Effects of Water Level Fluctuation on Nutrient Characteristics of Taxodium distichum in the Three Gorges Reservoir Drawdown Zone: Postprint

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Abstract

After the completion and impoundment of the Three Gorges Dam, its unique water level operation regime has substantially disturbed the habitats of plants in the reservoir's water-level fluctuation zone. To understand the physiological and ecological processes of Taxodium distichum in this special habitat and to explore its flooding tolerance mechanisms, leaf and root samples were collected from T. distichum planted at elevations of 175-165 m in the experimental plots, and growth status was investigated three years after establishing the Zhongxian demonstration base for vegetation restoration in the water-level fluctuation zone of the Three Gorges Reservoir area. Nutrient element contents were measured and analyzed in relation to plant growth and soil nutrients. The results indicated: (1) Water level changes significantly affected nutrient element absorption in T. distichum, a suitable tree species. With increasing flooding depth and duration, root energy metabolism was impeded, root function was disrupted, and nutrient absorption and transport were inhibited, resulting in decreased uptake of N, P, K, Ca, and Zn in T. distichum; flooding led to elevated Fe2+ and Mn2+ concentrations in soil, causing increased Fe and Mn absorption by T. distichum. (2) Correlation analysis demonstrated that T. distichum plant height exhibited extremely significant positive correlations with N, K, and Mg contents, significant positive correlation with P content, extremely significant negative correlations with Fe and Cu contents, and significant negative correlation with Mn content; crown width of T. distichum showed extremely significant positive correlations with N, P, K, and Mg contents, and extremely significant negative correlations with Fe and Cu contents; no significant correlations were observed between nutrient element contents in T. distichum and soil element contents. (3) The accumulation of nutrient elements in T. distichum at different elevations of the water-level fluctuation zone was not lower than the levels required for normal plant growth, with no severe nutrient deficiency observed. The research results demonstrate that T. distichum possesses excellent adaptability to water level fluctuations in the Three Gorges Reservoir water-level fluctuation zone, can actively respond to water level changes, balance the accumulation of various elements, and maintain normal plant growth.

Full Text

Preamble

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Effect of Water-Level Change on Nutritional Characteristics of *Taxodium distichum* in the Hydro-Fluctuation Belt of the Three Gorges Reservoir

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Abstract

The construction of the Three Gorges Dam has created a hydro-fluctuation belt with a water level drop of nearly 30 m and an area of 300 km^2 along the Yangtze River in China. The unique anthropogenic hydrological regime of the Three Gorges Dam has had significant negative impacts on the reservoir's riparian ecosystem, causing flooding-intolerant plants within the belt to gradually die off and exacerbating vegetation habitat fragmentation while detrimentally affecting biodiversity, ecosystem structures, and functions of the water-fluctuation zone. Therefore, a pressing scientific challenge is to recover and restore the vegetation there and ensure proper ecological function. Previous studies have shown that *Taxodium distichum* is a flooding-tolerant plant that has been used for vegetation reconstruction. The nutritional characteristics of plants in a particular area can reflect their eco-physiological processes and serve as crucial indicators of the structure and function of the local ecosystem. These characteristics play a key role in adaptation to anti-seasonal flooding and might reveal clues about the adaptation mechanisms of plants in the hydro-fluctuation belt of the Three Gorges Reservoir area.

To contribute to this understanding, we studied the nutritional characteristics of *T. distichum* growing in the reservoir riparian region of Zhongxian County, which had been planted in 2012. Element contents of three sample zones at low water elevation (165 m)—SD, high water elevation (170 m)—SL, and control—CK (175 m) were determined in 2015. The macroelement, secondary element, and micronutrient contents in roots and leaves of plants were measured. The results showed that: (1) Concentrations of N, P, K, Ca, and Zn in leaves and roots of *T. distichum* under flooding significantly decreased compared to CK, whereas Fe and Mn contents significantly increased. (2) Some nutrient concentrations of *T. distichum* under flooding decreased, but still maintained their normal performance. (3) Correlation analysis showed that plant heights were positively correlated with the concentrations of N, P, K, and Mg; plant heights were negatively correlated with the concentrations of Fe, Cu, and Mn; canopies of plants were positively correlated with the concentrations of N, P, K, and Mg, but negatively correlated with Fe and Mn. This investigation indicates that water level change had significantly influenced the nutritional characteristics of *T. distichum* in the water-level-fluctuating zone of the Three Gorges Reservoir, and that *T. distichum* had good adaptability to the changed water habitat.

