB can inform broader assessments of drought impacts in similar large river basins globally.

2.1.1. Drought events during the study period (2010–2013)

The study period, spanning from March 2, 2010, to June 25, 2013, captures multiple naturally occurring drought events of varying severity that impacted the LMRB. The early part of 2010 is considered a pre-drought phase, characterized by relatively stable hydrological conditions. However, toward the end of 2010, conditions began to shift, setting the stage for a major drought event in 2011, which brought below-average rainfall, elevated temperatures, and widespread vegetation stress as reported in the monthly climate reports from the National Centers for Environmental Information (NCEI). This period is recognized as one of the most severe droughts in recent history, with extensive areas of the LMRB experiencing severe to exceptional drought conditions (D2–D4). Although precipitation improved in 2012, residual drought impacts remained in regions with long-term soil moisture deficits, and recovery continued into 2013. Rather than isolating discrete drought years, we analyzed vegetation responses across this continuous time window to capture the cumulative and potentially compounding effects of overlapping drought and recovery periods. This approach reflects ecologically realistic stress-recovery dynamics. While we acknowledge that carry-over effects may influence vegetation responses, they are inherent to the climatic variability of the region and central to our study design.

2.2. Data acquisition

The drought severity dataset used in this study was obtained from the U.S. Drought Monitor (USDM), a weekly, spatially explicit dataset representing drought intensity across the United States. The USDM classifies drought severity into five categories based on multiple climatological indicators, such as Standardized Precipitation Index (SPI) and Crop Moisture Index (CMI), and expert judgment. Each category reflects increasing drought intensity: D0 (Abnormally Dry), D1 (Moderate Drought), D2 (Severe Drought), D3 (Extreme Drought), and D4 (Exceptional Drought). Weekly shapefiles were accessed through NCEI, which hosts historical spatial data on drought extent at a ∼ 1 km resolution across the U.S. This dataset is collaboratively produced by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the United States Department of Agriculture (USDA), and NOAA ((NDMC) et al., 2025). Weekly drought severity shapefiles were downloaded from the USDM's GIS Data portal (https://droughtmonitor.unl.edu/DmData/GISData.aspx) for the study period and then integrated into our analysis to assess relationships with riparian vegetation health. In this research, a total of 173 weeks were analyzed, and the cumulative number of weeks for each drought severity level was mapped for further analysis.

Vegetation health is interpreted as the capacity of riparian vegetation to maintain greenness during and after drought events, reflecting its resistance and recovery to climate-induced water stress. The riparian vegetation health data used in this study were acquired by analyzing NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)-derived NDVI (Tucker, 1979) imagery. To calculate NDVI from MODIS data, we used the following formula:

$$NDVI = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}}$$

where R_{NIR} is the reflectance in the near infrared section of the spectrum, and R_{red} is reflectance in the red section of the spectrum. NDVI values range from −1 to 1, typically with healthy vegetation ranging from 0.6 to 0.9 and sparse or stressed vegetation ranging from 0.2 to 0.6. Specifically, the MOD13Q1 dataset, which provides vegetation index products at 250-meter spatial resolution and 16-day intervals, was accessed via Google Earth Engine (GEE) (Gorelick et al., 2017). The dataset offers several advantages, such as minimizing cloud cover issues and reducing the impact of localized noise, for studying riparian vegetation resistance and resilience, particularly in large-scale, long-term studies. Additionally, in previous studies, MODIS NDVI has been widely validated for ecological and hydrological studies, providing us confidence in investigating vegetation health that responds to climate variability (Beck et al., 2011; Huete et al., 2002; Lunetta et al., 2022). To make sure that the NDVI is suitable to represent vegetation health impacted by the drought, a time series of MODIS NDVI imagery covering the period between April and October for each year of 2010 (pre-drought year), 2011, 2012, 2013 and 2014 (post-drought years), was extracted using custom scripts developed in GEE. The mean NDVI for the specified timeframe was calculated to represent vegetation conditions during the study period. The resulting mean NDVI raster dataset was then exported as a GeoTIFF at a 30-meter scale (resampled from the original 250 m resolution) for further spatial analysis.

Riparian buffer zone data were obtained from the U.S. Environmental Protection Agency's (EPA)'s EnviroAtlas Watershed Index Online (WSIO) Riparian Zone Mask. A standardized buffer of approximately 100 m was selected based on previous ecological studies indicating this distance effectively captures critical interactions between aquatic and terrestrial ecosystems (Richardson et al., 2012; Sweeney & Newbold, 2014). The dataset offers consistent, high-resolution spatial coverage suitable for regional analysis, and data extraction was performed using EPA ArcGIS REST services (https://gispub.epa.gov/arcgis/rest/services/r4/RZ/MapServer/layers). The zone mask is a spatial boundary layer and does not classify vegetation types within the buffer. Therefore, riparian vegetation in this study was treated uniformly in terms of spatial sampling, while variation in land cover types within the riparian buffer was accounted for separately using the NLCD land cover dataset. Within the buffer area, we randomly selected 5000 sample sites (30 m × 30 m) over the space to represent the health of riparian vegetation during the drought period.

2.3. Methods

To comprehensively evaluate the relationship between drought severity and vegetation dynamics, we applied a combination of statistical and spatial methods. Each method offers unique strengths: OLS regression identifies global relationships, ANOVA and Tukey HSD detect group differences, and spatial clustering (e.g., hotspot analysis) captures local patterns. This multi-method approach enables a more nuanced understanding of vegetation responses under varying drought conditions.

