Zinc tolerance and accumulation in the halophytic species *Juncus acutus*

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ABSTRACT

The research on species with capacity to tolerate and accumulate zinc is of paramount importance for phytoremediation purposes. An experiment was designed to investigate the effect of Zn from 0 to 100 mmol l\(^{-1}\) on the growth, photosynthetic apparatus and nutrient uptake of the halophytic species *Juncus acutus*. Gas exchange, chlorophyll fluorescence and photosynthetic pigments concentration were measured. We also determined total zinc, magnesium, potassium, phosphorus and sodium concentrations, as well as C/N ratio. *J. acutus* showed high tolerance to Zn-induced stress, since all plants survived and none of them showed any toxicity symptoms, such as chlorosis, necrosis or growth reduction at concentrations up to 100 mmol l\(^{-1}\) Zn. The integrity and functionality of the photosynthetic apparatus were unaffected even at zinc concentrations greater than 500 mg Kg\(^{-1}\) on tillers. Likewise, nutrient absorption was relatively unaffected. Zn tolerance was associated with the capacity to accumulate Zn in roots (with values up to 2500 mg Kg\(^{-1}\)) and largely avoid its transport to tillers. These characteristics, along with its ability to establish in a wide variety of ecosystems, render this species a useful phytostabilizer for revegetation of Zn-contaminated lands.

Keywords: Growth response; metal toxicity; nutrient absorption; photosynthesis; Zn-stress; photoinhibition.
1. Introduction

Environmental pollution by heavy metals is a serious problem worldwide, increasing in parallel with the development of human technology. Government, the industry and the public now recognize the potential dangers that metals pose to human health (Duruibe et al., 2007) through the food chain and the health of terrestrial and aquatic communities and ecosystems (Kabata-Pendias and Pendias, 2001). The danger of toxic metals is aggravated by their immutable nature and indefinite persistence in the environment (Garbisu and Alkorta, 2001; Aycicek et al., 2008). Among heavy metals, Zn is considered the main industrial pollutant of both terrestrial and aquatic environments (Barak and Helmke, 1993) and has the greatest mobility and bioavailability of all elements (Morillo et al., 2004). Although Zn is an essential microelement with many roles in plant metabolism (Kabata-Pendias and Pendias, 2001), its excess can lead to toxic effects in plants (Chaney, 1993), with specific effects on the Calvin cycle and photosystem activity (Van Assche and Clijsters, 1986).

Many remediation strategies have been considered to counter the detrimental effects of Zn excess, including physical, chemical and biological methods that immobilize or remove metals from the environment (Marques et al., 2011). Phytoremediation has recently gained importance on account of its cost-effective, long-term applicability and because it is an ecofriendly, promising clean-up solution for a wide variety of contaminated sites (Weis and Weis, 2004). This methodology depends on the use of plants to act upon the contaminants, by extracting, degrading or immobilizing them (Marques et al., 2011). The research on species which can be useful in metal phytoremediation has become a major issue (Zhang et al., 2010) and these
species should be chosen on the basis of their capacity to tolerate and accumulate particular contaminants (Marques et al., 2011).

There exists a wide variation in sensitivity to metal exposure. However, exists a lack of knowledge about metal toxicity thresholds for native plant species (Ross and Kaye, 1994) and for species used to restore sites contaminated by heavy metals, such as salt marshes. Species of genus *Juncus* have been employed in wetland restoration projects around the world (Sparks et al., 2013; Marques et al., 2011), but the information on the tolerance and accumulation patterns of heavy metals in these species is really scarce. The present study is focused on the species *Juncus acutus* L., a halophytic densely caespitose plant with subcosmopolitan distribution that is common in Spanish coastal marsh communities and can be found growing in sediments containing 100–4800 ppm Zn in several estuaries of the Iberian Peninsula (Sáinz and Ruiz, 2006). Moreover, this species has a wide ecological range, tolerating soils with high levels of sulphates and chlorides (Fernández-Carvajal, 1982) and soils with a sandy texture and hydric stress during the dry summer season. Our hypothesis is that all these circumstances highlight the potential of *J. acutus* to be used for metal remediation in polluted areas. However, no studies have analyzed its growth and physiological responses to zinc excess.