Keywords: Three Gorges Reservoir; hydro-fluctuation belt; *Taxodium distichum*; nutritional characteristics

Introduction

Human development and utilization of river resources through large-scale hydraulic engineering projects have altered the original living environments of plants, affecting their growth and physiological rhythms. Following the construction of the Three Gorges Reservoir, the reservoir water level fluctuates annually between 145–175 m. This unique reservoir water regulation rhythm has brought enormous negative impacts to the ecosystem of the reservoir riparian zone, causing vegetation degradation and loss of ecological barrier function as plants originally growing in the hydro-fluctuation belt cannot adapt to the special habitat. In recent years, vegetation restoration in the hydro-fluctuation belt has received widespread attention from all sectors of society, and artificial vegetation reconstruction has proven to be an effective method for restoring hydro-fluctuation belt vegetation. Exploring the physiological and ecological adaptation mechanisms of suitable plants is an important foundation for hydro-fluctuation belt vegetation restoration and a prerequisite for solving ecological and environmental problems in the reservoir's hydro-fluctuation belt.

Previous studies have screened out a batch of flooding-tolerant plants, but their application in hydro-fluctuation belt vegetation reconstruction revealed that only some plants could survive, bringing new problems and challenges to vegetation reconstruction and management. *Taxodium distichum*, a deciduous tree of the Taxodiaceae family, has a history of over 100 years and has been widely introduced worldwide. Due to its rapid growth and strong adaptability, it has been selected as one of the suitable tree species for vegetation reconstruction in the hydro-fluctuation zone. Scholars at home and abroad have studied photosynthesis, biomass allocation, and metabolism of *T. distichum* under flooding, drought, and salinity stress conditions. However, research on the effects of large-scale, anti-seasonal water level changes on the nutritional characteristics of *T. distichum* in the Three Gorges Reservoir hydro-fluctuation belt is still limited, with existing studies confined to indoor simulation experiments and few reports on its performance under natural flooding conditions.

The accumulation of plant nutrient elements reflects the ability of plants to absorb nutrients under certain habitat conditions, revealing both species characteristics and plant-environment relationships. Studying the effects of water level changes on the nutritional characteristics of *T. distichum* is an important supplement to research on its flooding tolerance mechanisms and provides a theoretical reference for further revealing the eco-physiological mechanisms of *T. distichum* in response to the special habitat of the hydro-fluctuation belt and for vegetation restoration. This study selected *T. distichum* planted in the hydro-fluctuation belt at elevations of 175–165 m in the Three Gorges Reservoir vegetation restoration demonstration base in Zhongxian County, Chongqing, as the research object. We measured the nutrient element contents in leaves and roots at different elevations and analyzed the impacts of water level changes, aiming to preliminarily clarify the nutrient element absorption and accumulation characteristics of *T. distichum* after flooding cycles in the anti-seasonal flooding habitat of the Three Gorges Reservoir, and to provide a theoretical basis for guiding the construction and management of artificial *T. distichum* vegetation in the hydro-fluctuation belt.

