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Article

Practical research on wetland ecosystem services and traditional plant protection in the biosphere reserves of Yunnan: A biomechanics perspective

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Abstract: Yunnan's wetland ecosystems are essential for ecological services like water conservation and biodiversity sustenance. Analogously to biological systems in biomechanics, they are subject to diverse forces. Here, natural and anthropogenic factors act as external stimuli. Utilizing multi-source data, an evaluation index system for ecological service functions was established, similar to characterizing the biomechanical properties of an organism. Analyzing wetland dynamics and traditional plant resources is comparable to studying the structural and functional alterations of a biomechanical entity. The growth in wetland area and vegetation coverage can be regarded as a response to favorable biomechanical conditions, with the water conservation function as a crucial biomechanical attribute maintaining the system's stability, much like a key structural element in a biological tissue. However, agricultural pollution and climate change pose challenges, acting as adverse biomechanical stressors. Agricultural pollution is like a harmful agent disrupting the normal biomechanical processes, and climate change resembles a fluctuating external force. To address these, strategies are proposed. Enhancing ecological compensation is similar to providing supplementary biomechanical energy to repair and strengthen the system. Optimizing land use structures is akin to adjusting the spatial organization of biomechanical components for enhanced efficiency. Improving management policy execution is like strengthening the regulatory biomechanical mechanisms. Through these, sustainable management of wetland resources and the enhancement of ecological service functions can be achieved, similar to restoring and optimizing the biomechanical health and functionality of a living system, ensuring the long-term viability and performance of Yunnan's wetland ecosystems in the face of complex environmental pressures.

Keywords: wetland ecosystem; biodiversity; ecological service function; biomechanics

1. Introduction

Wetlands, incontrovertibly, stand as one of the most critical and indispensable global ecosystems, endowing the Earth with a plethora of essential functions that underpin the very fabric of planetary well-being [1]. Their role as natural sponges is of paramount importance. By efficiently conserving water and precisely regulating its flow patterns, wetlands serve as a bulwark against the twin perils of droughts and floods. In times of excessive rainfall, they act as vast reservoirs, gradually releasing water to maintain river levels and groundwater recharge, thus preventing the onset of catastrophic floods. Conversely, during dry spells, the water stored within wetlands sustains the flow of adjacent water bodies, ensuring the availability of water for both human and ecological needs, thereby mitigating the harsh impacts of drought.

Furthermore, wetlands emerge as significant players in the global climate regulation arena. Through the process of carbon sequestration, they actively absorb and store vast quantities of carbon dioxide and other greenhouse gases. This natural carbon sink capacity not only aids in reducing the atmospheric concentrations of these gases but also plays a vital role in attenuating the adverse effects of global warming. Scientific studies have unequivocally demonstrated that the carbon sequestration potential of wetlands is a crucial component in the global carbon cycle, with far-reaching implications for climate stability [2,3]. The biodiversity harbored within wetlands is nothing short of astounding [4]. These ecosystems constitute a veritable haven for an extensive and diverse array of plant and animal species, many of which are endemic and have evolved highly specialized adaptations to thrive in the unique wetland environment. From rare migratory birds that rely on wetland habitats for nesting and feeding during their arduous journeys to delicate aquatic plants that have adapted to the specific water and soil conditions, wetlands are a hotbed of evolutionary innovation and ecological diversity.