The aim of this study was to evaluate the tolerance of *J. acutus* to elevated concentration of zinc in relation of its survival, growth and photosynthetic response, and quantify the capacity of this species for accumulating this element.

**2. Materials and Methods**
2.1. Plant material

Seeds of *J. acutus* were collected in December 2011 from the natural marshes of Doñana National Park (37º 15’ N - 6º 58´W; SW Spain) and stored at 4°C (in darkness) for three months. After that, seeds were placed into a germinator for a month (ASL Aparatos Científicos M-92004, Madrid, Spain) and subjected to an alternating diurnal regime of 16 h of light (photon flux rate, 400-700 nm, 35 μmol m\(^{-2}\) s\(^{-1}\)) at 25°C and 8 h of darkness at 12°C. Seedlings were then planted in individual plastic pots (11 cm of diameter) filled with perlite and placed in a glasshouse with controlled temperature of 21-25°C, 40-60% relative humidity and natural daylight (minimum and maximum light flux: 250 and 1000 μmol m\(^{-2}\) s\(^{-1}\) respectively). Pots were carefully irrigated with 20% Hoagland's solution (Hoagland and Arnon, 1938) as necessary. All the pots received the same irrigation.

2.2. Stress treatments

In October 2012, after five months of seedling culture, the pots (with between 5 and 6 tillers) were randomly allocated still inside the glasshouse to five Zn treatments (six pots per tray, one tray per Zn treatment): 0, 10, 30, 60 and 100 mmol l\(^{-1}\) Zn. The treatment with 0 mmol l\(^{-1}\) Zn was considered the control treatment. Zinc treatments were established by combining 20% Hoagland’s solution and ZnSO\(_4\)·7H\(_2\)O of the appropriate concentration. The control, 0 mmol l\(^{-1}\) Zn treatment, had exactly 0.002 mmol l\(^{-1}\) Zn, as Hoagland’s solution contains a small amount of Zn as an essential trace nutrient. Zn concentrations were chosen to cover variations recorded by Sáinz and Ruiz, (2006) in the salt marshes of the joint estuary of the Tinto and Odiel Rivers.
At the beginning of the experiment, 1 l of appropriate solution was placed in each tray (Hoagland al 20% + ZnSO₄·7H₂O) to a depth of 1 cm. During the experiment, the levels of trays were monitored and topped up to the marked level with 20% Hoagland’s solution (without additional ZnSO₄·7H₂O) to limit the change of Zn concentration caused by water evaporation from the nutrient solution. Also, the entire solution (including ZnSO₄·7H₂O) was changed every three days.

2.3. Growth analysis

At the beginning and the end of the experiment (after 50 days of treatment) three and five entire plants, respectively, from each treatment were dried at 80ºC for 48 h and weighed. Also, before and after the Zn treatment, the number and height of all fully developed tillers were measured.

The relative growth rate (RGR) in ash-free dry mass of whole plants was calculated using the formula:

\[
RGR = (\ln B_f - \ln B_i) \cdot \frac{1}{D} \text{ (g g}^{-1} \text{ day}^{-1})
\]

where \( B_f \) = final dry mass, \( B_i \) = initial dry mass (an average of the three plants from each treatment dried at the beginning of the experiment) and \( D \) = duration of experiment (days).