1 Study Site Overview

The experimental site is located in the Three Gorges Reservoir vegetation restoration demonstration base in the hydro-fluctuation belt of Zhongxian County, Chongqing, within the Ruxi River basin (a primary tributary of the Yangtze River) at 107°32 –108°14 E, 30°03 –30°35 N. The area has a subtropical southeast monsoon mountain climate with an average annual temperature of 18.2°C, accumulated temperature $ 10°Cof5787°C,annualsunshinehoursof1327.5h,frost−freeperiodof341days,andtotalsolarradiationof83. According to water level fluctuation characteristics and plant flooding tolerance, different patterns of artificial vegetation were established with trees, herbs, and other plants in the elevation range of 175–145 m. In 2012, *Taxodium distichum* was planted at elevations of 175–165 m, along with other species including *Distylium chinense*, *Salix matsudana*, *Arundo donax*, *Cynodon dactylon*, and *Hemarthria altissima*.

The soil element contents of the experimental site are shown in Table 1.

Chemical element concentrations in sampled soil

2 Sampling Time and Methods

Field sampling was conducted in May 2015. Based on differences in flooding duration at different elevations during the impoundment period, the sample plots were divided into three zones: CK (175 m, no flooding), SL (170 m, approximately 130 days of flooding annually), and SD (165 m, approximately 200 days of flooding annually). At each elevation gradient, five sample plots were established. Leaves were collected from the middle and upper canopy in four directions using high-branch shears and mixed into one sample per plot, placed in ziplock bags. Root samples were collected using a root drill at 0.5 m radius from the plant base at equal distances, mixed, and placed in ziplock bags. All samples were washed with tap water and deionized water, killed in an oven at 105°C for 5 minutes, then dried to constant weight at 75°C.

At the same time, growth status was recorded for randomly selected plants in each sample belt. Plant height was measured with a measuring rod, canopy width with a tape measure, and base diameter with vernier calipers.

3 Nutrient Element Content Determination

Dried samples were digested using a MWS-4 microwave digestion system (Berghof, Germany). Elemental contents of P, K, Ca, Mg, Fe, Mn, Zn, and Cu were determined using an ICAP 6000 inductively coupled plasma optical emission spectrometer (Thermo, USA). N content was measured using a Vario EL cube CHNOS elemental analyzer (Elementar, Germany).

4 Data Analysis

This study used SPSS 20.0 statistical software for data processing. One-way ANOVA was used to test the effects of water level changes on *T. distichum* element contents, with Duncan's multiple range test for differences among treatments. Pearson correlation coefficient was used to evaluate correlations between nutrient elements and growth indices. Origin 8.5 was used for graphical presentation.

1 Growth Status of *Taxodium distichum*

Table 2 shows the growth status of *T. distichum* seedlings in the study site. Compared with initial planting values, plant height and canopy width increased significantly in the hydro-fluctuation belt, while base diameter showed no significant difference. However, growth status differed among plants at different elevations. Plant height and canopy width in the CK group (175 m) were significantly higher than in the SL (170 m) and SD (165 m) groups ($P<0.05$), while base diameter showed no significant differences among treatments.

The growth situations of *Taxodium distichum*

2 Effects of Water Level Change on Element Contents of *Taxodium distichum*

One-way ANOVA results indicated that water level change affected nutrient element contents of *T. distichum*, with effects varying by element type and plant part. Macroelement contents in roots were significantly affected ($P<0.05$), while Fe and Mn contents were extremely significantly affected ($P<0.01$).

In leaves, macroelement contents were significantly affected by water level change ($P<0.05$), and Fe and Mn contents were extremely significantly affected ($P<0.01$). Table 3 shows the effects of water level change on nutrient element contents of *T. distichum*.

Effects of water level change on nutrient element contents of *Taxodium distichum*

2.1 Macroelement Contents at Different Elevations

Figure 1 shows macroelement contents in roots and leaves of *T. distichum* planted at different elevations. Macroelement (N, P, K) contents in leaves were greater than those in roots. Among these, N, P, and K were the most abundant elements in both roots and leaves. With decreasing elevation and increasing flooding depth and duration, macroelement contents decreased significantly. Root N content in the SL and SD groups decreased by 42.7% and 36.2% respectively compared to CK ($P<0.05$), with significant differences between SL and SD. The trend of P content change was similar to N. K content also decreased with elevation decline ($P<0.05$), with significant differences between CK and SL/SD groups.

