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Flood Resilience, Viability, and Growth Response to Seawater Immersion of Bermudagrass (*Cynodon dactylon* (L.) Pers.)

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Abstract: A holistic approach to sustainable coastal zone management assigns the development of nature-based and low-cost strategies for coastal protection during extreme meteorological events. This determines the growing interest in plant species with high salt tolerance, and the study of their flood resilience in order to determine their capacity for flooding and erosion control. Bermudagrass (*Cynodon dactylon* (L.) Pers.), with its vast rhizome system, has the major characteristic features of useful plant stabilisers of coastal sand dunes. This study aims to define the effects of flooding stress caused by storms on viability, survival ability, and growth response of bermudagrass in flooding simulations in order to define its flooding resilience. *C. dactylon* showed high resilience and tolerance to salt from seawater during flooding simulations. The Critical Decomposition Time of *C. dactylon* is estimated at 144 h, which is more than the maximum-duration flood recorded for the Bulgarian Black Sea Coast. Untreated rhizomes showed less viability than those treated with seawater in flooding simulations. Changes in resistance, viability, biomass, and vegetative allocation were more significant, with the water as an influencing factor. The temperature of seawater and duration of submergence had no significant effect. As a median value species between psammophytes from the *Poaceae* family and the *Cyperaceae* family, bermudagrass can be used as a model plant in flooding simulations.

Keywords: bermudagrass; *Cynodon dactylon*; salt tolerance; flood resilience; immersion tolerance; dune stabilisation; erosion and flooding control; flooding simulations; mitigation; ecosystem services

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1. Introduction

Considering the increasing trend of intensified unusual meteorological events such as storm surges, in combination with global climate changes and sea-level rise, more coastal areas will face seawater flooding and subsequent salt stress on the related biota [1–4]. This will cause infrastructure damage, economic losses, social disturbances, and reduced attendant development in flood-exposed areas [5–7].

In the context of the European Floods Directive (2007/60/EC), an increasing number of studies have proposed various models and scenarios for flood risk assessment. Most of them targeted socio-economic dimensions in order to predict possible adverse effects on coastal areas from flooding. Their main disadvantage is that they are not based on experimental data [2,8–11].

The decisive objective of sustainable coastal-zone management is the development of nature-based and low-cost strategies for coastal protection. These strategies should provide options for the effective reduction of the damaging impacts of extreme meteorological events on coastal zones by absorbing storm energy [12]. Central to these ecologically-sound ecosystem services is the substitution of artificial coastal protection and stabilisation facilities with dune systems stabilised with plants. These naturally or transplanted plants ought to be characterised by extensive root systems and high salt tolerance [13]. Thus, they can support, stabilise, and increase the dunes' ability for storm damage reduction. On the other hand, they effectively minimise erosion with a minimal negative effect on natural ecosystems [14,15]. Therefore, a crucial aspect of such mitigation strategies is searching for adequate plants and studying their flood resilience in order to determine their capacity for flooding and erosion control [16,17].

In the context of past experience, these transplanting techniques of introduction of non-native plant species were not always impeccably successful. Although they provide engineering solutions for eliminating or reducing flooding and erosion, the introduced species can become invasive. They are characterised by a rapid spread to a degree that causes damage to the native ecosystems, the human economy, and human health [18–20]. Numerous examples (e.g., *Ammophila arenaria* (L.) Link and *Thinopyrum ponticum* (Podp.) Z.-W. Liu and R.-C. Wang in North America) show a negative trend in these intentional or inadvertent introductions. That is why applying such mitigation techniques has to be performed carefully and after appropriate research and analysis. These two species, as well as bermudagrass, are native to the Bulgarian Black Sea Coast; therefore, their inadvertent spread cannot be considered an ecological problem.

Bermudagrass (*Cynodon dactylon* (L.) Pers.) is an enormously variable perennial plant from the *Poaceae* family, which has become truly cosmopolitan as a weed in disturbed habitats [21]. Bermudagrass has the major characteristic features of useful plant stabilisers, such as forming a vast rhizome system that can support the sand stabilisation of coastal sand dunes [13,17]. Monitoring of the Bulgarian Black Sea Coast, as well as field investigations, showed the contribution of this species in some dune communities at different percentages of participation [22,23]. Artificial planting of bermudagrass could have a negative effect on natural vegetation, expressed as displacement of other native species. This requires preliminary research and subsequent monitoring of the transplanted dunes.