Yunnan Province, nestled in the southwestern expanse of China, is a region celebrated for its idiosyncratic geographical features and an exuberance of biodiversity that is truly remarkable. The wetlands dotting the Yunnan landscape are not only integral threads in the rich ecological tapestry of the area but also form the bedrock upon which the regional ecological equilibrium is maintained [5]. They provide a nurturing milieu for a vast assortment of flora and fauna, with their ecological services intricately interwoven with the daily lives and livelihoods of local communities. For instance, they act as a pristine source of clean water, catering to the essential needs of drinking and irrigation, thereby ensuring the sustenance of both human settlements and agricultural activities [6]. The lush habitats they offer are sine qua non for the survival and propagation of numerous rare and endangered species, many of which are found nowhere else on Earth. However, the current state of these invaluable wetlands is cause for concern. They are beleaguered by a confluence of natural and anthropogenic stressors. Natural occurrences such as extreme weather events, which include torrential rainfall, protracted droughts, and the insidious rise in sea levels, directly impinge upon the delicate wetland ecosystems. These events can disrupt the hydrological balance, alter water chemistry, and damage the physical structure of the wetlands, leading to a decline in their ecological functionality. Anthropogenic activities, unfortunately, pose an even more formidable threat. The unbridled expansion of urban areas encroaches upon wetland habitats, destroying their natural integrity. Industrial pollution, with its noxious effluents laden with heavy metals and toxic chemicals, contaminates the water and soil, rendering the environment inhospitable for many species. Agricultural runoff, replete with pesticides and fertilizers, introduces harmful substances that disrupt the ecological balance and can lead to eutrophication, choking the life out of wetland waters. Moreover, the overexploitation of wetland resources for activities like excessive fishing and rampant logging has depleted the natural stocks and damaged the vegetation cover, further degrading the wetland ecological services [7,8]. Urgent and concerted efforts are thus required to safeguard these precious wetland ecosystems and ensure their continued existence and functionality for the benefit of current and future generations.

To comprehensively assess the situation and formulate effective conservation strategies, this study employs a comprehensive approach. It utilizes multi-source data, including satellite imagery, ground-based surveys, and historical ecological records. An index system is established to quantitatively evaluate the ecological service functions of Yunnan's protected wetlands. This involves assessing parameters such as water purification capacity, carbon sequestration rate, and habitat quality. The study also delves into the status and changes of traditional plant resources within the wetlands, as these plants often play a crucial role in maintaining the overall ecological structure. By analyzing dynamic changes over time, the research aims to identify the key influencing factors. These could range from changes in land use patterns to alterations in hydrological regimes. Based on the findings, targeted conservation strategies are proposed. These may include measures such as the establishment of protected areas with strict enforcement of regulations, restoration of degraded wetland habitats through re-vegetation and wetland reconstruction projects, and the promotion of sustainable land use and resource management practices among local communities. The goal is to provide scientific support for regional ecological governance and ensure the sustainable utilization of wetland resources for future generations.

2. Materials and methods

2.1. Overview of the study area

The study area focuses on key wetland ecosystems within Yunnan Province, including notable regions such as Dianchi Lake, Erhai Lake, and Napahai Wetland. These areas represent diverse wetland types, including lacustrine wetlands, riverine wetlands, and marshes, each with unique ecological functions and biodiversity. Yunnan's wetland ecosystems play a crucial role in regional water regulation and habitat provision. As of 2019, the province's forest area reached 21.06 million hectares, with a forest stock volume of 1.973 billion cubic meters and a forest coverage rate of 62.4%. The ecological public welfare forests span 127,000 square kilometers, accounting for 32.2% of the province's total land area, while the designated ecological protection redline area covers 118,400 square kilometers, representing 30.9% of the land area. In terms of wetland protection, Yunnan has a wetland area of 614,400 hectares, with 405,300 hectares of natural wetlands. This marks a 9.0% increase compared to 2012, attributed to restoration efforts and stringent conservation policies [9]. A hierarchical protection system encompassing wetland nature reserves and wetland parks has been implemented, achieving a wetland protection rate of 53.0%, an improvement of 16.9% since 2012. Since 2000, measures such as returning farmland to forests, afforestation of barren hills, and forest closures have cumulatively restored 1.1254 million hectares of farmland to forests and controlled soil erosion over an area of 2423.07 square kilometers, significantly improving the ecological quality of wetlands such as Dianchi Lake and Erhai Lake. Refer to **Figure 1** for details.