2.3.1. Vegetation health response

In this study, the concepts of vegetation resilience, namely resistance and recovery, were quantitatively assessed using indices derived from MODIS NDVI data. The resistance index was calculated as the ratio of NDVI during drought conditions relative to NDVI during pre-drought periods, representing the capacity of vegetation to maintain functionality during stress. Values closer to 1 indicate high resistance, reflecting minimal vegetation change under drought conditions. The recovery index was computed as the ratio of post-drought NDVI to pre-drought NDVI, capturing the vegetation's ability to recover after drought stress. Higher recovery index values, approaching or exceeding 1, indicate rapid recovery or improvement in vegetation conditions following drought. The formulas we employed for these two indicators are as follows:

$$R_s = \frac{NDVI_{2011}}{NDVI_{2010}}$$

$$R_c = \frac{NDVI_{i=(2012,2013,\ \mathrm{or}2014)}}{NDVI_{2011}}$$

where R_s and R_c represent the resistance index and recovery index, respectively. In this research, a series of three years recovery index was considered to examine the recovery status of riparian vegetation in the LMRB. The combination of these two indices is able to provide an insight into ecosystem vulnerability and recovery dynamics (Lloret et al., 2011; Vicente-Serrano et al., 2013).

2.3.2. Standardization and regression analysis

The statistical relationship between drought severity and vegetation response was assessed using ordinary least squares (OLS) regression, with a focus on vegetation resistance R_s as the dependent variable. The independent variables were the cumulative number of weeks each location experienced drought at varying severity levels (D0–D4) during the drought year. OLS regression was selected for its interpretability and efficiency in identifying linear relationships between drought severity and vegetation response. This approach enables us to quantify both the direction and strength of association for each drought severity category while controlling for the others in the same model. By estimating individual coefficients, the OLS model also allows for direct comparison of the relative influence of each drought level on resistance.

Although recovery indices (R_c) were also calculated to evaluate post-drought vegetation response, they were not modeled using drought severity as a predictor, given the less direct causal link. Recovery is likely influenced by a broader set of post-drought conditions, such as rainfall patterns, land use dynamics, and vegetation type, making it less appropriate to model solely as a function of prior drought severity. The general form of the OLS model used in this analysis is:

$$Y = \beta_0 + \beta_1 D_0 + \beta_2 D_1 + \beta_3 D_2 + \beta_4 D_3 + \beta_5 D_4 + \epsilon$$

where Y is the vegetation response (i.e, resistance), β_0 is the intercept, β_1 through β_5 are the regression coefficients with drought severity levels D_0 through D_4, and ϵ indicates the error. Prior to regression analysis, however, all dependent and independent variables were standardized using z-score normalization. This standardization was performed to allow for a direct comparison of coefficients and to control for differences in measurement scale. Specifically, the formula was following as:

$$Z = \frac{x - \mu}{\sigma}$$

where Z represents standardized value, x is the original value, μ is the mean of the variable and σ is the standard deviation of the variable.

2.3.3. Spatial analysis and modeling

To assess spatial patterns in riparian vegetation response to drought, Global Moran's I and Getis-Ord Gi* statistics were applied using the Spatial Statistics toolbox in ArcGIS Pro 3.4. Moran's I was used to evaluate spatial autocorrelation in NDVI-derived resistance and recovery indices, quantifying the degree to which similar values clustered in space. Positive values indicate spatial clustering, while negative values suggest dispersion (Moran, 1950). Getis-Ord Gi* hot spot analysis was employed to detect statistically significant local clusters of high (hot spots) and low (cold spots) values (Getis & Ord, 1992). This analysis highlights spatial concentrations of vegetation response, revealing patterns not evident through global statistics alone.

To statistically compare vegetation resistance and recovery across different drought severity levels (D0–D4), a one-way Analysis of Variance (ANOVA) was performed using the stats package in R (version 4.4.1). The ANOVA F-statistic compares between-group variance to within-group variance and is calculated as:

$$F = \frac{MS_{between}}{MS_{within}}$$

where MS represents the mean square variance between and within groups. A larger F value indicates greater separation between group means relative to within-group variability, suggesting significant group differences. When the ANOVA result was significant ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post hoc test was used (agricolae package) to identify specific pairwise differences among drought categories while controlling for Type I error (Tukey, 1949). The combined method ultimately provides a statistical foundation for examining the relationship between riparian vegetation response and drought severity levels across space.

3. Results

3.1. Spatial patterns of drought exposure in the LMRB

Fig. 2 illustrates the cumulative number of weeks, out of a total of 173 weeks in the study period, that each drought severity level (D0 to D4) was observed across the LMRB. The spatial patterns indicate that drought exposure varied widely across the region, with southern and western portions of the basin consistently experiencing more prolonged and severe drought conditions. The D0 (Abnormally Dry) and D1 (Moderate Drought) categories were the most widespread, occurring across nearly the entire study area, with maximum durations reaching 66 and 64 weeks, respectively. These categories show a high spatial frequency particularly in southern Louisiana and southwestern Mississippi. The distribution of D2 (Severe Drought) also covered much of the region, with localized intensification in the central and western basin, reaching up to 71 weeks in certain areas. In contrast, D3 (Extreme Drought) and D4 (Exceptional Drought) were more spatially restricted but highly concentrated in southwestern and northern Louisiana and western Arkansas. Notably, portions of Louisiana experienced up to 68 weeks of D3 and 34 weeks of D4 conditions, indicating persistent and severe drought stress in these areas. Northern sections of the LMRB, including parts of Missouri, Kentucky, and Tennessee, showed comparatively low exposure to severe drought categories, particularly D3 and D4, which were largely absent in those regions.