Most of the related studies have been undertaken on the molecular and physiological mechanisms of oxygen deficiency stress and salt tolerance. The impact of freshwater flooding on general weeds and crops [24,25], including *C. dactylon* [26], is well known. Our understanding of the tolerance and resilience of seawater flooding and post-immersion growth response is limited to some psammophytes, such as *Leymus racemosus* subsp. *sabulosus* [17,22,23], *A. arenaria* [23,27–30], *Galilea mucronata* (L.) Parl. [17,23], *Carex colchica* J. Gay [22,23], and *T. ponticum* [13].

The aforementioned studies stated that psammophytes are characterised by high viability under the stress of flooding. On the contrary, seawater inundation reduces the plant survival of ecologically and physiologically non-related species *Trifolium pratense* L. and *Plantago lanceolata* L. [31–33]. Hanley et al. [34] demonstrated reduced growth and yield of *Brassica napus* L. These first attempts to derive experimental data contrast with scarce literature documenting the influence of seawater flooding on the viability, survival ability, and growth response of *C. dactylon*.

The main goal of this study was to define the effects of flooding stress caused by storms on a number of plant life aspects (survival ability, viability, and growth response) of bermudagrass. By investigating the flood resilience of whole plants, and rhizome viability in flooding simulations, it aimed to receive data for further investigation and analysis for its capacity for dune stabilisation.

2. Materials and Methods

Whole *C. dactylon* plants and rhizomes were collected from typical coastal arable lands in North-eastern Bulgaria (43°20′52.38′′ N, 28°03′44.63′′ E) in May 2021. The simulated flooding and growth response experiments were conducted in the Botany Laboratory and Greenhouse of the Technical University of Varna (Bulgaria). All the experiments in this study were repeated two times.

2.1. Flood Resilience Experiment

Three equal groups, consisting of 10 coeval and one-size whole plants each, were planted in 10 × 10 × 17 cm plastic pots, together with a soil substrate from their natural habitat, and were acclimatised for a month. Pots with plants were placed in 100 L glass tanks and totally submerged in seawater (18‰ salinity) for 480 h. Each group was kept at the fixed and maintained temperature of 4 ± 1 °C, 13 ± 1 °C, and 23 ± 1 °C, respectively. The seawater was altered with new water several times per day [13].

The apparent degree of decay of roots, stems, and leaves was estimated as a percentage of the whole vegetative organ surface [13,17]. The onset of decay was the time when visible decomposition processes reached 15%. Visibly decaying surfaces of more than 50% were accepted as complete decay [13].

In order to assess flood resilience following flood duration, the parameter Critical Decomposition Time (CDT) was derived as the smallest degree of irreversible decay (under 15%) of the vegetative organ surface.

2.2. Post-Submergence Growth and Biomass Allocation Experiment

Three hundred rhizome replicates of equal age and size were fully immersed in three 100 l glass tanks full of seawater with 18‰ salinity. They were distributed in 3 equal series with maintained constant temperatures of 4 ± 1 °C, 13 ± 1 °C, and 23 ± 1 °C, respectively. Every 48 h (treatments for 48, 96, 144, 192, 240, 288, 336, 384, 432, 480, 528, 576, 624, 672, and 720 h, respectively), a group of 10 rhizomes was removed from each tank. Another substantive and comparable group of 10 additional untreated-with-seawater rhizomes was used as a control.

After respective treatment in seawater, the treated, as well as untreated series of rhizomes were planted in sterilised soil substrate taken from their natural habitats in 15 × 15 × 13 cm plastic pots. They were cultivated in a greenhouse with natural daylight at mean daily temperatures between 11.4 °C (±0.4) and 28.9 °C (±0.6), and relative air humidity varying between 83% and 93%. Rooted plants were irrigated with fresh water daily. All specimens were harvested a month after planting, washed, and oven-dried at 80 °C for 24 h [13,27].

Viability was expressed as the percent value of all dormant buds that yielded roots and shoots, and was defined as the parameter mean bud viability (MBV). The highest percentage value for each treatment was set as the maximum bud viability.

2.3. Statistical Analysis

All recorded data were subjected to one-way analyses of variance (ANOVA). Values were put as the mean with standard error of the mean. Differences with a p value less than 0.05 were considered statistically significant.

3. Results

3.1. Flood and Salt Resilience

Treated specimens preserved their viability during twenty-day flooding simulations. The decomposition onset of leaves was 144 h, which was significantly earlier than other vegetative organs (Table 1). No decay processes were observed in newly established roots during the submergence.

3.2. Viability

The viability experiments demonstrated the high survival rate of the rhizome buds. All treatments, as well as controls, demonstrated 100% maximum bud viability. At least one viable bud produced shoots in seventy percent of the longest simulations, and 5% of the rhizomes had maximum bud viability.

