

# The Impact of Climate and Landscape Diversity on Wetland Biomass: Research Progress and Future Prospects

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## Abstract

As one of the most productive ecosystems on Earth, wetlands play a crucial role in carbon cycling and maintaining biodiversity. In recent decades, due to the intensification of global climate change and increased human disturbance, wetland ecosystems have faced significant pressure, with wetland biomass dynamics influenced by both climate change and human activities. This paper briefly outlines the mechanisms by which various climate change factors-including temperature, precipitation, climate extremes, and landscape diversity-influence wetland biomass, as well as the ecological effects resulting from the interactions among these factors. It also identifies future research directions to provide guidance for wetland conservation and restoration. The high productivity of wetland ecosystems is primarily due to their unique hydrological conditions, high biodiversity, and biomass. Wetland biomass can characterize the productivity of wetland ecosystems and to some extent reflect their carbon sequestration capacity. However, under the backdrop of climate change, factors such as rising temperatures, altered precipitation patterns, and extreme weather events have led to diverse changes and distributions in wetland biomass. On the other hand, landscape diversity represents habitat heterogeneity, and landscape diversity can indirectly regulate the formation of wetland biomass by altering species coexistence mechanisms and resource utilization efficiency. Therefore, understanding the impact of climate and landscape diversity on the formation of wetland biomass is essential.

## Keywords

Wetlands; Landscape Diversity; Biodiversity; Climate Change.

## 1. The Impact of Climate Factors on Wetland Biomass

Climate change affects wetland biomass through a variety of direct and indirect mechanisms. As one of the most significant climate changes, it is a double-edged sword. On one hand, rising temperatures can extend the growing season of wetland plants, accelerate photosynthesis, and increase biomass. For example, in a study of the Yellow River Delta wetlands, rising temperatures led to an increase in reed biomass [1]. On the other hand, excessively high temperatures can cause physiological damage to wetland plants and inhibit their growth, such as in the Sanjiangyuan region where rising temperatures resulted in a decrease in vegetation biomass [2]. Additionally, research on the Three Gorges Reservoir wetlands revealed that climatic factors primarily influence plant biomass indirectly by regulating soil conditions; observations of the Poyang Lake South Ji wetlands indicated that rising temperatures alter wetland hydrological cycles, leading to changes in the distribution of wetland plant communities and biomass accumulation patterns [3, 4].

Changes in precipitation have significantly impacted wetland biomass. Precipitation divides the water supply process of most wetlands, making water volume and timing crucial factors in

determining wetland hydrological conditions, which directly affect the development of vegetation within wetlands. Changes in wetland area are positively correlated with precipitation [4]. For example, in semi-arid regions, reduced precipitation leads to smaller wetlands and lower biomass. In snowmelt-fed wetlands, increased temperatures can cause greater snowmelt, resulting in expanded wetland areas and increased biomass [5]. Additionally, differences in the seasonal distribution of precipitation also affect plant phenology and the rhythm of biomass accumulation. For example, the rhythm of reed biomass accumulation in the Chongming Dongtan Wetland is influenced by the delay in the rainy season [6].

The increased frequency and intensity of extreme climate events such as droughts and floods can suddenly impact wetland biomass. Studies on wetlands in the lower reaches of the Yellow River have found that extreme drought events can lead to soil water shortages, thereby reducing plant productivity; frequent flood disturbances can alter soil nutrient cycling, change plant community composition, and thus alter the overall biomass distribution pattern of the ecosystem [7, 8]. Extreme drought events in the lower reaches of the Yellow River have caused soil moisture deficiency, resulting in a significant decrease in reed productivity. Additionally, during the restoration of the Sanya mangrove wetland, it was found that extreme events under the backdrop of climate change increase the risk of invasive species threatening native plants [9].

Precipitation combined with local soil conditions is another significant influencing factor. According to Liu Li et al.'s study on the Yellow River Delta wetland, water depth and soil salinity are the dominant factors in the spatial differentiation of reed and saltwort biomass, both of which are indirectly regulated by precipitation and temperature changes; meanwhile, in the reclaimed area of the Chongming Dongtan Wetland, soil total nitrogen content shows a significant positive correlation with reed aboveground biomass, indicating that precipitation indirectly regulates biomass by influencing soil nitrogen cycling [1, 6].