3.2. Resistance and recovery patterns

The box of pre-standardized NDVI-derived resistance and recovery indices (Fig. 3) illustrate the variability and central tendencies of riparian vegetation response to drought from 2011 to 2014. The median resistance value is slightly below that of the recovery indices, indicating that, on average, vegetation experienced a moderate decline in greenness during the drought year (2011), but demonstrated measurable recovery in the subsequent years. Notably, the median recovery values for 2012, 2013, and 2014 are greater than 1, and the majority of data points in each year also exceed 1, indicating a consistent post-drought rebound in vegetation health relative to 2011 status.

Despite similar median values across recovery years, Recovery 2014 exhibited a wider interquartile range and more pronounced outliers, indicating greater variability in vegetation responses across the landscape. This suggests that while some areas may have fully recovered or even surpassed pre-drought NDVI levels, others lagged in their recovery, potentially due to localized hydrological or ecological conditions. Fig. 4 illustrates how riparian vegetation health responds to different durations of drought exposure under five drought severity levels (D0 to D4). Each subplot represents one drought category, with the x-axis showing 5 weeks exposure intervals and the y-axis indicating mean vegetation health response. Resistance generally declines with increasing drought severity, while recovery patterns vary across years and are more sensitive under moderate to extreme drought conditions (D2–D4). In contrast, vegetation response under D0 and D1 shows relatively minor fluctuations across exposure durations.

Table 1 presents the results of OLS regression analysis examining the relationship between standardized vegetation resistance and drought severity levels (D0–D4). The model shows that several drought categories had statistically significant negative effects on resistance. Specifically, D0, D2, D3, and D4 all exhibited significant negative coefficients ($p < 0.001$ or $p < 0.01$), indicating that longer exposure to these drought levels was associated with reduced resistance in riparian vegetation. Among these, D3 (Extreme Drought) had the strongest effect (β = -0.11, t = -6.05), followed by D0 (Abnormally Dry, β = -0.10), suggesting that both low-level and high-severity drought conditions can substantially reduce vegetation stability during drought events. In contrast, D1 (Moderate Drought) was not significantly associated with resistance (p = 0.322), and its coefficient was small and statistically

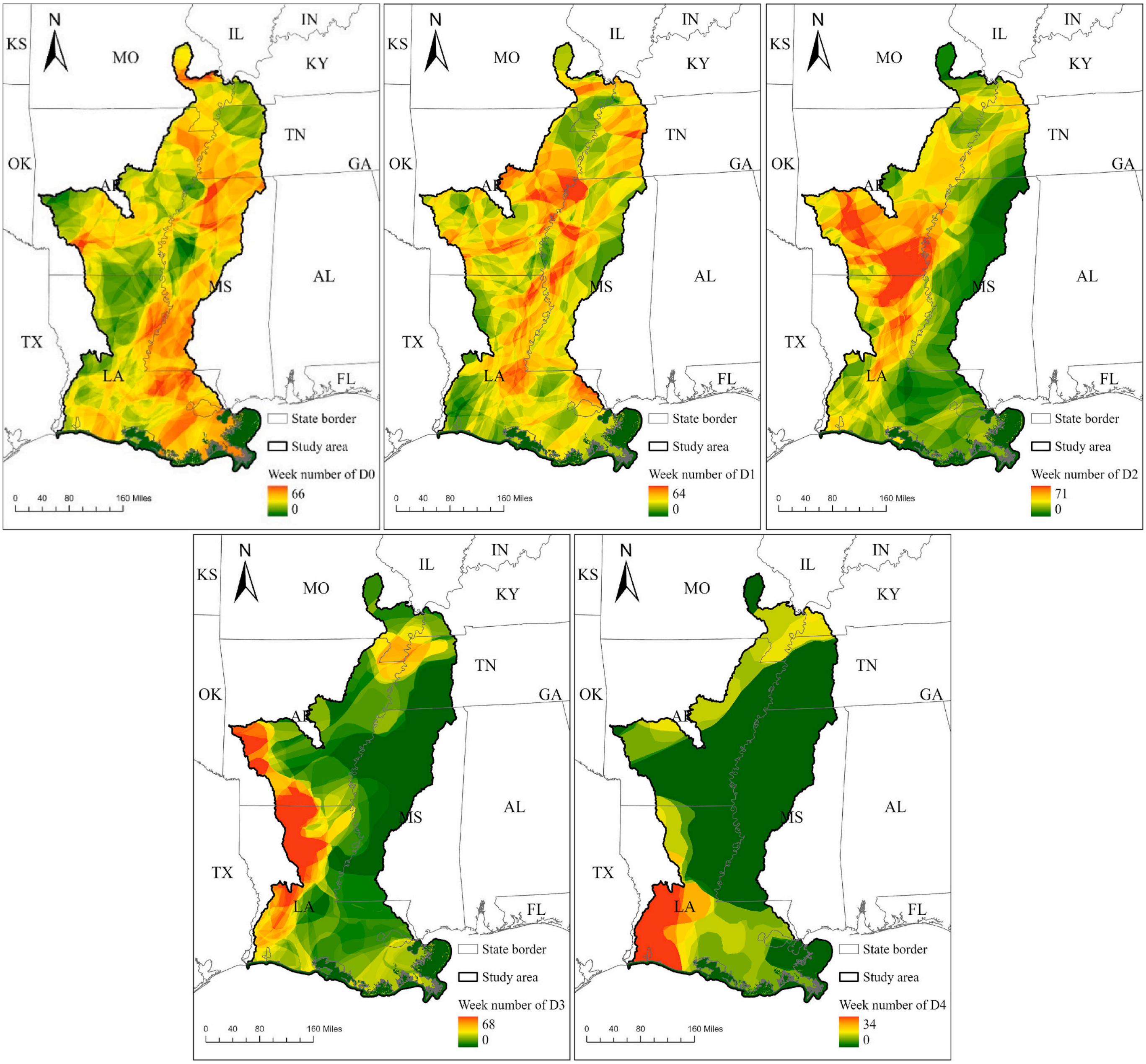

Fig. 2. Cumulative number of weeks each drought severity level.