Linking MBV and seawater submergence demonstrated a trend characterised by gradually increasing and reaching a peak at the 384th hour of water submergence, followed by slightly decreasing until the end of the simulation (Figure 1).

Statistical analyses showed that the MBV of untreated controls had lower values than all of the treatments, and treatment with seawater amplified viability slightly ($F = 7.33$, $p = 0.042$). No significant differences in rhizome viability in the various temperature treatments were observed ($F = 6.02$, $p = 0.089$).

Table 1. Results from flooding simulations (in hours). Decomposition onset of vegetative organs of the specimens (n/a—not applicable).

Parameter (h)	4 °C	13 °C	23 °C
Decomposition onset of leaves	144	144	144
Decomposition onset of stems	264	264	264
Decomposition onset of roots	360	360	360
Full putrefaction of leaves	408	408	402
Full putrefaction of stems	n/a	n/a	n/a
Full putrefaction of roots	n/a	n/a	n/a
Growth of stems	120	120	120
Growth of root sprouts	144	144	144
Putrefaction onset of newly grown stems	460	460	450
Putrefaction onset of newly grown roots	n/a	n/a	n/a
Full putrefaction of newly grown stems	n/a	n/a	n/a
Full putrefaction of newly grown root	n/a	n/a	n/a

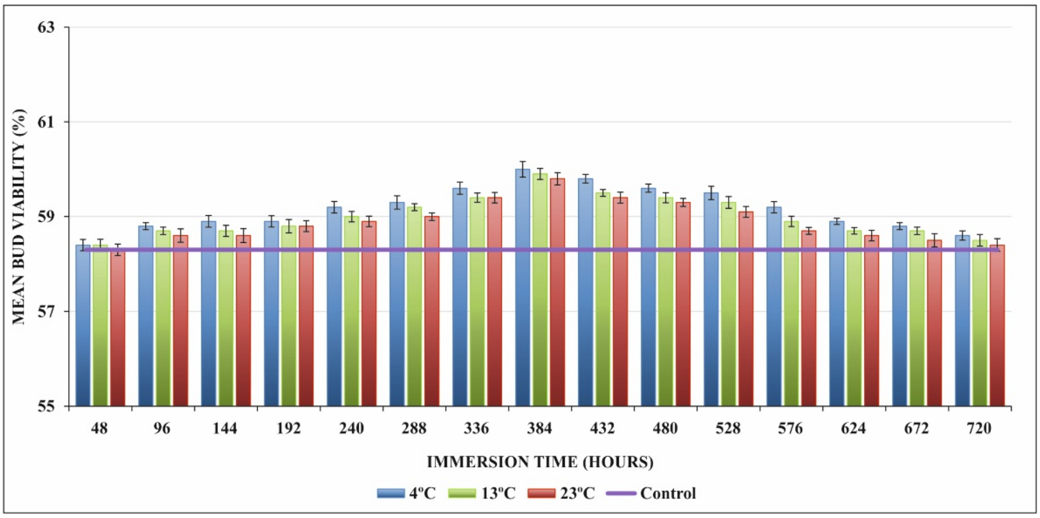

Figure 1. Mean bud viability ± S.E. vs. seawater submergence.

3.3. *Post-Submergence Changes*

The study of changes in dry weight biomass demonstrated a similar trend, characterised by an increase to a maximum at the 384th hour of the simulations and a decrease until the end of the experiment. At the 720th hour, the values of biomass were higher than the values of the controls (Figure 2). All the treated series of rhizomes were not affected significantly by water temperature ($F = 6.44$, $p = 0.082$) or simulation duration ($F = 7.50$, $p = 0.068$).

Figure 3 illustrates the relationship between seawater immersion and R:S ratio. Treated replicates showed a slight increase in biomass allocation to roots, which show a possible stimulation effect on the root system, and thus, retention of more substrate. Higher water temperatures did not statistically affect the R:S ratio ($F = 7.87$, $p = 0.064$).