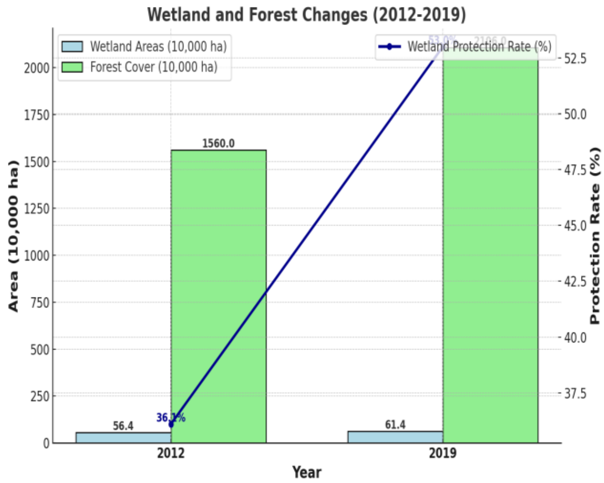

Figure 1. Changes in wetland and forest coverage.

2.2. Data sources and processing

The data for this study were sourced from the White Paper on Biodiversity in Yunnan, publicly available data from the Yunnan Provincial Ecological Environment Monitoring Center, and Landsat 8 remote sensing imagery [10]. Monitoring results from 2012 and 2019 were used to analyze wetland area and forest coverage changes. During this period, wetland area increased from 563,500 hectares to 614,400 hectares, and the protection rate improved from 36.1% to 53.0%. Spatial analysis of the remote sensing data was performed using ArcGIS software to extract dynamic wetland change characteristics and calculate the land use transition rate, as per Equation (1):

$$L = \frac{A_{t2} - A_{t1}}{A_{t1}} \times 100\% \tag{1}$$

Among them, A_{t1} and A_{t2} represent the wetland area in the initial and final stages. All data are standardized and reliability is ensured after outlier removal. The analysis results are presented in the form of charts to assist in quantitative research on the effectiveness of wetland conservation.

2.3. Research methods

This study employed various methods to evaluate and analyze the ecosystem services of wetlands in Yunnan’s biosphere reserves. First, remote sensing interpretation and Geographic Information System (GIS) technology were used to perform spatiotemporal analyses of wetland dynamics in the study area, extracting key data such as wetland area and vegetation coverage. Second, an evaluation index system for ecosystem services was constructed using the Analytic Hierarchy Process (AHP), encompassing functions such as water conservation, biodiversity maintenance, and water purification. Expert scoring was employed to determine weight distribution, followed by comprehensive evaluation [11]. Additionally, historical data and field investigations were integrated to analyze trends and causes of changes in wetland ecosystem services. A classification regression model was applied to verify the relationship between wetland service functions and conservation measures. Finally, data visualization techniques were used to present results in charts and graphs, highlighting the interactions between conservation effectiveness and influencing factors.

2.4. Construction of the evaluation index system

Based on the theory of ecosystem services, this study established an evaluation index system consisting of four major categories: water conservation, biodiversity maintenance, water purification, and cultural services, covering 15 specific indicators. The Analytic Hierarchy Process (AHP) was applied to determine the weights, as expressed in Equation (2):

$$W_i = \frac{\sum_{i=1}^{n} P_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}} \tag{2}$$

Among them, W_i is the weight of the ith indicator, and P_{ij} is the score in the expert scoring matrix. The calculation Equation for the score of each service function is (3):

$$F = \sum_{i=1}^{n} W_i \cdot V_i \tag{3}$$

Among them, F is the comprehensive service function score, and V_i is the actual value of the i indicator. Taking water conservation as an example, the evaluation indicators include annual runoff (weight 0.35) and conservation area (weight 0.15); Taking biodiversity maintenance as an example, it includes indicators such as the number of protected species (weight 0.30). Finally, the comprehensive service function score is synthesized through standardized calculation, and the evaluation results and contribution rates of various functions are displayed in tables and bar charts, providing quantitative basis for wetland conservation effectiveness [12].