indistinguishable from zero. This may indicate that vegetation exposed to moderate drought often maintains greenness levels similar to baseline conditions, potentially due to shorter drought durations or localized buffering effects. Vegetation types in the LMRB are spatially distinct – croplands dominate central and western areas, while forests and wetlands cluster near major river channels. Wetlands and bottomland forests often depend on river connectivity and shallow groundwater, which may buffer them against drought more than upland vegetation.

3.3. Spatial clustering of vegetation response

We first implemented global Moran's I to understand the spatial autocorrelation of the vegetation responses. The statistics indicated statistically significant positive spatial autocorrelation for all vegetation response variables ($p < 0.001$; Table 2). Specifically, resistance exhibited a Moran's I of 0.087, while post-drought recovery showed slightly higher spatial clustering, with Moran's I values ranging from 0.098 (2013) to 0.140 (2012). These results suggest that both resistance and recovery patterns were not randomly distributed across the landscape but instead formed distinct spatial clusters.

Fig. 5 illustrates the results of the Getis-Ord Gi* hot spot analysis for vegetation resistance and recovery across the study area. Spatial clustering of vegetation response significantly varies by year. For the resistance period (A), cold spots (low resistance) were notably concentrated in the northwestern, central, and southwestern portions, while hot spots (high resistance) appeared predominantly along the eastern and north-central regions. For recovery in 2012 (B), clusters became more pronounced, with extensive cold spots in the northern areas and distinct hot spots forming centrally. However, in the subsequent recovery years of 2013 (C) and 2014 (D), spatial clusters of cold and hot spots became progressively less distinct and more dispersed across the study area. This diminishing spatial clustering suggests that vegetation recovery patterns became increasingly homogenized in later post-drought years. While Fig. 5 highlights statistically significant hot and cold spots, the majority

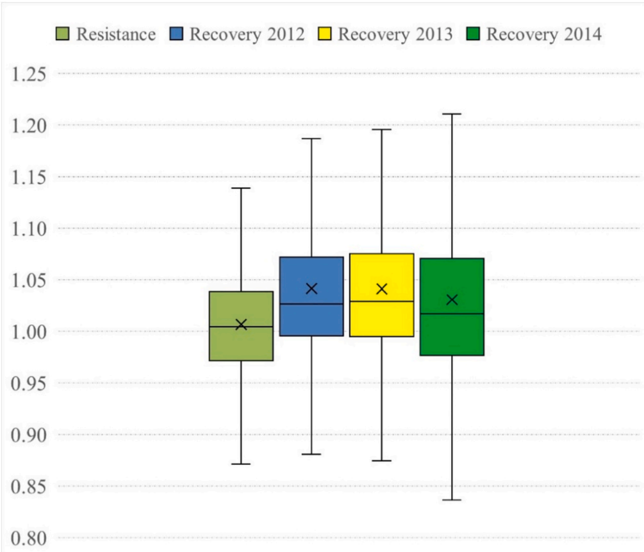

Fig. 3. Box plots of NDVI-derived resistance and recovery indices.

of the study area falls into non-significant clusters, indicating more neutral or variable vegetation responses to drought that do not form spatially cohesive patterns.

To further investigate the relationship between drought severity and vegetation responses identified in the hot spot analysis, we conducted a one-way ANOVA followed by Tukey's HSD post-hoc tests (Tables 3 and 4). ANOVA results showed significant differences in drought severity exposure across resistance and recovery clusters, particularly for lower and moderate drought categories (D0–D2). Specifically, resistance significantly varied across D0, D1, and D4 drought levels ($p < 0.01$), whereas recovery in 2012 showed significant differences for D0, D1, and D2 ($p < 0.01$). Recovery in 2014 remained significantly associated with drought severity levels D0–D2 ($p < 0.05$), whereas only D1 drought was marginally significant for recovery in 2013 ($p < 0.05$). Tukey's HSD tests further clarified these results, for example, our findings suggest that high resistance of riparian vegetation experienced less weeks of D0 exposure and surprisingly more weeks of D1 exposure. Areas of low resistance were predominantly associated with exceptional drought exposure (D4), with an average of 1.115 weeks more than those places of neutral spots.

Recovery patterns were significantly associated with exposure to mild and moderate drought severity (D0–D2). Specifically, high recovery clusters experienced fewer weeks of mild drought (D0) compared to neutral spots immediately following the drought event in 2012 (mean difference = 2.289 weeks, $p < 0.01$). Counterintuitively, however, these high recovery areas also showed greater exposure to moderate drought levels (D1 and D2) in 2012, with significant mean differences ranging from approximately 3.3 to 5.1 weeks compared to cold and neutral spots. In 2013, moderate drought (D1) was significantly associated with spatial differences in recovery patterns overall (Table 3), but pairwise post-hoc comparisons did not clearly distinguish recovery clusters. By 2014, an unexpected pattern emerged where lower recovery areas experienced fewer weeks of mild drought (D0) relative to neutral areas (mean difference = -2.306 weeks, $p < 0.05$), likely reflecting lingering ecological stress or threshold effects from previous severe drought exposure. Similar to 2012, however, higher recovery clusters in 2014 continued to be significantly associated with increased exposure to moderate drought severity (D1 and D2), indicating that vegetation

Table 1
Regression analysis between standardized resistance and drought severity.