It should be noted that the spatial heterogeneity of climate change's impact on wetland biomass is particularly pronounced. Dong Liqin and Zhang Guangxin pointed out that wetlands in humid regions are more sensitive to precipitation changes, while those in arid regions are driven by temperature; regional heterogeneity highlights the need to consider local climate backgrounds and the unique characteristics of wetland types when evaluating the impact of climate change on wetland biomass [10].

## 2. The Impact of Landscape Diversity on Wetland Biomass

Landscape diversity can exert multi-level effects on wetland biomass through habitat heterogeneity and ecological processes. Habitat heterogeneity is one of the most important characteristics of landscape diversity, providing cohabitation space for different plant species while also enabling plant species with distinct ecological niches to coexist, thereby enhancing biomass accumulation [11]. Similarly, an experiment conducted at the Haizhu Wetland in Guangzhou established six configuration patterns, demonstrating that high-heterogeneity habitats can support more species coexistence, with overall productivity increasing by 20% [12]. Additionally, the Guanyin Lake Wetland in Suining, Sichuan, utilized landscape pattern configurations to maintain ecosystem diversity and productivity, thereby promoting better wetland development.

Plant community structure is a component of landscape diversity, and the diversity of species composition and functional traits within communities influences biomass. The aboveground biomass of the eight different plant community types in the Three Gorges Reservoir wetland showed significant differences [3]. Additionally, landscape connectivity indirectly increases biomass by promoting seed dispersal and nutrient cycling. For example, the optimized water network design in the Suining Guanyin Lake Wetland increased wetland biomass by 15% [13].

Moderate species diversity can enhance the complementary and selection effects on community productivity. However, when exceeding a certain threshold, it may lead to competitive effects among species within the community. This conclusion was also validated in the Three Gorges Reservoir study, where species diversity exhibited a linear negative correlation with aboveground biomass, indicating that a trade-off between community diversity and productivity may occur once an ecological threshold is reached.

The impact of plant community diversity on biomass exhibits a threshold effect. Among the eight plant communities in the Three Gorges Reservoir wetlands, species diversity was linearly negatively correlated with aboveground biomass, suggesting that excessive diversity may lead to resource competition [3]. Therefore, landscape spatial configuration is exceptionally important, as it determines how matter and energy circulate and are distributed within the system, directly influencing changes in wetland biomass. Zheng Qingzhi and Tan Yanshan employed the BCON method to alter the original water network and habitat patch layout of the Haizhu Wetland, guiding the system's material and energy flows toward directions conducive to enhancing wetland biomass, resulting in positive outcomes [13]. Additionally, research on land-sea ecological corridor nodes showed that reasonable design can reduce human disturbance, facilitate seed dispersal by birds, and indirectly promote plant growth; enhancing landscape connectivity can improve nutrient cycling and seed dispersal, thereby generating high biomass [14].

Soil-plant feedback is an important pathway through which landscape diversity influences biomass. Zhang Quanjun et al. found through their study of the Poyang Lake wetland that different plant communities result in significant differences in soil organic matter and nutrient content, and that soil influences plant growth [15]. Wang Chuanying et al. found through research on the Yellow River Delta wetlands that soil nutrient chemical properties are correlated with vegetation cover [7]. According to Liu Li et al., the spatial distribution of biomass in the Yellow River Delta wetlands shows a decreasing trend from land to sea, which is closely related to the distribution of river channels and salt marsh patches in the area, indicating that landscape diversity also indirectly alters soil environments to influence biomass formation [1].

### **3. The Interaction between Climate and Landscape Diversity**

Climate and landscape do not independently influence wetland biomass; rather, they exert their effects through a complex interplay. Numerous studies have confirmed the existence of this synergistic relationship. Climate and landscape exert regulatory effects on wetland biomass, with wetlands serving as both sources and sinks of greenhouse gases. Fu Guobin and Li Kelang argue that wetlands, as important carbon reservoirs, have their carbon budgets determined by both climate and landscape factors [16]. Under the backdrop of climate warming, wetlands with higher landscape diversity exhibit stronger adaptability to climate change and smaller fluctuations in biomass; however, extreme drought (such as in the Sanjiangyuan region) may reverse this positive effect. Han Dayong et al. also mention in their review on wetland degradation that the coordinated relationship between climate and landscape determines changes in biomass [17].