2.4. Gas exchange

Measurements were taken on random, fully developed photosynthetic tillers (n =
10, two measurements per plant) using an infrared gas analyser in an open system (LI-6400, Li-Cor Inc., Lincoln, NE, USA) after 50 days of treatment. Maximum net photosynthetic rate (A), intercellular CO₂ concentration (Cᵢ) and stomatal conductance to CO₂ (Gₛ) were determined at CO₂ concentration of 400 μmol CO₂ mol⁻¹ air, temperature of 25-30°C, 42.4 ± 0.4% relative humidity and a photon flux density of 1000 μmol m⁻² s⁻¹ once a steady-state was reached. A, Cᵢ and Gₛ were calculated using standard formulas of Von Caemmerer and Farquhar (1981). Photosynthetic area was approximated as the area of a cylinder. Intrinsic water use efficiency (WUEᵢ) was calculated as the ratio between A and Gₛ.

2.5. Tiller water content

Tiller water content (TWC) was calculated after 50 days of treatment as (n = 5, one measurement per plant):

\[ TWC = \frac{FW - DW}{FW} \times 100 \]

where FW is the fresh mass of the tillers and DW is the dry mass after oven-drying at 80°C for 48 h.

2.6. Photosynthetic pigments

At the end of the experimental period, photosynthetic pigments in fully developed, photosynthetic tillers (n=5) from each treatment were extracted using 0.05 g of fresh material in 10 ml of 80% aqueous acetone. After filtering, 1 ml of the
suspension was diluted with a further 2 ml of acetone and chlorophyll a (Chl \( \text{a} \)), chlorophyll b (Chl \( \text{b} \)) and carotenoid (C\( \times+c \)) contents were determined with a Hitachi U-2001 spectrophotometer (Hitachi Ltd., Japan) using three wavelengths (663.2, 646.8 and 470.0 nm). Concentrations of pigments (\( \mu g \text{ gfw}^{-1} \)) were obtained through calculation following Lichtenthaler (1987).

2.7. Measurement of chlorophyll fluorescence

Chlorophyll fluorescence was measured using a portable modulated fluorimeter (Mini-PAM, Heinz Walz, Germany) after 50 days of treatment, in tillers similar to those used previously. Measurements were made on each plant in the five zinc treatments (\( n = 10 \), two measurements per plant). Light and dark-adapted fluorescence parameters were measured at dawn (stable 75 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) ambient light) and at midday (1500 \( \mu \text{mol m}^{-2} \text{s}^{-1} \)) to investigate whether zinc concentration affected the sensitivity of plants to photoinhibition (Qiu et al., 2003).

Plants were dark-adapted for 30 minutes using leaf-clips designed for this purpose. The minimal fluorescence level in the dark-adapted state (\( F_0 \)) was measured using a modulated pulse (<0.05 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) for 1.8 \( \mu \text{s} \)) too small to induce significant physiological changes in the plant (Schreiber et al., 1986). The data stored were an average taken over a 1.6 seconds period. Maximal fluorescence level in this state (\( F_m \)) was measured after applying a saturating actinic light pulse of 10000 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) for 0.8 s (Bolhår-Nordenkampf and Öquist, 1993). The value of \( F_m \) was recorded as the highest average of two consecutive points. Values of the variable fluorescence (\( F_v = F_m - F_0 \)) and maximum quantum efficiency of PSII photochemistry (\( F_v/F_m \)) were
calculated from $F_0$ and $F_m$. This ratio of variable to maximal fluorescence can be used to quantify photoinhibition (Maxwell and Johnson, 2000).

The same tiller section of each plant was used to measure light-adapted parameters. Steady state fluorescence yield ($F_s$) was recorded under ambient light conditions. A saturating actinic light pulse of 10000 µmol m$^{-2}$ s$^{-1}$ for 0.8 s was then used to produce the maximum fluorescence yield ($F_m'$) by temporarily inhibiting PSII photochemistry.

Using fluorescence parameters determined in both light- and dark-adapted states, the following were calculated: quantum efficiency of PSII ($\Phi_{\text{PSII}} = (F_m' - F_s) / F_m'$) (Genty et al., 1989); photochemical quenching ($qP = (F_m' - F_s) / (F_m' - F_0')$, where $F_0'$ corresponds to open reaction center traps in the light-acclimated state), and non-photochemical quenching ($\text{NPQ} = (F_m - F_m') / F_m'$, Schreiber et al., 1986). Photochemical quenching gives an indication of the proportion of PSII reaction centres that are open (Maxwell and Johnson, 2000).