Variable	Coefficient	t-Statistic	P-Value	95 % CI
D0	−0.10	−5.35	<0.001	[-0.141, −0.066]
D1	−0.02	−0.99	0.322	[-0.048, 0.016]
D2	−0.08	−4.85	<0.001	[-0.108, −0.046]
D3	−0.11	−6.05	<0.001	[-0.143, −0.073]
D4	−0.04	−2.78	<0.01	[-0.074, −0.013]

Table 2
Global Moran's I statistics for pre- and post-drought vegetation responses.

Variable	Moran's I	Z-Score	P-Value
Resistance	0.087	18.826	<0.001
Recovery 2012	0.140	30.068	<0.001
Recovery 2013	0.098	21.016	<0.001
Recovery 2014	0.100	21.609	<0.001

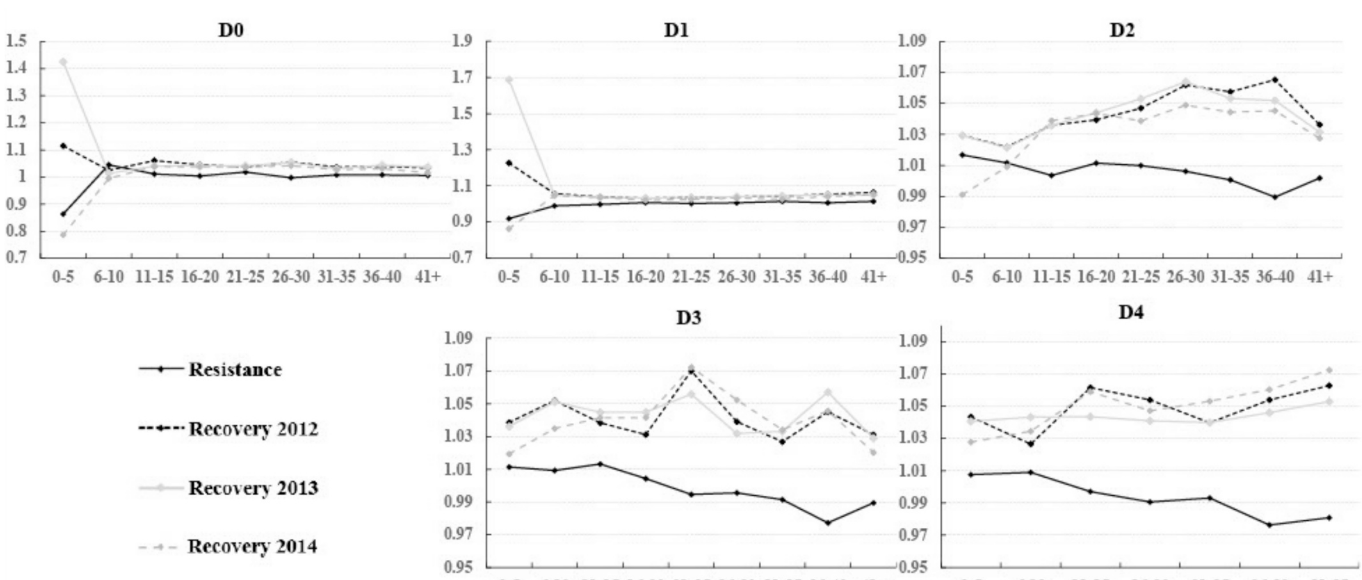

Fig. 4. Mean vegetation health response across 5-week exposure intervals by drought severity level (D0–D4). (Y-axis: mean NDVI-derived Index; X-axis: drought exposure duration in weeks).