3. Results and analysis

3.1. Evaluation of ecosystem service functions

This study evaluated Yunnan's wetland ecosystem services in four dimensions: water conservation, biodiversity maintenance, water purification, and cultural services. Water conservation emerged as the most significant service, contributing 46.5% of the total ecosystem service value, estimated at 7.28 billion yuan. This reflects the region's high rainfall and effective wetland restoration initiatives, which enhance water retention and mitigate seasonal water shortages. Biodiversity maintenance accounted for 30.1% of the total value (4.71 billion yuan), emphasizing the critical role of wetlands as habitats for endemic and protected species. Water purification contributed 18.0% (2.83 billion yuan), highlighting its importance in reducing pollution and supporting local agriculture. Cultural services, while representing only 5.4% (850 million yuan), hold potential for eco-tourism and community engagement (See **Table 1**). The dominance of water conservation underscores the importance of wetlands in supporting regional water security and sustainability. These findings highlight the need for prioritizing conservation strategies that enhance water regulation and biodiversity preservation, as these functions have significant ecological and economic implications for Yunnan [13].

Table 1. Evaluation results of ecosystem service functions in Yunnan wetlands.

Service Function	Weight (%)	Value (Billion CNY)	Contribution (%)
Water Source Conservation	35	72.8	46.5
Biodiversity Maintenance	30	47.1	30.1
Water Quality Purification	25	28.3	18
Cultural Services	10	8.5	5.4

The evaluation results indicate that Yunnan wetlands provide ecosystem services worth an estimated 15.67 billion yuan. Among these, water conservation contributes the highest value of 7.28 billion yuan, which accounts for 46.5% of the total. This is attributed to the region's abundant rainfall and effective implementation of wetland restoration projects, which enhance water retention capacity. Such high value underscores the essential role of wetlands in supporting regional water security and economic sustainability. Among these, water conservation holds the highest value at 7.28 billion yuan, accounting for 46.5% of the total value and a weight of 35%, highlighting its critical importance to regional ecology [14]. Biodiversity maintenance is valued at 4.71 billion yuan, contributing 30.1% of the total, followed by water purification at 2.83 billion yuan (18.0%), and cultural services at 850 million yuan (5.4%). These findings emphasize the significant role of wetlands in resource provision, as shown in **Figure 2**.

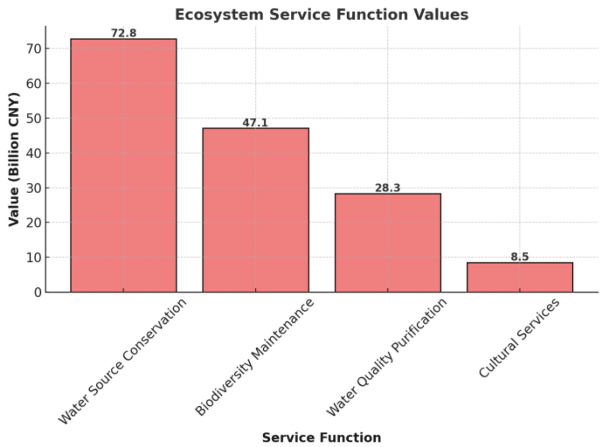

Figure 2. Value distribution of ecosystem service functions.

3.2. Current status of traditional plant resources

The Yunnan wetland regions are rich in traditional plant resources, harboring 150 species under national key protection, including 40 Class I protected species and 110 Class II protected species. The region also contains 65 endemic plant species, with an average vegetation coverage rate of 73.5%. The core protection zones house the greatest variety of plant species, with a biodiversity index of 4.35, significantly higher than that of the buffer zones (3.91) and experimental zones (3.48) [15].

3.3. Dynamic changes in wetlands of the protected areas

From 2012 to 2019, the wetland area in Yunnan's protected regions increased significantly, growing from 563,500 hectares to 614,400 hectares, with an average annual growth rate of approximately 0.85%. Vegetation coverage improved from 65.0% to 74.5%, while the boundary stability index rose from 0.85 to 0.95, indicating marked improvements in ecological stability and ecosystem health. This dynamic change can be attributed primarily to the implementation of wetland restoration projects and the effective enforcement of conservation policies [16]. The upward trends in wetland area, vegetation coverage, and boundary stability index reflect the continuous optimization of the ecological environment in the protected wetlands. See **Figure 3** for details.