2.8. Chemical analyses of plant tissue samples

In accordance with protocols of Mateos-Naranjo et al. (2008), at the end of the experiment, tiller and root samples were dried at 80ºC for 48 h and ground. Tillers and roots were carefully washed with distilled water before any further analysis. Then, 0.5 g samples from tillers and roots (taken from five plants per treatment) were digested in triplicate with 6 ml HNO$_3$, 0.5 ml HF and 1 ml H$_2$O$_2$. Ca, Mg, K, P, Na and Zn concentrations in tillers and roots were measured by inductively coupled plasma (ICP) spectroscopy (ARL-Fison 3410, USA). Total N and C concentrations were determined for undigested dry samples with an elemental analyzer (Leco CHNS-932, Spain).
2.9. Statistical analysis

Statistical analysis was carried out using Statistica v. 6.0 (Statsoft Inc.). Pearson coefficients (r) were calculated to assess correlation between different variables. Data were analysed by means of a one-way analysis of variance (F-test). Data were first tested for normality with the Kolmogorov-Smirnov test and for homogeneity of variance with the Brown-Forsythe test. Significant test results were followed by Tukey tests for identification of important contrasts. Differences between measurements of fluorescence at dawn and midday were compared by the Student test (t-test).

3. Results

3.1. Growth

Total dry mass of plants under 100 mmol l\(^{-1}\) Zn was lower than for all the other treatments except that of 60 mmol l\(^{-1}\) Zn (Anova, P < 0.05; Fig. 1A). Compared to the control, the reduction in total dry mass for 100 mmol l\(^{-1}\) Zn was 38% after 50 days of treatment (Fig. 1A).

A similar trend was reported for RGR (Anova, P < 0.05; Fig. 1B) and this was correlated with the reduction in the number of tillers (r = 0.97, P < 0.01; Fig. 1C) but not with mean height of tillers. However, mean height of tillers was also smaller in 100 mmol l\(^{-1}\) Zn treatment than in control (Anova, P < 0.05; Fig. 1D). Compared to the control, the reduction in RGR for 100 mmol l\(^{-1}\) Zn treatment was 21% (Fig. 1B).
3.2. Gas exchange

Net photosynthetic rate (A), stomatal conductance (Gs) and intercellular CO₂ concentration (Ci) did not vary with zinc treatments, with values around 12 µmol CO₂ m⁻² s⁻¹, 0.62 mol H₂O m⁻² s⁻¹ and 350 µmol CO₂ mol⁻¹ air respectively (Table 1).

Similarly, Zn increment did not affect intrinsic water use efficiency (WUEᵢ) and tiller water content (TWC) of J. acutus after 50 days of treatment, with around 20 µmol CO₂ mol⁻¹ H₂O and 75% respectively (Table 1).

3.3. Photosynthetic pigments

Pigment concentrations (Chl a, Chl b and Cₓ+c) decreased significantly with Zn concentration (Chl a: r = -0.6, P < 0.05; Chl b: r = -0.68, P < 0.05; Cₓ+c: r = -0.74, P < 0.5; Fig. 2A-C). However, only in plants grown at 100 mmol l⁻¹ Zn there was a significant reduction compared to the control treatment (Anova, P < 0.05), with a mean reduction ca. of 30% for all photosynthetic pigments.

3.4. Chlorophyll fluorescence

$F_v/F_m$ values at dawn were uniformly high at all external Zn concentrations, with values around 0.84 (Fig. 3A). $F_v/F_m$ at midday were always lower than at dawn (t-test, P < 0.05), probably because of the lower $F_m$ at midday than at dawn (data not presented). $F_v/F_m$ at midday did not show differences among treatments (Anova, P > 0.05).
\[ \Phi_{\text{PSII}} \] at dawn and at midday did not vary with Zn concentration, but values at midday were lower than at dawn in all treatments (t-test, P < 0.05; Fig. 3B).