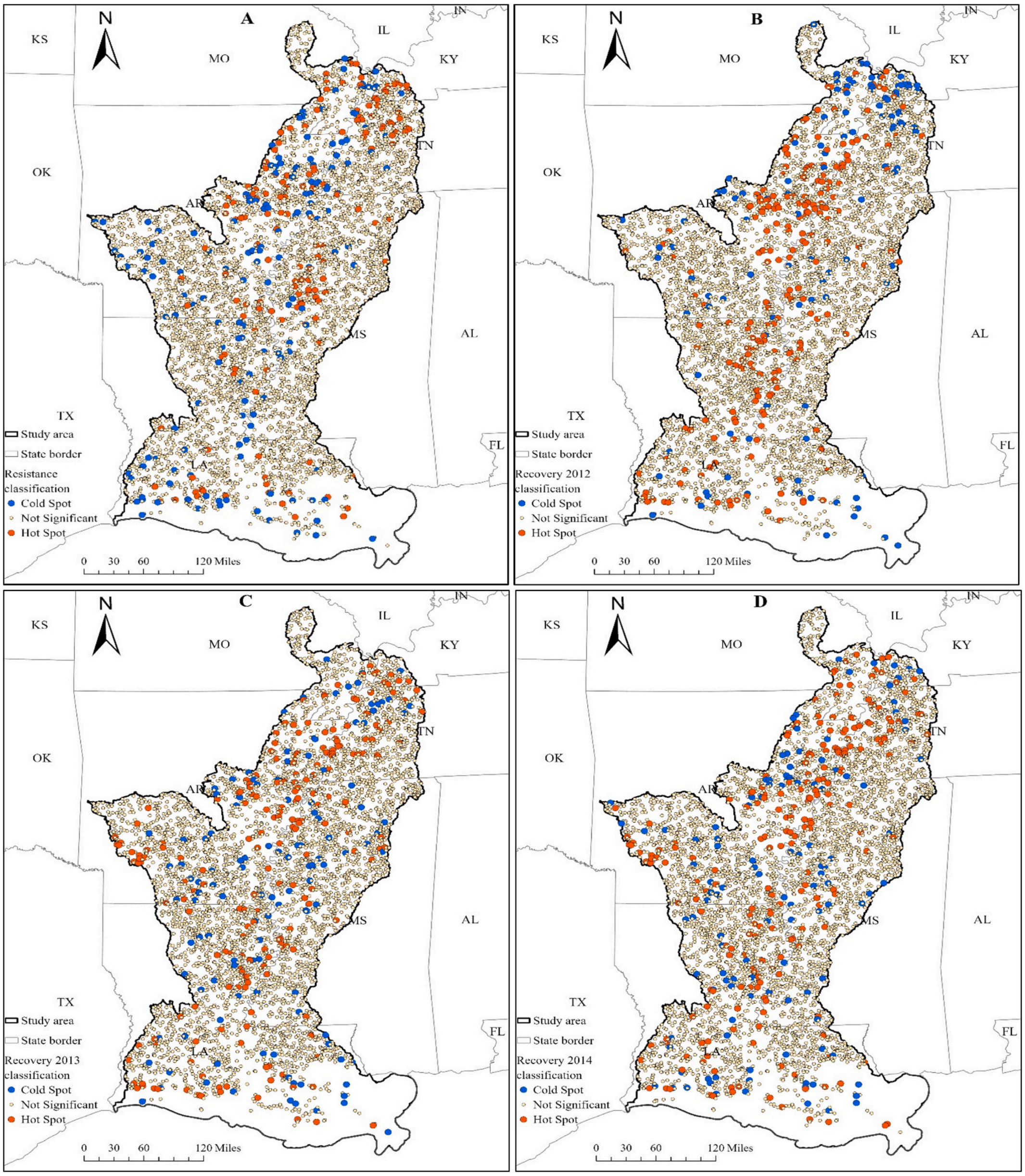

Fig. 5. Hot Spot Analysis of Riparian Vegetation Resistance and Recovery. (A: Resistance; B: Recovery in 2012; C: Recovery in 2013; D: Recovery in 2014. Note: Hot and cold spots indicate statistically significant clustering at 90%, 95%, and 99% confidence levels).

Table 3
F-statistics of one-way ANOVA between drought severity and vegetation responses.

	F-statistic Resistance	Recovery 2012	Recovery 2013	Recovery 2014
D0	12.091***	7.106***	0.429	3.836**
D1	11.452***	17.142***	3.219**	4.675**
D2	2.415	6.267**	2.548	3.755**
D3	2.853	0.801	0.523	2.015
D4	3.241***	2.046	0.216	0.050

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

recovery capacity might be tied to ecological adaptations, land-use practices, or active management strategies that effectively mitigate moderate drought impacts. Collectively, these results emphasize the complexity of drought severity and vegetation recovery dynamics, highlighting the importance of both drought intensity and ecological context in shaping post-drought vegetation responses.

4. Discussion

We believe that the LMRB is a promising study area for our research questions as it features a complex interplay of natural riparian systems and human-managed landscapes, such as agricultural lands. The region's diversity in frequent drought exposure and various land uses provides a unique opportunity to understand how riparian vegetation health responds to drought periods. Importantly, some of our findings, such as high resistance occurring in areas with more exposure to moderate drought, are meaningfully counterintuitive. Yet, these patterns were consistently supported by both statistical models and spatial analysis, underscoring the importance of integrating multiple methods to uncover nuanced drought-vegetation dynamics in coupled human-natural systems.

The findings of OLS regression demonstrate that all drought severity levels contribute negatively to vegetation health response but with

Table 4
Summary of significant post-hoc Tukey HSD test for drought exposure across resistance and recovery clusters.

	Drought level	Comparison	Mean Difference†	Lower Bound	Upper Bound
Resistance	D0	N vs. H	3.739***	1.85	5.63
	D1	C vs. H	−3.413**	−5.79	−1.03
		N vs. H	−3.480***	−5.18	−1.78
	D4	C vs. N	1.115**	0.09	2.14
Recovery 2012	D0	N vs. H	2.289**	0.67	3.91
	D1	N vs. H	−3.551***	−5.01	−2.09
	D2	C vs. H	−5.102**	−9.12	−1.08
		N vs. H	−3.296**	−5.67	−0.93
Recovery 2013	D1	–	–	–	–
Recovery 2014	D0	C vs. N	−2.306**	−4.48	−0.14
	D1	N vs. H	−1.794**	−3.23	−0.36
	D2	N vs. H	−2.563**	−4.89	−0.23

Note: The value represents drought severity level exposure (in weeks) between resistance and recovery cluster types. Group comparisons include cold spots (C), neutral areas (N), and hot spots (H). Asterisks indicate significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
†: Mean differences represent drought exposure (weeks) calculated by subtracting the second listed cluster from the first (e.g., N vs. H = Neutral − Hot); positive values indicate higher drought exposure in the first cluster.

various significance. Specifically, the coefficient for D1 (moderate drought) was not statistically significant. In contrast, ANOVA and hot spot results suggest that D1 plays a role in shaping vegetation response over clustering analysis. We do not interpret the non-significance of D1 in the OLS model as definitive, given the limitations of global regression approaches in capturing spatial heterogeneity. This contradiction likely reflects the fact that OLS estimates global, linear relationships, while spatially complex systems like the LMRB are influenced by non-linear thresholds and localized variation(Peters et al., 2004; Turner, 2005). That said, areas experiencing moderate drought may often coincide with actively managed landscapes (e.g., agriculture), where interventions like irrigation and crop rotation could buffer drought impacts. This hypothesis is supported more clearly by our spatial analyses than by OLS regression. These findings underscore the value of a multi-method approach, combining regression with spatial statistics, to better capture nuanced, context-dependent drought–vegetation dynamics.