Threshold effects and nonlinear responses are key characteristics of such processes. Song Changchun's research indicates: Only when the magnitude of climate change is sufficiently large does landscape diversity begin to negatively impact biomass, and the previous positive effects reverse; extreme drought makes it difficult for high-diversity landscapes to maintain high levels of productivity [18]. In addition to causing significant impacts on host systems, climate change also makes the introduction of invasive species more likely during mangrove restoration in Sanya and makes it difficult for local landscapes to maintain a certain level of biomass [9].

Scale dependency refers to the need to study interactions from a scale-based perspective. Liu Hongyu argues that wetland landscape research must consider multi-scale effects: at the local scale, landscape diversity may primarily influence biomass through species interactions; at the regional scale, climate factors are the most decisive [19]. Meng Huan et al.'s study of wetlands in China's interior indicates that climate change has a significant impact at the large scale, while at medium and small scales, the primary factor is differences in landscape diversity [5].

Adaptive management methods should only be applied once a certain level of understanding of interactions has been achieved. Wang Fei et al. found through long-term monitoring of the Honghu Wetland that landscape zoning management (such as reducing human disturbance in core zones) significantly enhances the system's adaptability to climate change [20]. Li Guozheng also advocates integrating wetland conservation, climate adaptation, and landscape optimization [21]. The successful experience of the Parrot Island Wetland demonstrates that zoned management and reducing human disturbance can enhance the system's resilience to climate change impacts, and similarly, mangrove restoration based on climate adaptability can achieve better restoration outcomes [14, 22].

#### 4. Research Shortcomings

Despite significant progress, there is still much room for improvement, with the primary shortcomings lying in the lack of a thorough understanding of the mechanisms underlying biomass formation. Additionally, most studies rely on correlation analysis and lack necessary experimental validation. For instance, in regions such as the Sanjiangyuan area and the Yellow River Delta, researchers have inferred the impacts of climate or landscape through correlation analysis alone, without controlled experimental validation [23]. Future research could begin with controlled experiments, setting up landscape interventions under different climate scenarios to reveal the relative contributions of various factors in vegetation and biomass formation processes.

The lack of long-term monitoring data limits the ability to predict trends. For example, studies on the Chongming Dongtan Wetland are based solely on short-term observations, making it difficult to capture the lagged response of biomass to climate change. It is argued that wetland degradation research must be supported by long-term, fixed-point observational data. By establishing a comprehensive monitoring network covering different climate zones and wetland types nationwide, and integrating remote sensing and ground-based data in data acquisition, the accuracy of predicting biomass dynamic trends can be significantly improved. Wang Fei and Xie Qiming's research has already demonstrated the importance of long-term data [20].

Limitations in model development. Dong Liqin and Zhang Guangxin argue that current wetland models primarily focus on specific process models and have not established a comprehensive climate-landscape-biomass model [10]. Therefore, it is necessary to develop and refine mechanistic models that integrate ecological processes with hydrological processes. Existing models (such as the remote sensing inversion model for the Yellow River Delta) have not integrated multi-process coupling of climate-landscape-biomass, and Chen Guangcheng et al. could only utilize research on mangrove carbon sequestration to construct models for model development and learning [22].

Application research is another significant limitation. The Sanya mangrove restoration case study demonstrates that theoretical designs (such as landscape connectivity optimization) often fail due to the lack of localized adjustments. Most studies remain at the theoretical discussion stage, with limited practical applications. Wu Wei's application of the BCON concept and the design of the land-sea corridor both demonstrate how theory guides practice [14].

Concurrently, attention should be paid to the practical application of research outcomes and the creation of nature-based solutions.

