

Article

Tall Wheatgrass (*Thinopyrum ponticum*): Flood Resilience, Growth Response to Sea Water Immersion, and Its Capacity for Erosion and Flooding Control of Coastal Areas

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Abstract: Integrated coastal zone management proposes nature-based mitigation strategies based on the replacement of artificial coastal stabilization and protection structures with dunes stabilized with plant species. These psammophytes stabilize sands and act as supporters, increasing dunes' ability to reduce storm damages and effectively minimize erosion with minimal negative impacts to natural ecosystems. That is why searching for native salt-tolerant plants with extensive root systems and studying their capacity for erosion and flooding control is fundamental to the practice of ecologically-sound ecosystem services. The aim of the present study is to define the effects of flooding stress on a number of wheatgrass (*Thinopyrum ponticum*) plant life aspects (survival ability, viability, and growth response) in order to determine wheatgrass's capacity as dune stabilizer. Conducted experiments established that *T. ponticum* was very tolerant to immersion impact and salt and oxygen deficiency stress, and its rhizomes were able to regenerate after 30 days in seawater. The temporal expression of its survival is presented as critical decomposition time (CDT) by linking the maximum duration of floods along the Bulgarian Black Sea Coast and the resilience of tall wheatgrass in flooding simulations. A statistical analysis of the experimental data demonstrated that immersion in sea water increases rhizome viability, biomass, and allocation to root biomass, whereas other factors, such as the duration of immersion, salinity, and temperatures of sea water have no significant effect. According to flood resilience and growth response to sea water submergence, *T. ponticum* demonstrated high potential to be a dune stabilizer.

Keywords: wheatgrass; *Thinopyrum ponticum*; immersion tolerance; viability; dune stabilization; erosion and flooding control; flooding simulations; salt tolerance; ecosystem services

1. Introduction

The risk of flooding and erosion is increasing for many coastal areas due to a cumulative effect of global climate changes, frequent storm surges, sea level rise and intensified anthropogenic impact [1–8]. These areas, with their naturally established coastal dunes, perform important ecosystem services such as protection against storm waves, storm surges, and high tides [9]. Thereby, they act as a buffer for low-lying inland urbanized and agricultural territories, while at the same time providing habitats for many endangered and rare species [10–13].

The most significant issues in coastal dune management are related to the mitigation of negative impacts during and consequences after unusual storms and floods with different origins [8]. The holistic approach of integrated coastal zone management recommends nature-based mitigation strategies based on the replacement of artificial coastal protection and stabilization structures with dunes stabilized with plants [12,14]. Natural dune vegetation reduces wind velocity, and with its extensive

system of horizontal and vertical rhizomes, holds a large amounts of trapped sand that absorbs wave energy [9,15–17]. Thereby, plants stabilize sand and act as supporters that increase the dunes' ability to reduce storm damages and effectively minimize erosion with minimal negative impacts to natural ecosystems [13,15,18]. That is why searching for native salt-tolerant plant species with extensive root systems and investigating their capacity for flooding and erosion control is fundamental to the practice of ecologically sound ecosystem services [8,13,19].

Introducing invasive non-native species to provide desired services for reducing or eliminating erosion and flooding are not always appropriate. A classic example with negative consequences was the introduction of *Ammophila arenaria* (L.) Link in North America, which has nowadays become the most problematic noxious weeds of coastal dunes [20,21]. Another inadvertently introduced invasive species is tall wheatgrass (*Thinopyrum ponticum*), which is expanding its range in North America and is a potential future problem [22,23].

Thinopyrum ponticum (Podp.) Z.-W. Liu & R.-C. Wang (syn. *Elymus elongatus* (Host) Runemark, *Agropyron elongatum* (Host) P. Beauv.) is an erect, perennial, grass species from the family *Poaceae* [24]. It forms open communities with *A. arenaria* (marram grass), *Leymus racemosus* (Lam.) Tzvelev subsp. *sabulosus* (M. Bieb.) Tzvelev (mammoth wildrye) along the Bulgarian Black Sea Coast. [12]. These closely-related species are major psammophytes, which dominate sand dunes and form an extensive systems of vertical and horizontal rhizomes that support the sand stabilization of coastal sand strips along the Bulgarian Black Sea Coast [25]. Conducted field observations and monitoring show different percentages of participation of these species [13,26,27].