The further investigation of a spatial pattern of local resistance outlines a conclusion that drought severity classifications may not reveal their hierarchical influences on riparian vegetation health. Moreover, a severity level-based suffering estimation can be misled by solely comparing the numbers of weeks of drought exposure. An initial counterintuitive result shows that high-resistance areas experienced more weeks of moderate drought (D1), while low-resistance areas (cold spots) were associated with more weeks of exceptional drought (D4). A closer examination of land cover in the LMRB suggests that many of the high-resistance clusters overlap with the land type of cultivated crops (Fig. 6). These areas are often actively managed, with irrigation, crop rotation, and drought-resistant crop varieties helping to maintain vegetation greenness during periods of moderate drought (Yang et al., 2019). For instance, Xiao et al. (2023) found that irrigation significantly enhances the drought resistance of croplands, enabling them to maintain healthy vegetation under water stress conditions. Additionally, crop rotation has been shown to improve soil structure and water retention, contributing to increased resilience against drought (Bowles et al., 2020). Another reason for high vegetation resistance in cultivated areas may be edaphic factors, such as soil texture and water-holding capacity, which influence plant water availability during drought (Abel et al., 2024). As such, NDVI-based resistance may remain high despite prolonged D1 exposure, not because the vegetation is unaffected, but because human intervention offsets water stress. In contrast, cold spots of resistance—areas experiencing significantly more weeks of D4 drought—are likely to reflect regions where vegetation has surpassed its ecological drought

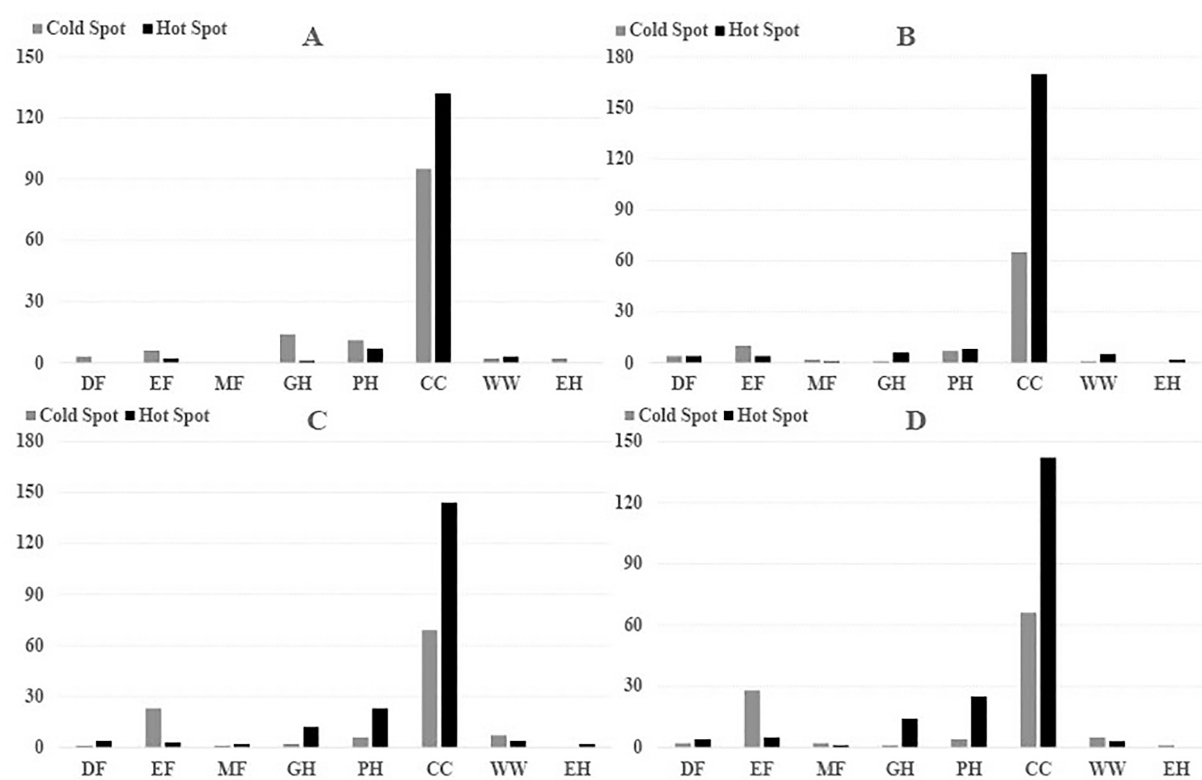

Fig. 6. Classification of riparian vegetation cover in hot and cold spots across post-drought periods. (A–D represent resistance in 2011 and recovery in 2012–2014. Y-axis: number of spots; X-axis: vegetation types. DF: Deciduous Forest, EF: Evergreen Forest, MF: Mixed Forest, GH: Grassland/Herbaceous, PH: Pasture/Hay, CC: Cultivated Crops, WW: Woody Wetlands, EH: Emergent Herbaceous Wetlands).

threshold, leading to declines in photosynthetic activity. These regions may include unmanaged riparian zones or less resilient vegetation types that are more vulnerable to prolonged water deficits. Together, these patterns highlight the role of both ecological and anthropogenic mechanisms in shaping drought resistance and underscore the need to consider land use and management context when interpreting spatial vegetation response to drought.