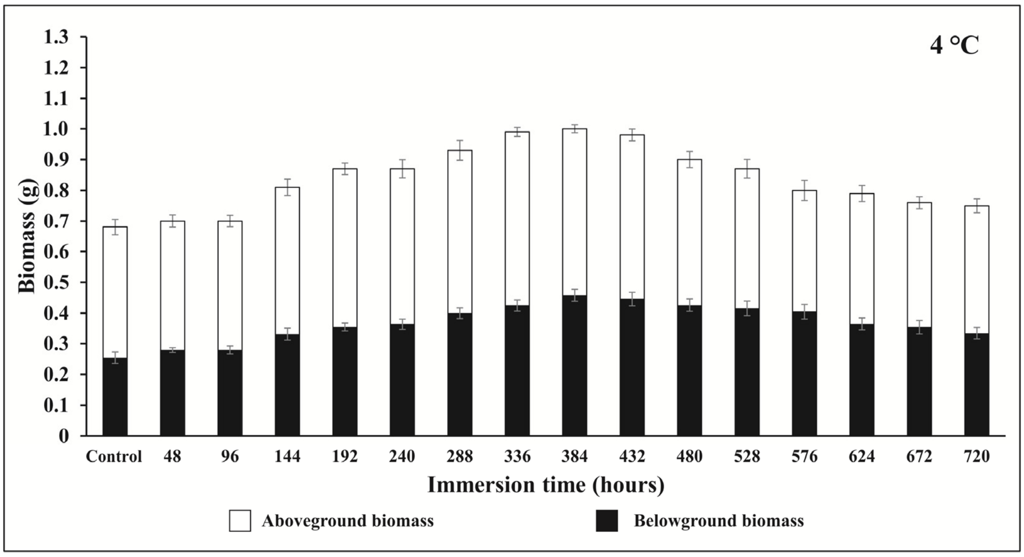

Figure 2. Effect of seawater immersion on dry weight biomass and allocation. Graph presents data for 4 °C due to the incoherence of dry weight biomass ± S.E. and water temperature.

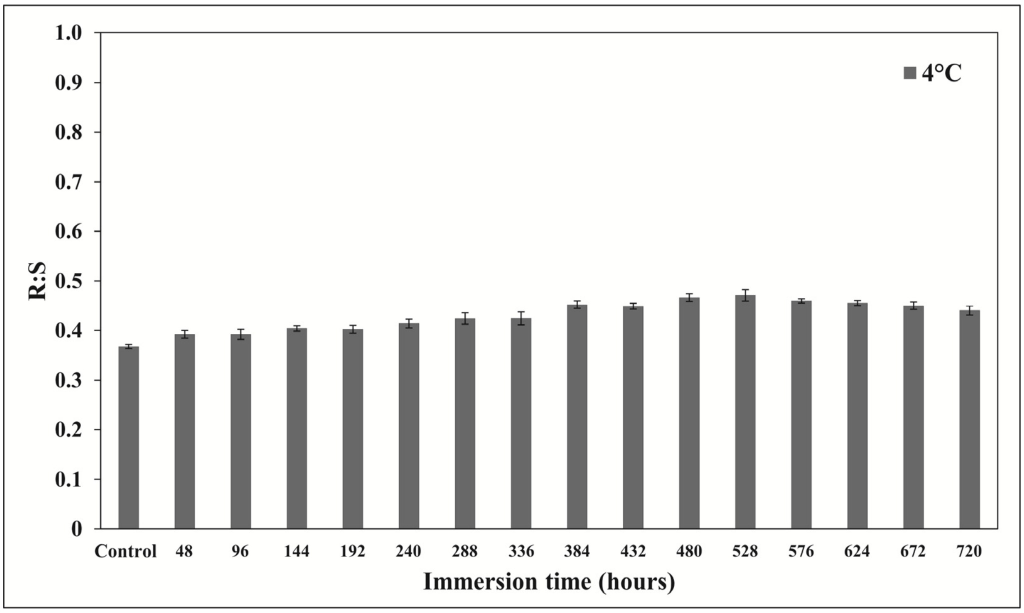

Figure 3. Effect of seawater submergence to R:S ratio. Graph presents data for 4 °C due to the incoherence of R:S ratios ± S.E. and water temperature.

4. Discussion

Research into the literature showed that studies of salt resilience are mostly focused on analysing the effects of salt aerosol and substrate salinity [13,17]. Characterising the drivers of compound flooding events and negative effects during floods demonstrated that a distinction between the repercussions for plants from flooding and salt stress has to be made [31,33]. The fact that seawater inundation may have a duration of hours [10] imposed the design of direct flooding simulations [13]. Extreme meteorological events are the main cause of floods in the Bulgarian Black Sea Coast due to the lack of big rivers and tides. The duration of storm events varies between 72 and 122 h, according to the direction and return period [10]. In accordance with previous flooding experiments, the time frame of flooding simulations was set to 480 and 720 h, respectively [13]. The rhizomes of different psammophytes treated for 0–72 h revealed outcomes that were comparable to the untreated controls. Similar values were seen in treated groups from 73 to 96 h. The duration of several studies was set to 24 or 48 h due to the poor survival rate of the studied species [31–34].