The risk of coastal flooding over the Bulgarian Black Sea Coast is particularly low due to the small amplitude tides and the lack of big rivers flowing into the sea [28]. The only threat comes from unusual storm surge levels in combination with reinforced waves upon the shore [29]. These extreme meteorological events may cause the flooding of low-lying areas and the erosion of dunes (Figure 1a). As a result, the coastal areas lose their buffering function permanently or till the recovery of plant communities of dominant sand stabilizers, mostly within one vegetation season (Figure 1b).



Figure 1. Communities of *Leymus racemosus* subsp. *sabulosus*, *Ammophila arenaria*, and *Thinopyrum ponticum* (former protected area Kamchiyski Pyasatsi, 43°00'48.20'' N, 27°53'28.12'' E): (a) Considerable damages after the storm in March 2015; (b) recovered plant communities of dominant sand stabilizers after one vegetation season.

Recorded damages from storms over the Bulgarian Black Sea Coast showed the negative impact to the dunes and the high potential of the roots of *T. ponticum* to accumulate sand and prevent washout after the destruction of communities of dune pioneers *L. racemosus* subsp. *sabulosus* and *A. arenaria* [25,28,30] (Figure 1).

Though numerous studies have analyzed the physiological and molecular mechanisms of tolerance to salinity stress, oxygen deficiency stress, and the effect of fresh water flooding to general crops and

weeds [31,32], our understanding of growth response and tolerance to the impact of sea water flooding is limited to some psammophytes such as *A. arenaria* [25,28,33–36], *L. racemosus* subsp. *sabulosus* [25,28], *Carex colchica* J. Gay [8,28], and *Galilea mucronata* (L.) Parl. [12,13,28], which show a high viability to the stress of flooding in short-term intervals. These studies focused to different aspects of the response and the experimental parts were conducted in different conditions. Reasonably, the results of the rhizome viability of species (e.g., *A. arenaria*) ranged from 312 h to 1680 h in sea water. This contrasts with an insufficient literature documenting the impact of flooding to *T. ponticum*. Most of investigations have been descriptive and designated tall wheatgrass as one of the most saline-tolerant commercially available grasses [37–40]. Though, as a psammophyte, *T. ponticum* is able to cope with some degree of exposure to salinity from sea water, it is vulnerable and sensitive to the impact of flooding [25,41].

The aim of the present study was to define the effects of flooding stress caused by storms on whole plants of *T. ponticum* and how long its rhizomes can remain viable in sea water, as well as to investigate post-immersion changes in plant biomass and allocation to above- and below-ground biomass in order to determine its capacity as a dune stabilizer. The present study applied a complex investigation to a number of plant life aspects (survival ability, viability, and growth response) of tall wheatgrass.

2. Materials and Methods

Two flooding simulations were carried out in the botanical laboratory and greenhouse of the Department of plant production of Technical University of Varna in two repetitions. The rhizomes and whole plants of *T. ponticum* were collected at a sandy beach of the former protected area Kamchiyski Pyasatsi, north-eastern Bulgaria, 42°59′35.55″ N, 27°53′26.72″ E) in April 2018 and January 2018, respectively.

2.1. Flood Resilience Experiment

Thirty two-year-old whole plants were eradicated from their natural habitat, and then they were planted in washed and sterilized mixed quartz and carbonate-silicate sand taken from their natural habitats in 10 × 10 × 17 cm³ plastic pots (1.4 dm³). After a month of acclimatization, the plants with pots, separated in three equal groups, were completely submerged in three 100 dm³ (100 L) glass tanks full of sea water (18‰ salinity) with maintained constant temperatures of 4 ± 1, 13 ± 1, and 23 ± 1 °C, respectively, for 480 h. The water was changed twice a day in order to avoid water putrefactive processes.