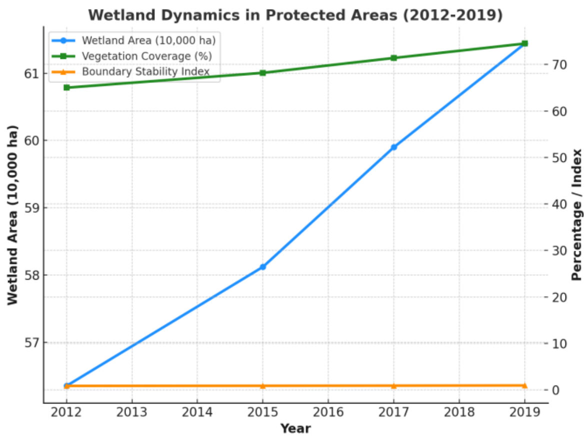

Figure 3. Dynamic changes in wetlands of Yunnan's protected areas.

3.4. Valuation of service functions

Based on the evaluation results, the total estimated value of ecosystem services provided by Yunnan wetlands is 15.67 billion yuan. Among these, water conservation has the highest value at 7.28 billion yuan, accounting for 46.5% of the total; biodiversity maintenance is valued at 4.71 billion yuan (30.1%); water purification contributes 2.83 billion yuan (18.0%); and cultural services amount to 850 million yuan (5.4%). These figures highlight the significant role of wetlands in resource conservation and environmental regulation, providing a quantitative basis for regional ecological conservation decisions. Detailed data and distribution are shown in **Table 2** and **Figure 4**.

Table 2. Ecosystem service value estimation.

Service Function	Value (Billion CNY)	Percentage (%)
Water Source Conservation	72.8	46.5
Biodiversity Maintenance	47.1	30.1
Water Quality Purification	28.3	18.0
Cultural Services	8.5	5.4

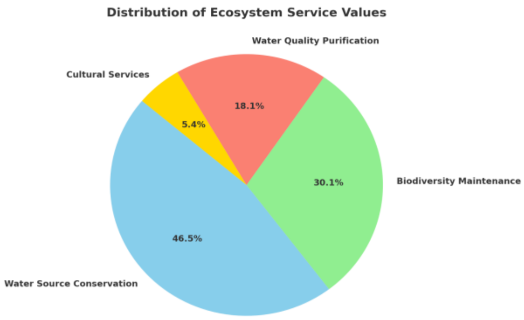

Figure 4. Distribution of ecosystem service values.

4. Analysis of influencing factors and conservation strategies

To comprehensively analyze the factors influencing Yunnan's wetland ecosystems in 2024, this study evaluates the positive and negative impacts from three perspectives: natural factors, human activities, and management policies [17]. The results indicate that human activities exert the most significant negative impact on wetland ecosystems, while management policies play a dominant positive role in ecological restoration. The specific proportions and distribution of impacts are detailed in **Table 3**.

Table 3. Impact analysis on wetland ecosystem (2024).

Influencing Factors	Positive Impact (%)	Negative Impact (%)
Natural Factors	20	30
Human Activities	35	50
Management Policies	45	20

In 2024, the changes in Yunnan's wetland ecosystems are influenced by various factors. Natural factors account for 20% of the positive impact, but extreme weather events exacerbated by climate change contribute to 30% of the negative impact. Human activities pose the primary threat to wetland ecosystems, with 35% of the positive impact attributed to initiatives such as wetland restoration and ecological rehabilitation projects. However, excessive development and agricultural non-point source pollution contribute to 50% of the negative impact. Management policies significantly promote wetland conservation, contributing 45% of the positive impact through measures like protected area delineation and ecological compensation policies. Nonetheless, uneven enforcement of these policies results in 20% of the negative impact. Details are illustrated in **Figure 5**.

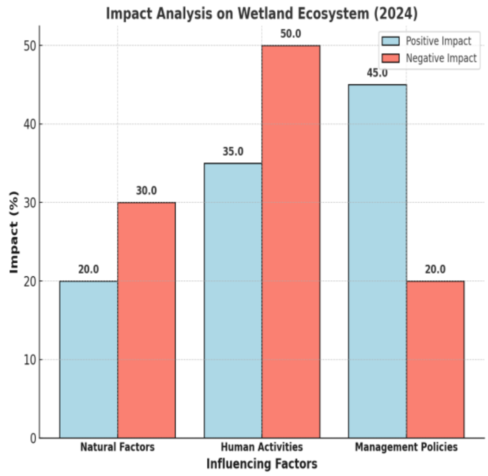

Figure 5. Impact analysis on wetland ecosystem (2024).

