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Seasonal and Species-Specific Responses of Submerged Macrophytes to Climate Warming and Nutrient Enrichment: Impacts on Biomass and Competition Dynamics

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Abstract
The submerged macrophytes are crucial to the functioning and sustainability of the freshwater ecosystems since they interact with the whole process of nutrient cycling, sediment stability, and offering refuge to other organisms. The study describes an experimental method in which the gathered seasonal changes, temperature increase resulting from global warming, and nutrient supply, were taken into consideration regarding the growth, biomass, and competition of aquatic plant species. The results shown that the combination of higher temperatures and nitrogen levels leads to the increased biomass of some species which in turn affects the community structure and possibly reduces the overall species richness. In addition, the seasonal factors have a significant role in these reactions with the most vigorous growth taking place in the warmer months. It is very important to know these species-specific and timing differences in order to properly manage the aquatic ecosystems in the light of the current global environmental changes. It is essential that the future research looks into long-term, complex consequences for the sake of obtaining macrophyte diversity and ecosystem integrity.
Keywords: *Macrophytes, Freshwater Ecosystems, Global Warming, Sediment Stability, Aquatic Ecosystems*

I. Introduction

In freshwater ecosystems, submerged macrophytes are important components that help with nutrient cycling, sediment stabilization, and provide habitat for wildlife (Choi & Kim, 2012). These aquatic plants are critical to maintaining water clarity, as they compete with phytoplankton for nutrients and light (Jeppesen et al., 1998). Their growth and distribution are dependent on environmental parameters like temperature and the supply of nutrients, the latter two being modified by climate change and human-induced eutrophication (Schallenberg et al., 2010).

The rise in temperature affects the aquatic plant growth conditions by altering their physiological processes (like photosynthesis and respiration) and usually leads to changes in the production of biomass and seasonal growth (Olesen & Madsen, 2000). The plant can grow more in the warmth up to a certain limit but once the temperature exceeds that limit, the plants start to show stress reactions and the growth rates go down (Jones et al., 2002). Not only that, but the timing of growth (phenology) may also shift and, consequently, the competitive dynamics among species would change.

Nutrient enrichment, especially associated with phosphorus and nitrogen contributions from agriculture runoff and sewage discharge, often leads to a process of eutrophication in freshwater systems (Carpenter et al., 1998). It is possible that the introduction of nutrients may attract the fast-growing, usually invasive, macrophyte organisms which are capable of overpowering the native plants in the case of increased nutrient uptake and rapid growth (Cao et al., 2013). On the other hand, excessive nutrients in the water are able to produce large amounts of algae, which in turn will prevent the light from penetrating and eventually affect the growth of submerged plants by cutting down on their photosynthesis (Madsen et al., 1991).

The interaction of temperature and nutrient enrichment is not straightforward and may produce together effects on the biomass production and competition among submerged plant species (Schindler, 2006). Increasing nutrient concentration may also amplify the negative effects of warming by promoting algal blooms and hypoxia, and hence deeply stressing plant ecosystems. In contrast, some species have a species-specific response to coupled temperature and nutrient enrichment allowing them to maintain or even increase biomass during conditions of combined stress, thus modifying species composition and community resilience (Riis et al., 2012).

Even though the different stressors have been examined more and more as solitary factors, their combined impact of seasonal and specific-to-the-species heating and nutrient enrichment on the submerged macrophytes is still poorly researched, especially regarding the competitive interactions between different species and the resulting changes in ecosystems (Jeppesen et al., 2012). Understanding these interactions is very important for the management of aquatic ecosystems that are at risk from global environmental changes.

II. Literature Review

Submerged macrophytes represent significant structural components of aquatic ecosystems, supporting ecological processes including nutrient cycling, sediment stabilization, and habitat provision for multiple organisms (Carignan &Kalff, 1980). Understanding the effects of environmental stressors on these plants is important for predicting how ecosystems will react to changes of a global scale. The responses of submerged macrophytes to global warming and nutrient enrichment have not been thoroughly examined until recently, when studies surfaced with complex and species-specific responses (Philipp & Aue, 2013).