Visible morphological changes of different parts of the plants (leaves, stems, roots) and the effect of flooding on the viability of the studied specimens were recorded and assessed in 12 parameters (Table 1). The beginning of decomposition of different parts was set to a time point when visible changes of decay were more than 15% of the whole vegetative organ surface. Complete decomposition was when the visible decomposition of an organ exceeded 50% of its surface [28].

The temporal expression of plant species survival can be presented as a critical decomposition time (CDT) by linking the duration of flooding and resilience of plant species. CDT is a parameter that is subjectively defined on visible morphological changes and represents the smallest degree of irreversible decay of vegetative organs (more than 15% of the whole vegetative organ surface), and it indicates that the plants will not survive flooding with longer duration and their communities will not be able to recover [3,8,12,28,29].

Table 1. Results from simulated flooding experiment (in hours). Visible morphological changes of different parts of the specimens (leaves, stems, and roots) were assessed in 12 parameters. (n/a—not applicable).

Parameter	4 °C	13 °C	23 °C
Beginning of decomposition of			
leaves	168	168	168
stems	n/a	n/a	n/a
roots	n/a	n/a	n/a
Complete decomposition of			
leaves	450	450	450
stems	n/a	n/a	n/a
roots	n/a	n/a	n/a
Growth of			
stems	168	168	168
root sprouts	168	168	168
Beginning of decomposition of newly grown			
stems	n/a	n/a	n/a
roots	n/a	n/a	n/a
Complete decomposition of newly grown			
stems	n/a	n/a	n/a
roots	n/a	n/a	n/a

2.2. Post-Immersion Growth Experiment

Three equal groups (60 replicate rhizomes from two-year-old plants per group) were subjected to submergence in three 100 dm³ (100 L) glass tanks full of sea water (18‰ salinity) with maintained constant temperatures of 4 ± 1, 13 ± 1, and 23 ± 1 °C. Every fifth day (treatments for 120, 240, 360, 480, 600, and 720 h), ten rhizomes were removed from each tank. Ten additional rhizomes were retained as an untreated with sea water control and were planted directly. All rhizomes (treated and untreated) were planted in washed and sterilized mixed quartz and carbonate-silicate sand taken from their natural habitats in 15 × 15 × 13 cm plastic pots (2.925 dm³). They were grown on under greenhouse conditions with natural daylight without supplemental lighting. Mean daily temperatures varied between 11.3 (±0.5) min and 29.7 °C (±0.9) max, and relative air humidity was between 82% and 95%. All planted rhizomes were watered with fresh tap water daily and were harvested one month after planting [28,36]. All plant materials were cleaned from the substrate and oven-dried at 80 °C for 24 h.

In order to determine the viability and to measure the plant growth after treatments, measurements of mean bud viability (MBV), mean dry weight biomass, and root mass to shoot mass ratio (R:S ratio) were taken. Caespitose and rhizomatous species have dormant buds. Mechanical disturbances and sometimes environmentally unfavorable conditions can drive these buds to produce roots and shoots [42]. MBV was measured as the percent of all dormant buds that produced vegetative shoots and roots following treatment. The maximum bud viability for each treatment was measured as the bud viability of the rhizome replicate with the highest bud viability for each treatment [36].

The mean dry weight biomass (mean roots mass and mean shoots mass combined) was taken as a measure of plant growth [43]. The R:S ratio (the ratio of mean root mass to mean shoot mass) measured how immersion affected plant allocation to above and below-ground biomass [44].

Data transformation was performed in order to obtain homogeneous variances. All investigated parameters were analyzed with a one-way analyses of variance (ANOVA). A *p*-value of less than 0.05 was regarded as statistically significant.

3. Results

3.1. Critical Decomposition Time

Twenty-days of sea water immersion had no lethal effect on the treated specimens. The beginning of the decay of leaves and growth of stems and root sprouts were observed at the 168th h (Table 1). The newly grown stems, roots, and rhizomes during the experiment (20 days) did not show signs of decomposition. Critical decomposition time (CDT) was estimated at 168 h and was unrelated to different water temperatures.