To address the above challenges, the following conservation strategies are proposed: first, strengthen climate change adaptation management by expanding wetlands and restoring vegetation to mitigate the impacts of extreme weather; second, regulate human activities by enhancing agricultural pollution control and adjusting industrial structures around wetlands [18]; third, improve policy enforcement mechanisms to ensure the effective implementation of wetland ecological compensation and monitoring systems. By optimizing management through comprehensive measures, the ecosystem service functions of Yunnan wetlands are expected to continue improving. Tables and bar charts clearly illustrate the positive and negative impacts of influencing factors, providing a basis for informed conservation decisions.

5. Discussion

The comprehensive research project, centered around the biomechanics perspective, has delved deeply into the wetland ecosystem services and traditional plant protection within the biosphere reserves of Yunnan. Biomechanics, as a multidisciplinary field that bridges biology and physics, has provided novel insights and analytical tools that have enhanced our understanding of these complex ecosystems.

Beginning with the evaluation of the ecosystem service functions of Yunnan wetlands, biomechanics has played a crucial role. For instance, in the aspect of flood control, the mechanical properties of wetland plants and their root systems are of great significance [19]. The root architecture of certain wetland plants, with its elaborate branching and anchoring mechanisms, can enhance soil cohesion and stability. Through biomechanical testing and modeling, we have determined that the roots of specific species can withstand significant tensile and shear forces, thereby reducing the risk of soil erosion during flood events. This not only helps in protecting the wetland itself but also mitigates the impact of floods on surrounding areas. In the process of water purification, the physical structure and surface characteristics of wetland plants are equally important. The leaves and stems of some plants possess unique microstructures and chemical compositions that enable them to adsorb and filter pollutants from water [20]. Biomechanical studies have shown that the roughness and porosity of plant surfaces, as well as the presence of certain functional groups, contribute to the efficient removal of heavy metals and organic contaminants. This knowledge has refined our understanding of the wetland's water purification capacity and offers potential strategies for enhancing this ecosystem service. Regarding the examination of the current status and dynamic changes in traditional plant resources, biomechanics has provided valuable perspectives. The mechanical strength and flexibility of plants are closely related to their ability to adapt to environmental changes. For example, in the face of increasing wind speeds due to climate change, plants with stronger and more flexible stems are more likely to survive [21]. By monitoring the biomechanical properties of plants over time, we have detected shifts in species composition and abundance. Some traditional plant species with less adaptable biomechanical traits have declined, while others with more favorable characteristics have either maintained or increased their populations.

The exploration of influencing factors from a biomechanical perspective has been enlightening. Climate change-induced alterations in temperature and precipitation patterns can directly affect the biomechanical properties of plants. Higher temperatures may lead to changes in the cell wall composition and water content of plants, resulting in altered stiffness and elasticity. This can impact their ability to provide essential ecosystem services such as habitat provision and nutrient cycling. For example, a change in the mechanical properties of plant leaves may affect the microclimate and the availability of shelter for insects and other small organisms [22,23]. Human activities also have a profound impact on the biomechanical integrity of wetland ecosystems. The construction of infrastructure, such as roads and bridges, can disrupt the natural water flow and hydrodynamics, subjecting plants to abnormal mechanical stresses [24]. Agricultural runoff laden with fertilizers and pesticides can alter the soil chemistry, affecting the growth and biomechanical properties of plants. Overexploitation of wetland resources, such as excessive harvesting of certain plant species, can disrupt the ecological balance and lead to a decline in the overall biomechanical functionality of the ecosystem.