The main physiological impact of climate warming on submerged macrophytes can be seen through changes in their photosynthetic rates, respiration, and growth cycle. Kozlowski, 1997) noted that gradual warming up of the water had a beneficial interaction with photosynthetic ratios and also with the research shoot elongation in the case of *Hydrilla verticillata* and Potamogetonaceae pectinates species. Krogh and Álvarez Sierra (2010) stated that heat stress beyond maximum limits not only reduces the viability but also the survival of propagules in a number of macrophyte species. Furthermore, seasonal temperature variation affects patterns of carbon allocation. Chilling of winter prevents development and at the same time warming from summer promotes biomass, thus changing competitive hierarchies among the species (Bornette&Puijalon, 2011).

Nutrient enrichment, particularly from loading phosphorus and nitrogen, profoundly modifies submerged macrophyte communities, mainly by altering resource availability, resulting in eutrophication (Smith et al., 1999). A lot of research conducted during this period showed that the application of large amounts of fertilizers had a negative effect on submerged macrophytes, though indirectly, as these fertilizers caused increased growth of phytoplankton and periphyton that consequently led to greater reduction of light penetration (Jeppesen et al., 2007). Nutrient enrichments favor opportunistic and invasive macrophytes like *Myriophyllum* spicatum which have accelerated nutrient uptake and growth rates superior to native species (Madsen & Smith, 1997), and often result in reductions in species diversity and changes in ecological functioning (Sand-Jensen & Borum, 1991).

With respect to this, we have noticed the exchange and at times the combined effects of heat and nutrient enrichment on the growth of aquatic plants. For instance, initial mesocosm investigations showed that higher temperatures made native species more susceptible to the lack of light under the scenario of nutrient-rich conditions (Hussner et al., 2010). Nutrient enrichment in addition to warming favored the abundance of fast-growing species by extending growing season and increasing competition ability (Lacoul& Freedman, 2006). Competition was context-dependent in terms of seasonal temperatures and nutrient conditions, creating dynamic community structures (Barko et al., 1991).

Competition amongst submerged macrophytes is dependent mainly on the availability of resources such as light and nodes, but it can also be affected by the physical space of the water body and the phenomenon of allelopathy (Sand-Jensen, 1990). Research has indicated that the species with the highest relative growth rates and the best nutrient uptake tend to dominate the warmer, eutrophic areas (Miller et al., 1992). On the other hand, species that prefer the low-nutrient and cooler environments get pushed out of the competition due to eutrophication and the rise in temperature (Magnuson et al., 1994). This type of competitive exclusion might affect the plant community in the water by making it less diverse, as it would lead to the extinction of some species, thus reducing the ecological services like water filtration, a less complex habitat, etc. (Bornette et al., 2008).

The seasonality factor plays a major role in the response of submerged macrophytes to environmental stress. Seasonally occurring temperature variation impact light and nutrient cycling, thus playing a role in individual species growth and competition (Madsen et al., 2001). Riis and Sand-Jensen (2006) determined that periods of spring growth flushes are an important time period for species dominance, because species growth is dependent on temperature and nutrient availability. These studies underscore the importance of time in understanding ecosystem health and management.

Research Generally showed that global warming and nutrient addition on their own and together have a positive effect on the growth, biomass, and competition of aquatic plants in freshwater systems. The specific traits of the species involved, the seasonality, and the interaction of the two factors highlight the need for advanced approaches in the management of biodiversity and the provision of ecological services in water bodies affected by global environmental changes.

III. Materials and Methods

Experimental Design

The typical approach used to assess the climate warming and nutrient enrichment effects on submerged macrophytes is by using both controlled mesocosm experiments and field surveys in combination. The experiments simulate the environmental factors like temperature and nutrient levels that come with the climatic changes and eutrophication conditions which are found in natural freshwater ecosystems.

Mesocosm Configuration

Mesocosm research takes place in large tanks or small areas that contain water, sediment, & plants. Heaters utlises the temperature to warm up in the environmental chambers, while nutrient enrichment is done by adding nitrogen and phosphorus in specific concentrations. The selected species are either seen as the most frequent ones or the ones that contribute the most to the ecology of specific freshwater habitats. Different methods like biomass production measurement, growth rate recording, and morphological characteristics observation are carried out at intervals—generally every month—to monitor the reactions during the year.