3.2. Viability

Treated rhizomes retained their viability when submerged in sea water till the end of the simulations (720 h). Though treated replicates were tested in different sea water temperature conditions, MBV showed identical trends (Figure 2). MBV gradually increased and reached its maximum at the 480th hour of sea water immersion, followed by slight decrease till the 720th h of the flooding simulation (Figure 2). All the treatments had higher values than the MBV of the untreated controls and appeared to be enhanced slightly by sea water ($p = 0.042$).

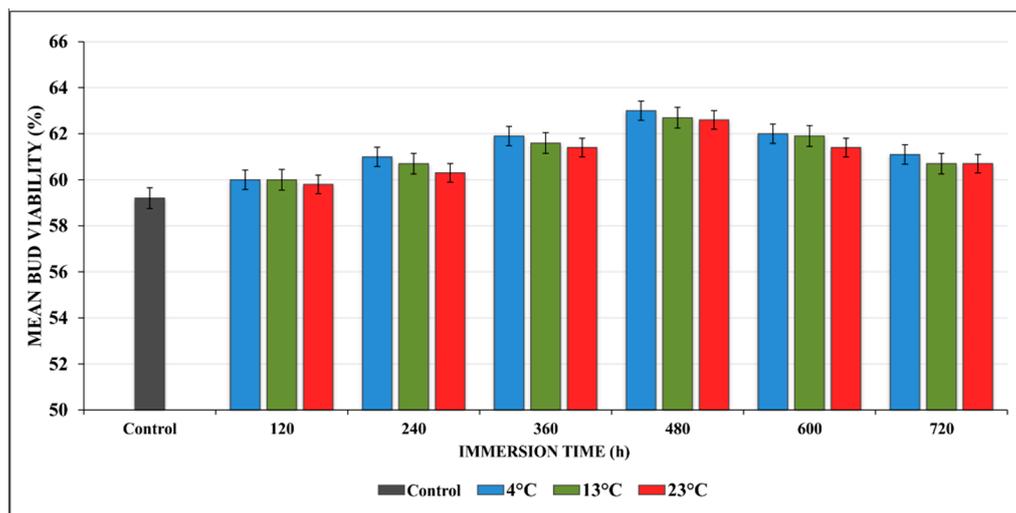


Figure 2. Mean bud viability (MBV) (means \pm S.E.) following sea water immersion. Control represents the MBV of the untreated rhizomes, others represent data for those treated with sea water replicates.

Controls and all treatments had a maximum bud viability of 100%. Eighty percent of the treated group of 720 h at least one viable bud produced shoot, and 5% of the rhizomes demonstrated maximum bud viability. There were no significant differences in rhizome viability between different temperatures treatments ($p = 0.093$).

3.3. Growth Response

The dry weight biomass demonstrated the same trend as other variables, characterized by increasing till the 360th h of the experiment followed by decreasing to values of biomass that were higher than those of the controls (Figure 3). Rhizomes in all treatments were not affected significantly by submergence duration ($p = 0.065$) and water temperature ($p = 0.077$).