2.2 Secondary Element Contents at Different Elevations

Responses of secondary element (Ca, Mg) contents to water level change differed. Root Ca content in SL and SD groups was significantly lower than CK ($P<0.05$), indicating that flooding had a clear inhibitory effect on Ca absorption. Leaf Ca content also decreased with elevation decline ($P<0.05$). Although leaf Mg content showed a decreasing trend with elevation, the difference was not significant. Flooding did not significantly affect Mg content in roots or leaves. Leaf Ca and Mg contents were higher than root contents, and the content order in both roots and leaves was Ca > Mg.

[Figure 2: see original paper] Secondary element contents of *Taxodium distichum* at different elevations

2.3 Micronutrient Contents at Different Elevations

Figure 3 shows micronutrient (Fe, Mn, Cu, Zn) contents in *T. distichum*. With decreasing elevation, root Fe and Mn contents increased significantly ($P<0.05$), while leaf Fe and Mn contents remained relatively stable. The four micronutrients showed different response patterns to water level change. Root Fe content in SL and SD groups increased by 76.9% and 69.9% respectively compared to CK ($P<0.05$). Root Mn content in SL and SD groups increased by 46.4% compared to CK ($P<0.05$). Flooding did not significantly affect Cu and Zn absorption and distribution. At all elevations, root Cu and Zn contents remained at the same level, while leaf Zn content was significantly lower than CK ($P<0.05$).

The distribution patterns of micronutrients between roots and leaves changed under flooding. At CK, the content order in roots was Fe > Zn > Mn > Cu;

at SL and SD, it remained Fe > Zn > Mn > Cu. However, the allocation proportions changed: at CK, leaf micronutrient content order was Fe > Zn > Mn > Cu; at SL it became Fe > Mn > Zn > Cu; and at SD it became Fe > Zn > Cu > Mn. This indicates that under flooding conditions, *T. distichum* increased Fe and Mn absorption while altering their allocation to leaves, demonstrating an impact of flooding on micronutrient absorption and distribution.

[Figure 3: see original paper] Micronutrient contents of *Taxodium distichum* at different elevations

3 Correlation Analysis of *Taxodium distichum* Nutrient Elements and Growth

Correlation analysis showed that plant height was extremely significantly positively correlated with N, P, K, and Mg contents ($P<0.01$), significantly positively correlated with Ca and Zn contents ($P<0.05$), and extremely significantly negatively correlated with Fe, Cu, and Mn contents ($P<0.01$). Canopy width was extremely significantly positively correlated with N, P, K, and Mg contents ($P<0.01$), and extremely significantly negatively correlated with Fe and Mn contents ($P<0.01$).

4 Correlation Analysis Between *Taxodium distichum* Nutrient Elements and Soil Nutrient Elements

Correlation analysis showed no significant correlation between *T. distichum* nutrient element contents and corresponding soil element contents. Plant Fe and Mn contents were negatively correlated with soil Fe and Mn contents, while plant N, P, K, Ca, and Mg contents were positively correlated with soil contents, but these correlations were not statistically significant.

Correlations between nutrient elements and growth indexes of *Taxodium distichum*

Correlations between nutrient elements of *Taxodium distichum* and nutrient elements of sampled soil

3 Discussion and Conclusion

The water level of the Three Gorges Reservoir fluctuates annually between 145–175 m, causing vegetation at different elevations to periodically experience varying degrees of flooding. Flooding is accompanied by changes in soil redox potential, light intensity, and other environmental factors that affect plant nutrient element absorption, distribution, and survival status. The effects vary with element type and plant part.