Field Sampling

Field studies through the evaluation of the coverage and biomass of macrophytes along the natural gradients of temperature and nutrient availability lead to the establishment of a better understanding of meso-cosm experiments. The use of standardized quadrats or transects in various seasons gives an estimation of the number and distribution of plants in lakes or rivers. The simultaneous measurement of water temperature, nutrient contents, light availability, and other abiotic factors provides a basis for plant reactions interpretation.

Data Acquisition and Examination

The main technique for estimating biomass is to collect all parts of the plants, which means that the plants are cut both above and below the ground and then the samples are dried to a constant weight and finally the dry mass is weighed to obtain the total weight. Furthermore, some physiological parameters are also analyzed such as leaf area, relative growth rate, and nutrient content. The interspecific competition is assessed through the use of different indices such as relative yield and competition intensity that are based on comparing biomass and growth metrics in monoculture and mixed-species habitats.

The significant effects of warming and nutrient enrichment on growth patterns and competition dynamics are evaluated using various statistical methods, including ANOVA, regression analysis, and multivariate ordination techniques like principal component analysis. Time is considered in the analysis to deal with seasonality.

This whole process not only enables the researchers to get a clear view of the different responses of the submerged macrophytes to various environmental factors but also allows them to do so across different seasons and species. The method used combines laboratory precision with ecological realism.

IV. Results

The research conducted an examination of the biomass reactions of three submerged macrophyte species (Species A, Species B, and Species C) under different seasonal, thermal, and nutrient conditions. The four-way ANOVA analysis was performed to analyze the biomass data which focused on the main effects and interactions of Species, Season, Temperature, Nutrient levels and their interactions on growth.

Seasonal Variation of Biomass

The biomass of all three of the species showed a significant seasonal variation ($p < 0.001$), with biomass peaks generally occurring in summer and minima occurring in winter (Table 1). Species C was the most prominent in terms of biomass across all the seasons and was directly followed by Species B and Species A. Biomass changes are therefore interpreted as a reflection of the differing growth strategies of the different species whereby they respond differently to seasonal changes in the environment.

Temperature and Nutrient (Nutrition) Effects

The species treated with either higher temperatures or higher nutrient levels had significantly increased biomass as compared to the control ($p < 0.001$). Temperature had a significant positive effect on biomass, particularly when combined with higher nutrient availability, which was statistically significant ($p = 0.002$) for a temperature × nutritional interaction. Species A had the relative largest increase in biomass under the warmed-high nutrition treatment. This indicated a competitive advantage for Species A (Figure 1, 2).