Seawater exposure duration is one of the main limiting factors of the viability, survival ability, growth response, and allocation of the bermudagrass under flooding conditions [13]. The survival ability of plants and their communities can be expressed as CDT by linking the flooding duration and resilience of plant species [17]. The CDT for *C. dactylon* was 144 h, which is out of the timeframe of the maximum-duration flood recorded for the Bulgarian Black Sea Coast of 122 h [8,10]. This CDT rate is consistent with previous results from the *Poaceae* family psammophytes (*A. arenaria, T. ponticum*, and *L. racemosus* subsp. *sabulosus*) [13,17,23,27–30] and the *Cyperaceae* family (*G. mucronata* and *C. colchica*) [17,22,23], and contrary to results of seawater flooding simulations of *Artemisia vulgaris* L., *Crambe maritima* L., and *Eryngium maritimum* L. [35]. Interpretation of the high survival rate, as well as the analysis of the experiments, leads to the conclusion that *C. dactylon* communities will recover after the extreme events within one vegetation season. It seems likely that they can quickly regain the ability to stabilise dunes, which act as a buffer.

Treatment with seawater enhanced viability slightly. This can be explained by the fact that unfavourable environmental conditions and mechanical disturbances can drive dormant buds to shoot and root production [36].

Notably, the experimental results of MBV are in good agreement with those from the literature [27–30,37]. *C. dactylon* showed a lower viability rate in flooding simulations than *L. racemosus* subsp. *sabulosus* [13,22,23,29] and *A. arenaria* [23,27–30], but a higher rate than other psammophytes from the *Cyperaceae* family [17,22,23]. As a median-value species, bermudagrass can be used as a model plant in flooding simulations.

One of the most important features of plants used in transplanting techniques is their ability to stabilise dunes by collecting substrates [13,17]. The established greater biomass and allocation to the root system in flooding simulations, compared to controls, showed the favourable behaviour of psammophytes during floods compared to glycophytes [38]. The most probable reason for this is the existence of reserve buds and nutrients required in case of repeated mechanical disturbances [39].

The Black Sea Coast experiences storm surges most frequently in the winter and early spring, when the mean sea surface temperature is 4 °C [10]. Two additional treatments with the average surface sea water temperature (13 °C) and the average summer surface sea water temperature (23 °C) were tested in the flooding simulations in order to illustrate the effects of different water temperatures. Nevertheless, there was not a significant relationship between resilience, viability, and biomass allocation and growth response and water temperature. This contrasts with literature data about *A. arenaria*, whose rhizomes retained more viable buds in experiments with cooler water [28,30].

Finally, treated rhizomes demonstrated a higher degree of viability than those which were untreated. The results emphasise that the water was a more significant cause of changes to several plant life aspects (resilience, viability, biomass, and vegetative allocation) of bermudagrass. Other factors, such as the duration of submergence and the temperature of seawater, had no significant effect.

Although experiments on the influence of salinity during floods were not conducted, previous studies with physiologically and ecologically relevant species from the *Poaceae* family show that salinity has no significant effect on survival ability and growth response [13,17,20,22,23,27,28]. This is also consistent with the high salt-stress tolerance of *C. dactylon* established in a number of studies [40–42].

Some key parameters, such as viability, survival ability, growth response, and allocation, can be used as indicators for successive analysis of the capacity of bermudagrass for dune stabilisation.

5. Conclusions

Bermudagrass showed high flooding resilience and high tolerance to salt from seawater during the flooding simulations. The parameter Critical Decomposition Time, which demonstrated the correlation of flooding duration and resilience of *C. dactylon*, was evaluated to 144 h. This value exceeds the longest recorded flood for the Bulgarian Black Sea Coast. The *C. dactylon* communities were able to recover after extreme events within one vegetation season. They are able to rapidly regain their ability to stabilise dune systems and serve as a buffer due to their high viability and survival rate.

In this study, untreated rhizomes showed viability lower than those which were treated. It can be concluded that water as an influencing factor was the reason for the more significant causes of changes in resilience, viability, biomass, and vegetative allocation. The results evidenced that other factors, such as the temperature of seawater and the duration of submergence, had no significant effect.

In terms of flood resilience, viability, and growth response to seawater submergence, it can be assumed that *C. dactylon* has high potential to be a dune stabiliser. Further analyses are needed.

As a median-value species between psammophytes from the *Poaceae* family and the *Cyperaceae* family, bermudagrass can be used as a model plant in flooding simulations.

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