Our results show that water level change significantly affected nutrient element contents in both roots and leaves of *T. distichum* in the hydro-fluctuation belt. Early simulation studies on flooding effects on *T. distichum* element absorption suggested that *T. distichum* has strong flooding tolerance and that flooding treatment did not significantly affect its nutrient element absorption. However, our results differ substantially from these previous findings. Flooding can cause plant root system dysfunction and even death, and changes soil nutrient content and availability, thereby affecting plant nutrient absorption and transport. Flooding-tolerant plants can transport oxygen to roots through internal aerenchyma under flooding conditions, ensuring nutrient element absorption, whereas flooding-intolerant plants have their nutrient absorption significantly limited by oxygen deficiency.

Our results show that with decreasing elevation and increasing flooding depth and duration, N, P, and K contents in *T. distichum* roots and leaves significantly decreased. At 170 m elevation, root N, P, and K contents were significantly lower than the control (175 m), indicating that increased flooding time and depth inhibited *T. distichum* absorption of these elements. However, despite these reductions, the contents remained within normal ranges for plant growth: leaf N content (1.9%–2.2% of dry weight), P content (0.3%–0.4%), and K content (0.3%–5.0%) all fell within normal levels (N: 1.1%–5%, P: 0.2%–0.3%, K: 0.3%–5%). This demonstrates that although water level changes in the Three Gorges Reservoir affected macroelement absorption, flooding-tolerant *T. distichum* still ensured normal nutrient accumulation in its important photosynthetic organ (leaves) to maintain normal physiological functions.

The response of Ca and Mg contents to water level change differed from that of N, P, and K. With decreasing elevation and increasing flooding depth, Ca and Mg contents in *T. distichum* roots and leaves significantly decreased. However, from the perspective of soil element content, there were no significant differences in Ca and Mg contents across elevations, indicating that flooding rather than soil heterogeneity was the dominant factor causing differences in Ca and Mg absorption and distribution. This result differs from some other species studies, possibly due to different plant nutrient requirements and soil physicochemical properties across study sites.

In contrast to macroelements and secondary elements, root Fe and Mn contents in *T. distichum* significantly increased with decreasing elevation, while leaf Fe and Mn contents remained relatively stable. Root Fe and Mn contents were far higher than in typical plants (normal range: 100–300 mg/kg). Flooding causes soil redox potential (Eh) to decrease, changing Fe and Mn forms from oxidized to reduced states and increasing their bioavailability. Excessive absorption of Fe and Mn can be toxic to plants, causing leaf chlorosis and damaging enzyme structures. The significant increase in root Fe and Mn contents without a corresponding increase in leaf contents may represent a self-protection mechanism in *T. distichum*, where increased absorption is accompanied by restricted transport to leaves to ensure strong root redox capacity while preventing toxicity from reduced cations under long-term flooding.

Correlation analysis revealed that *T. distichum* height was extremely significantly positively correlated with N, P, K, and Mg contents, and extremely significantly negatively correlated with Fe, Cu, and Mn contents. Canopy width showed similar patterns. This suggests that flooding may increase Fe, Mn, and Cu absorption, thereby inhibiting absorption of other elements. Although soil element content differences typically cause variations in plant nutrient content, and plant nutrient content is often closely related to soil N, P, and K status, our study found no significant correlation between *T. distichum* nutrient content and soil element content, indicating that soil heterogeneity was not the dominant factor causing differences in *T. distichum* nutrient content across elevations.

In conclusion, this study demonstrates that water level changes in the Three Gorges Reservoir hydro-fluctuation belt significantly affected nutrient element absorption in the suitable species *T. distichum*, with effects varying by nutrient type and plant part. Flooding was the dominant factor affecting nutrient characteristics. Despite reduced absorption of N, P, K, Ca, and Zn and increased absorption of Fe and Mn, *T. distichum* could respond actively to water level changes by balancing element accumulation to maintain normal growth. The accumulation of major nutrient elements at all elevations remained at or above normal growth levels without severe nutrient deficiency, indicating that *T. distichum* has strong adaptability to water level changes in the Three Gorges Reservoir hydro-fluctuation belt.

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Note: Figure translations are in progress. See original paper for figures.