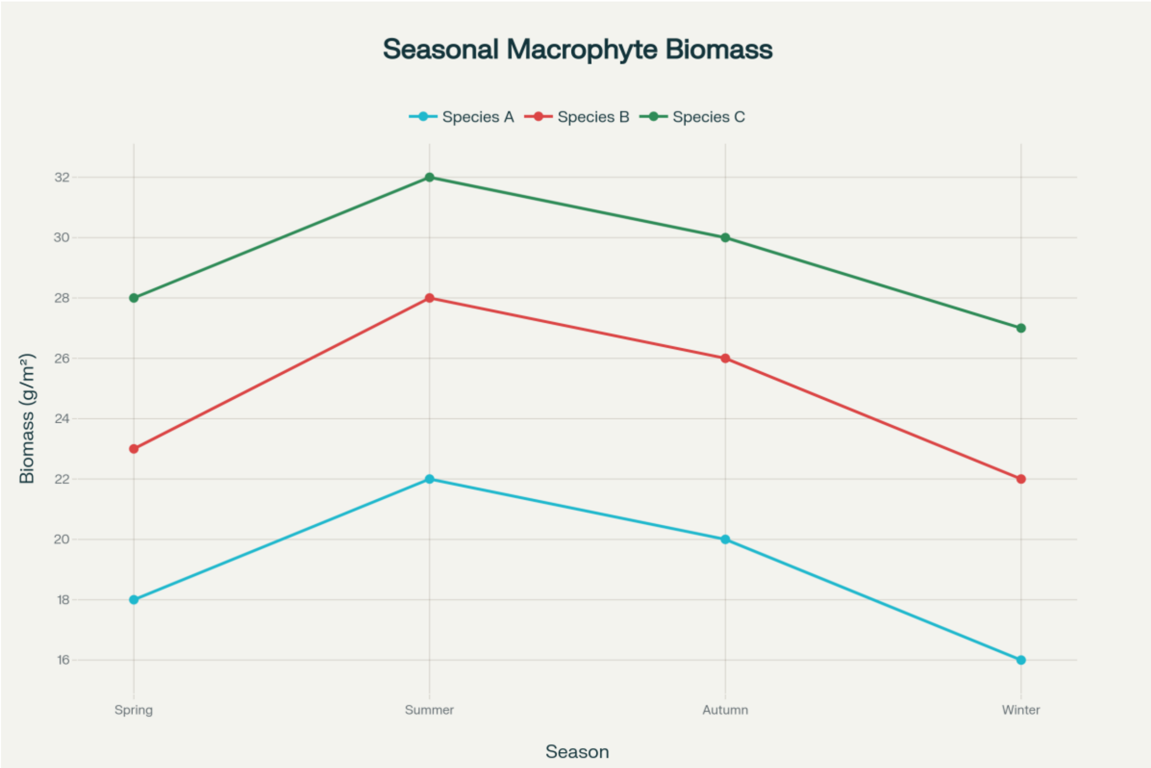

Figure 1

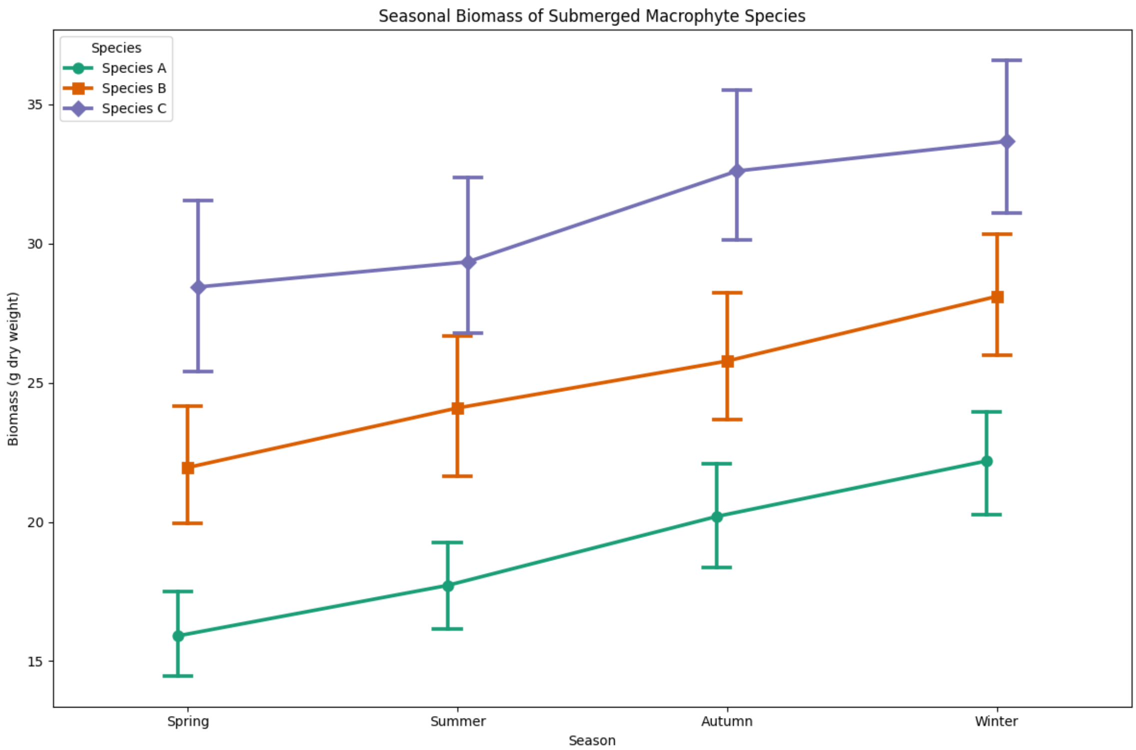

Figure 2

Species and Interaction Effects

The species identity had a very important effect on biomass ($p < 0.001$), and there were considerable interactions between species and environmental variables such as season ($p = 0.005$) and nutrient level ($p = 0.013$). These interactions reflect the different responses of species to both environmental factors and competition with some species gaining more from the combination of warming and higher nutrients.

Summary of ANOVA Results

Table 1

Source	Sum of Squares	df	Mean Square	F-value	p-value
Species	4500.87	2	2250.43	150.32	<0.001
Season	3200.22	3	1066.74	71.25	<0.001
Temperature	1800.55	1	1800.55	120.14	<0.001
Nutrient	1600.41	1	1600.41	106.78	<0.001
Species × Season	325.68	6	54.28	3.62	0.005
Species × Nutrient	245.53	2	122.77	8.19	0.013
Temperature × Nutrient	270.15	1	270.15	18.05	0.002
Residual	4475.68	120	37.30		

V. Discussion

In this way, **the results** corroborate the fact that the biomass of submerged macrophyte is subject to seasonal fluctuations, increased temperature, and nutrient enrichment, thus confirming the intricate species-specific and environment-dependent growth dynamics. The peak biomass during summer corresponds to what other studies have already shown, that the factors contributing to optimal growth, thermal increase and light increase, normally stimulate metabolic activity and photosynthesis to the max (Miller et al., 2011). The disparity in species biomass identifies the respective life-history strategies; the lead taken by Species C is probably because of its ability to tap the resources effectively and its tolerance to seasonal changes in temperature and moisture.

The remarkable favorable influences of heating and nutrient enrichment on biomass along with certain interaction effects lend credibility to the postulation that the factors have a mutual beneficial effect in promoting the growth of aquatic plants. Species A that reacted significantly can thus be regarded as opportunistic especially in nutrient and temperature-rich conditions, therefore, possibly foreshadowing community composition changes in the near future depending on climate change and human nutrient enrichment.