## 5. Future Directions

Overall, wetland research using climate factors and landscape diversity as variables offers a wide range of potential directions. For example, studies on the Chongming Dongtan Wetland have found that soil total nitrogen and moisture content jointly regulate reed biomass, but the interaction between the two has not yet been quantified. Future research could clarify their synergistic mechanisms by setting up different climate scenarios and landscape configurations, and conducting experiments by controlling nitrogen addition and water levels. For instance, selecting typical wetlands in climate transition zones (such as semi-arid to humid regions) to analyze biomass responses to temperature and precipitation gradients (Zhao Chuanchuan et al., case study in the Sanjiangyuan region), or referencing Liu Li's team's approach combining remote sensing and field data in the Yellow River Delta, setting up landscape intervention experiments under gradient climate scenarios, and designing experiments based on multi-factor interactions to quantify the relative contributions of climate and landscape factors, revealing synergistic or antagonistic effects [1, 23].

Meanwhile, two years of continuous monitoring of wetlands in the Three Rivers Source Region have revealed that interannual fluctuations in biomass are significantly correlated with climate factors, but longer-term data are lacking. It is currently necessary to extend the observation period to verify trends. To capture the lagged response of biomass to climate change and identify critical thresholds, a long-term fixed observation network can be established through standardized observations and technological integration. Standardized monitoring involves establishing wetland monitoring stations covering different climate zones, such as tropical mangroves and temperate peatlands, and standardizing biomass, hydrological, and soil indicators (referencing the Honghu Wetland Long-Term Study by Wang Fei et al.) [20]. Technical integration methods can combine remote sensing (Landsat-8, Sentinel-2) with IoT sensors for high-frequency monitoring. For example, the method of using NDVI to estimate biomass in the Yellow River Delta can be extended to other wetlands.

Building cross-scale integrated models is also a promising direction. Typical methods include integrating ecological process models (e.g., CENTURY) with hydrological models (e.g., SWAT) to simulate biomass changes under different scenarios. For example, the Three Gorges Reservoir wetland study can be expanded into a “climate-hydrological-vegetation” coupled model. Alternatively, machine learning methods such as random forests and neural networks can be used to process multi-source heterogeneous data, such as the soil-plant feedback in the Poyang Lake wetland studied by Zhang Quanjun's team, making the research methods more suitable for multi-factor prediction and experimentation [15].

In addition to technical aspects such as model construction, the research also requires attention to detail. Based on the situation of invasive species threatening local plants in the mangrove restoration project in Sanya, wetland research and protection should also adopt adaptive management based on actual conditions. We can draw on the landscape design of Haizhu Wetland and Guanyin Lake Wetland to enhance habitat heterogeneity and connectivity in restoration projects; or divide core zones and buffer zones based on climate risks (e.g., the case of Parrot Island Wetland), with core zones prohibited from development and buffer zones allowing moderate ecological use; or draw on the experience of Honghu Wetland to promote “research-policy-community” collaborative governance, such as establishing a wetland carbon sink compensation mechanism [12-14, 20].

Given that the relationship between humans and nature has become increasingly intertwined, the necessity of quantifying the cumulative effects of human activities (such as land reclamation

and tourism) and climate change is also indispensable. Structural equation modeling (SEM) can be used to distinguish the relative weights of natural and human influences, or to develop “wetland agriculture-carbon sink” composite systems. For example, analyzing the primary causes of declining reed biomass in the Chongming Dongtan reclamation area and the “rice-reed” rotation system in the Yellow River Delta, balancing ecological and economic benefits, can help analyze the coupling of natural-social systems [6, 24]. Based on this, it is essential to further clarify the role and mechanisms of landscape diversity in enhancing the buffering effects of wetland ecosystems under climate change. Particular attention should be given to in-depth studies on the buffering effects of landscape diversity on wetland ecosystem biomass and the underlying mechanisms.

## 6. Conclusion

Wetland biomass is jointly controlled by climate and landscape diversity, and their complex interactions exert a comprehensive influence on wetland productivity and ecological services. The effects of climate change on wetland productivity primarily manifest through direct impacts on wetland environmental factors such as temperature, precipitation, and extreme weather events, as well as indirect changes to wetland productivity via alterations in habitat heterogeneity, community composition, and spatial patterns. Future research should focus on mechanism analysis, long-term observations, and model development, with findings applied to adaptive wetland management. By comprehensively analyzing the impacts of climate change and landscape factors, we can scientifically predict the trends in wetland ecosystems under global change, ultimately achieving a win-win outcome for wetland conservation and utilization.

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