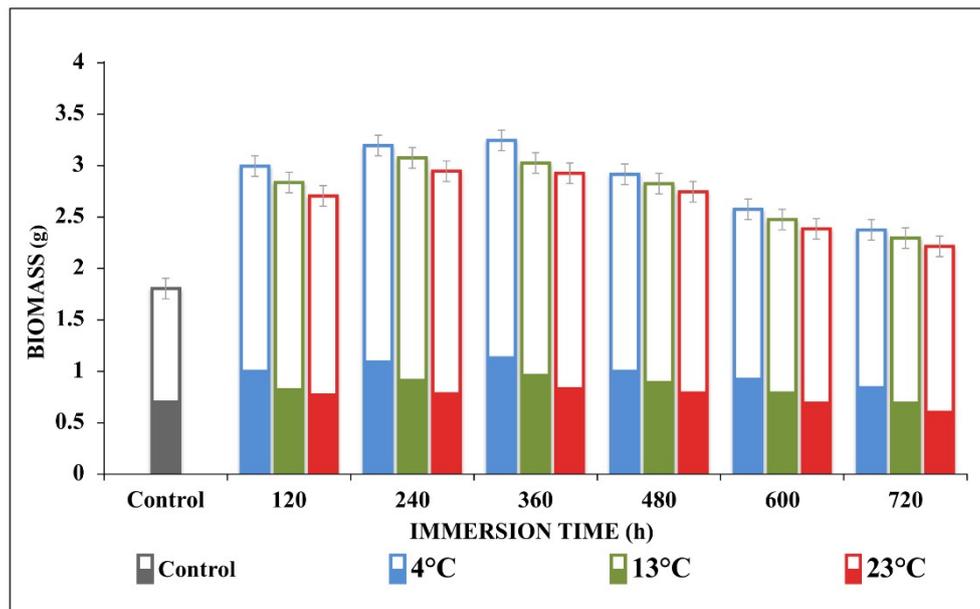


Figure 3. Effects of sea water immersion on dry weight biomass (means ± S.E.). The shaded portion of the bars represents underground biomass, and the blank portion represents belowground biomass. Control represents the dry weight biomass of the untreated rhizomes, others represent data for those treated with sea water replicates.

The R:S ratio had a tendency to be decreased by higher water temperatures (Figure 4), but the effect was statistically insignificant ($p = 0.068$). Treated plants demonstrated a slight increase of biomass allocation to roots (Figure 4).

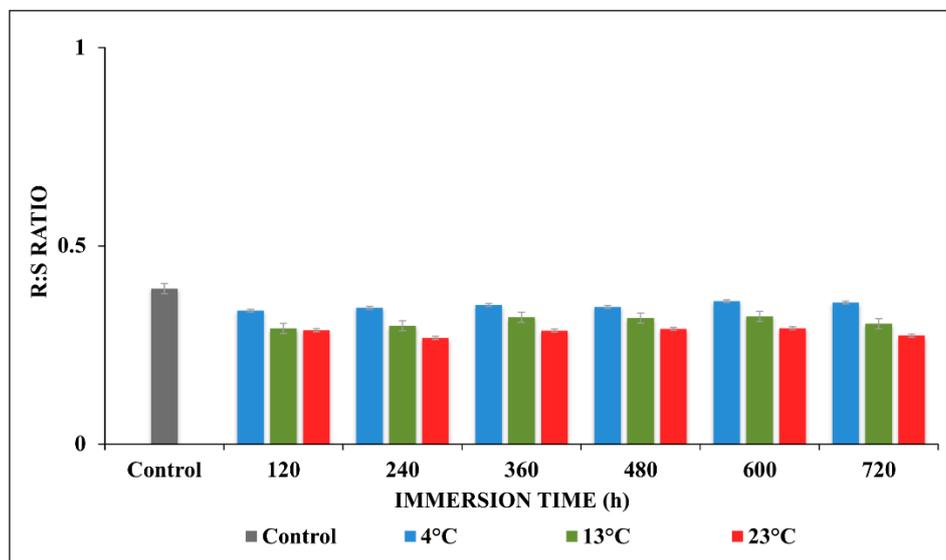


Figure 4. Effects of sea water submergence on the root mass to shoot mass ratio (R:S ratio) (means ± S.E.). Control presents R:S ratio of the untreated rhizomes, others represent data for those treated with sea water replicates.

4. Discussion

One of the most important factors in the assessments of dune plants' capacity for erosion and flooding control is their flood and sea water salt resilience. Typical studies usually focus on two factors: Substrate salinity and the effect of salt aerosol. Simulations of response to these factors are irrelevant to

psammophytes because of their regular exposure to sea water and specific physiological mechanisms of neutralizing salt [8,12,28,31]. Characterizing the drivers of flooding impacts requires a distinction between plant response to storm surge events and salinity stress in crop or halophyte species [43,45]. However, in this study, the flooding simulations were designed on the basis of direct methods in order to evaluate the resilience of investigated species to the stress of sea water flooding [25,29].