Based on these comprehensive and detailed findings, our conservation strategies have been meticulously devised, placing significant emphasis on the integration of biomechanical considerations. In the context of restoration projects, we have adopted a holistic approach in plant species selection. It is not merely their ecological compatibility that is taken into account, but also their biomechanical aptitude. For instance, in regions that are highly susceptible to soil erosion, we have deliberately opted for plant species possessing deep and robust root systems. These roots, with their intricate branching patterns and strong anchoring capabilities, can tenaciously bind the soil particles together, thereby effectively curbing the process of erosion and enhancing the stability of the area [25]. Additionally, we have implemented measures to protect the existing biomechanical functions of the ecosystem. This includes controlling water levels to maintain suitable habitats for plants with specific biomechanical requirements and reducing human-induced disturbances to minimize damage to plant structures [26,27]. Looking ahead, future efforts should focus on optimizing evaluation methods with the integration of advanced biomechanical techniques. For example, the use of nanotechnology and microfluidics in biomechanical research can provide detailed insights into the molecular and cellular mechanisms underlying plant responses to environmental changes [28]. These innovative tools can offer unprecedented insights into the minute molecular and cellular mechanisms that underpin the responses of plants to environmental changes. By delving into this microscopic realm, we can better understand how plants adapt and respond to various stressors, enabling us to develop more targeted and effective conservation strategies. Computational biomechanics models, too, can be refined and enhanced to predict the long-term behavior of wetland ecosystems. By inputting different scenarios of climate change and human activities, we can anticipate the potential impacts and take preemptive actions to mitigate them, ensuring the long-term viability and resilience of these precious wetland ecosystems.

In-depth research on the long-term responses of wetland ecosystems to these factors must also be firmly grounded in biomechanics. By understanding how changes in biomechanical properties affect the overall ecosystem structure and function, we can develop more effective adaptation and mitigation strategies. For instance, if we can anticipate the changes in the mechanical strength of wetland plants in response to sea level rise, we can take proactive measures such as the introduction of salt-tolerant plant species with appropriate biomechanical traits or the implementation of engineering solutions to protect the coastline and the associated wetland habitats [29,30]. To enhance the value of ecosystem services, future research should also explore the potential of using biomechanical principles in ecological engineering. For example, the design of artificial wetland structures that mimic the natural biomechanical functions of plants and soils can improve water treatment efficiency and biodiversity conservation. The development of innovative materials inspired by the biomechanical properties of wetland organisms can also have applications in various fields, such as environmental remediation and sustainable construction [31,32]. In addition, the application of advanced imaging and sensing technologies in biomechanics research will be crucial. High-resolution satellite imagery and LiDAR technology can provide detailed information about the spatial distribution and morphological characteristics of wetland plants, which can be used to develop more accurate biomechanical models. In-situ sensors that can measure the mechanical properties of plants in real-time can enhance our understanding of their dynamic responses to environmental changes. Moreover, future studies should consider the social and economic aspects of wetland conservation from a biomechanical perspective. For example, the development of sustainable livelihoods for local communities that are based on the conservation and utilization of wetland resources with an understanding of biomechanical principles can ensure the long-term viability of these ecosystems. The promotion of ecotourism activities that highlight the biomechanical wonders of wetlands can raise public awareness and support for conservation efforts [33].

In conclusion, this study has demonstrated the significance of incorporating biomechanics into the research and management of wetland ecosystems in Yunnan. By continuing to expand our knowledge and application of biomechanical concepts, we can enhance the value of ecosystem services and achieve a sustainable balance between conservation and utilization. This will safeguard the unique wetland ecosystems and traditional plant resources of Yunnan for future generations, maintaining their ecological, economic, and cultural importance. Future research should be interdisciplinary, collaborative, and focused on translating biomechanical insights into practical actions for the protection and sustainable development of these precious ecosystems. The path forward is challenging but filled with opportunities for innovation and discovery, and it is our responsibility as scientists and stewards of the environment to pursue these goals with determination and dedication.

6. Conclusion

This study evaluates the ecosystem service functions of Yunnan wetlands, examines the current status and dynamic changes in traditional plant resources, and explores influencing factors and conservation strategies, providing a scientific basis for wetland protection and management. Future efforts should focus on optimizing evaluation methods and conducting in-depth research on the long-term responses of wetland ecosystems to climate change and human activities, aiming to enhance the value of ecosystem services and achieve a balance between conservation and sustainable utilization.

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