Vegetation recovery patterns following drought in the LMRB displayed both expected and counterintuitive dynamics across the post-drought years. In 2012, high-recovery areas were associated with fewer weeks of mild drought (D0), as anticipated, but also experienced more exposure to moderate drought (D1 and D2). This paradox is also reflected in the high-recovery pattern of 2014, which occurred despite more weeks of exposure to D1 and D2. These findings may reflect post-drought resilience in vegetation communities that are either naturally drought-adapted or supported by active land management. In such areas, interventions like irrigation or crop selection may have helped facilitate rapid recovery, while mild drought alone may not have been sufficient to trigger an adaptive response. Over time, however, the spatial distinction of recovery clusters became less pronounced, particularly in 2013 and 2014, suggesting a possible homogenization of vegetation responses across the basin. Under this case, we realized that during a drought period, a recovery process would probably be related to the early steerable drought stages. These stages can cover human intervention, in-situ drought-adapted landscapes and even a period of overwhelmingly extreme drought. Interestingly, in 2014, low-recovery areas were associated with fewer weeks of D0 exposure than neutral areas, an unexpected result that may point to legacy effects of earlier, more severe droughts, where vegetation stress persisted despite subsequent improvements in drought severity. This 2014 local recovery pattern suggests that even mild drought in already stressed systems may contribute to poor recovery outcomes if compounded by previous ecological damage or differences in land cover type. We believe that these findings highlight the temporal complexity of post-drought vegetation response and underscore the importance of considering both drought history and land management context in assessing riparian ecosystem resilience.

Overall, as discussed above, this study offers important insights into how riparian vegetation responds to varying levels of drought severity across space and time, highlighting the complex interactions between ecological thresholds, land management, and spatial processes. By integrating statistical modeling with spatial analysis, the research demonstrates the value of multi-method approaches for understanding drought impacts beyond our intuition that drought severity classifications reveal their hierarchical influences on riparian vegetation health. The patterns uncovered in this study, particularly those counterintuitive findings, underscore the importance of context-specific interpretations and offer a framework for future studies examining climate stress in coupled human–natural systems. These findings have practical implications for drought resilience planners, especially those who use these USDM-based drought severity classifications, suggesting that identifying spatial clusters of vulnerability can guide more targeted conservation and resource allocation efforts. However, we would admit that this research may contain limitations as well. The study's reliance on remotely sensed NDVI and generalized drought indices presents uncertainties. NDVI is limited in capturing subsurface processes and may not fully reflect vegetation conditions in multi-strata or mixed-use landscapes. The OLS and ANOVA models assume linear, homogeneous responses, which may oversimplify ecological feedback; spatial heterogeneity was partially addressed through hot spot analysis instead of nonlinear or machine learning approaches. Future research would benefit from incorporating ground-based vegetation data, soil moisture conditions, and dynamic modeling to more precisely capture the mechanisms of drought impact and recovery. Additionally, exploring long-term ecological impacts and management-driven resilience strategies across different riparian land covers would enhance our understanding of drought–vegetation dynamics. Nevertheless, we believe that this work can provide a foundation for scholars and practitioners seeking to understand and manage the uneven ecological consequences of climate extremes in riparian landscapes.

Our findings also have implications for conservation and water resource management. Identifying areas with low resistance or recovery may help target restoration or adaptive flow regimes in vulnerable riparian zones. Furthermore, the combined use of drought severity classifications, NDVI-based metrics, and spatial clustering provides a practical framework for ecosystem monitoring and early drought impact detection in large river basins.

5. Conclusions

This study provides a comprehensive assessment of how riparian vegetation in the LMRB responds to varying levels of drought severity. By integrating NDVI-based resistance and recovery indices with drought severity classifications and spatial analysis, we offer new insights into the complex and sometimes counterintuitive ways in which vegetation responds to climate stress. The findings reveal that drought impacts on riparian ecosystems are shaped not only by severity level but also by spatial context, ecological thresholds, and land use practices. Through the lens of our three research questions, we demonstrate the importance of distinguishing between resistance and recovery dynamics, accounting for spatial clustering in vulnerability, and recognizing the role of human-managed landscapes in shaping vegetation outcomes. Specifically, our results highlight areas of low resistance and slow recovery that can be targeted for ecological monitoring and restoration, while demonstrating the importance of sustainable land management practices, such as irrigation and crop selection, in enhancing riparian biodiversity conservation and ecosystem resilience. These contributions help advance a more nuanced understanding of drought-vegetation relationships and offer a methodological framework that can support future research and inform adaptive conservation strategies under a changing climate.

CRediT authorship contribution statement

Hui Wang: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Zhe Wang:** Writing – review & editing, Visualization, Investigation, Data curation. **Shijin Qu:** Writing – review & editing, Investigation. **Xiang Que:** Writing – review & editing, Investigation, Conceptualization. **Zhiyuan Yao:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank the editor and three anonymous reviewers for their valuable comments on the original manuscript. The authors also acknowledge the financial support from the National Natural Science Foundation of China (42202333).

Data availability

Data will be made available on request.

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