The main factor that affects and controls the viability, survival ability, and growth response of psammophytes is exposure time to sea water in naturally occurring flooding conditions or flood simulations [8]. The CDT for investigated species is 168 h, which is longer than floods with a maximum duration for the Bulgarian Black Sea Coast [15,29]. This value of the CDT is comparable with the results of psammophytes from the family *Poaceae* (*A. arenaria* and *L. racemosus* subsp. *sabulosus*) [25,28] and the family *Cyperaceae* (*C. colchica* and *G. mucronata*) [8,12,28]. In the present study, the CDT was unrelated to different water temperatures, contrary to the results of sea water submergence of *Crambe maritima* L., *Artemisia vulgaris* L., and *Eryngium maritimum* L., in which decomposition processes were accelerated by higher water temperatures [28,29]. These species have a high survival rate, and their communities can recover after flooding and erosion events within one vegetation season. Even more, statistical analyses showed that treatments had higher values than the MBV of the untreated controls and appeared to be slightly enhanced by the sea water. This is in agreement with studies of *A. arenaria*, which have evaluated its rhizome viability from 13 days to 70 days submerged in sea water [21,28,33–36] due to the different experimental conditions. This high viability seems to be due to the imposition of dormancy on subordinate rhizome buds, which has the effect of keeping reserve buds and nutrients against the threat of repeated mechanical disturbance [46].

The time frame of the flooding simulations is consistent with previous studies of psammophytic species and was limited to 20 and 30 days for the two experiments, complying with the maximum duration of the flooding caused by storms over the Bulgarian Black Sea Coast. Preliminary unpublished studies of different psammophytes showed that the rhizomes treated for 0–72 h demonstrated results similar to those of the untreated controls. Treated groups from 73 to 120 h showed identical parameters. On the contrary, in a number of studies, the duration of the simulations was set to 24 h or 48 h due to the low survival rate of the investigated species [41,43,45,47].

It should be noted that the average water salinity of the Black Sea is 18‰ lower than the ocean water salinity. Previous studies were conducted in similar conditions but in water with higher salinity. Different conditions explain the ranged results in the different studies.

The highest frequency of unusual storm surges over the Black Sea Coast is observed in the winter and spring when the average surface sea water temperature is about 4 °C [48]. In order to demonstrate the consequences of dissimilar water temperatures to investigated parameters, two other treatments with temperatures of average surface sea water temperature (13 °C) and average summer surface sea water temperature (23 °C) were tested in the flood simulations. There was not a significant relationship between investigated parameters and water temperature. On the contrary, in some case studies of *A. arenaria*, rhizomes retained viable buds for longer in cooler water, and untreated replicates showed similar levels of viability [33]. Treated rhizomes demonstrated a higher viability than the untreated ($p = 0.036$). The water itself as defining factor was a more significant cause of change of viability than the water temperature.

Even though the different temperatures, all treated replicates showed identical trends of MBV following time of sea water submergence. The same trend was observed for the MBV of other psammophytes [8,12,28]. *T. ponticum* was less tolerant to water submergence and demonstrated a lower viability rate than *L. racemosus* subsp. *sabulosus* and *A. arenaria*. On the contrary, studies of physiologically and ecologically irrelative species *Plantago lanceolata* L. and *Trifolium pratense* L. demonstrated that immersion in sea water reduced species survival, particularly at longer durations [41,43,45,47].

The defining factor for the ability of plants to collect and deposit sands is the size of the above-ground part of the plants, and the defining factor the ability of plants to contribute to dune

stabilization is the size of their root systems [8,28,49]. Treated replicates demonstrated a higher biomass and slight increase of biomass allocation to roots than the control replicates, which is consistent with results of experiments with glycophytes [50,51].

5. Conclusions

The investigated species showed a high tolerance to sea water submergence and high viability during the flooding simulations. A statistical analysis of experimental data demonstrated that submergence in sea water increased rhizome viability, biomass, and allocation to root biomass, whereas other factors, such as duration of immersion, salinity, and temperatures of sea water had no significant effect. According to flood resilience and growth response to sea water submergence, *T. ponticum* demonstrated a high potential to be a dune stabilizer.

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