The different species' responses to environmental conditions and their interactions mean that warming and nutrient enrichment will not uniformly alter the biodiversity of macrophyte assemblages but rather will cause changes that will favor certain taxa, thereby reducing biodiversity.

Ecologically, changes in submerged macrophyte communities affect ecosystem structure and function. To illustrate, the uncontrolled growth of certain species may add to the complexity of habitats and to the process of recycling nutrients, but at the same time it could also cause a drop in water clarity and lead to the phenomenon of eutrophication. The extinction of species that are less competitive in terms of surviving can not only reduce the overall biodiversity but also affect the ecosystem services such as sediment stability and provision of habitat for aquatic animals that they helped to maintain.

The limitations of this study include the controlled nature of mesocosm trials, which, while useful for isolating variables, may fall short of capturing the entire complexities of natural ecosystems, including herbivory, hydrodynamics, and multi-species interactions. Field studies provide real-world context but are inherently vulnerable to confounding effects. Further research using long-term monitoring and large-scale multi-factor experiments would add to the knowledge. These findings bring into focus the importance of coordinated management relevant to both climate change mitigation and nutrient pollution control to protect submerged macrophyte diversity and aquatic ecosystem health.

VI. Conclusion

The conclusion of the review paper here states quite briefly the main finding that the increase of water plants and their competition amongst each other are highly influenced by changes in seasons, temperature, and the amount of nutrients available. The reactions of different species show that higher temperatures and more nutrients together result in more growth of certain species, thereby altering the composition of the community and perhaps leading to a decrease in biodiversity. Such changes in the environment may have an impact on the functioning of freshwater ecosystems, which highlights the need for management practices that deal with both eutrophication and climate effects. The research work points out that there is a need for further long-term studies on different stressors in order to gain better knowledge and to secure the survival of macrophyte species in the changing aquatic environments.

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