Finally, NPQ showed no relationship with Zn concentration at dawn, whereas at midday it increased compared to the control when the plants were exposed to external concentrations of 30 mmol l\(^{-1}\) Zn or higher (Anova, P < 0.05; Fig. 3C).

3.5. Chemical analyses of plant tissue samples

At the end of the experiment, tissue Zn concentration was greater in roots than in tillers (t-test, P < 0.05). Tillers Zn concentration increased gradually with external Zn concentration (r = 0.91, P < 0.01). The trajectory of Zn concentration in roots was different, showing an increment which was marked from 0 to 10 mmol l\(^{-1}\) Zn but gentler from 10 to 60 mmol l\(^{-1}\) Zn (Anova, P < 0.05; Fig. 4A). In contrast, roots and tillers Ca, K, Mg and P concentrations showed no significant overall response to Zn concentration, although roots and tillers Ca and Mg concentrations were lower at the highest level of zinc than in control (Anova, P < 0.01; Fig. 4B, F). Contrary, root K and P concentrations were lower in absence of zinc than in the rest of treatments (Anova, P < 0.01; Fig. 4D, E). On the other hand, tissue Na concentration in roots was higher than in tillers, increasing with external Zn concentration in both tissues (r = 0.98, P < 0.01; r = 0.96, r = 0.01, for roots and tillers respectively; Fig. 4C).

Finally, C/N ratio was higher in roots than in tillers and this ratio decreased in presence of zinc in the nutrient solution for both tissues (Fig. 5), with little difference among Zn treatments.

4. Discussion
The research on biological resources which could be used as bio-tools for managing heavy metal pollution is one of the fundamental guidelines for the design and development of effective methodologies for environmental remediation. Hence, the location of species with a high capacity for metal-accumulation and for growth under metal-polluted conditions can be of paramount importance for the remediation of metal pollution (Tripathi et al., 2007; Zhang et al., 2010).

Our experiment showed that *J. acutus* demonstrated hypertolerance to zinc stress, since all plants were able to survive even with external Zn concentrations as high as 100 mmol l\(^{-1}\). Furthermore, *J. acutus* plants did not show any visible Zn toxicity symptoms such as chlorosis, necrosis or a strong growth inhibition even at concentrations of zinc in *J. acutus* above-ground tissues of 560 mg Kg\(^{-1}\). This zinc concentration is higher than the upper toxic levels of 100-500 mg Kg\(^{-1}\) dry mass considered for high plants (Kabata-Pendias and Pendias, 2001). This tolerance is higher than that reported for other species of genus *Juncus*, such *J. articulatus*, which showed no live leaf biomass at Zn concentration of 0.3-1 mmol l\(^{-1}\) (Matthews et al., 2004). Furthermore, hypertolerance of *J. acutus* was supported by the high value of the effective concentration of Zn (EC50, substrate Zn concentration resulting in 50 percent biomass reduction; Paschke et al., 2000), greater than 100 mmol l\(^{-1}\) Zn. At this concentration, *J. acutus* showed a 38 percent of biomass reduction after 50 days of treatment. *J. acutus* EC50 value is considerably higher than those reported by several authors for many different species. For example, Paschke et al. (2000, 2006) found plant EC50 values of 1.2-3.4 mmol l\(^{-1}\) Zn for five reclamation grass species and six restoration forbs used for restoration of contaminated areas. In the current experiment, RGR underwent only a 21% reduction in plants grown at 100 mmol l\(^{-1}\) Zn. This
decrease was attributed to a reduction in the number of tillers rather than to a reduction in the mean height of tillers. This fact indicated that *J. acutus* would be able to maintain the state of development of its tillers regardless of the external Zn concentration, as indicated by the few differences between different treatments in total height of tillers. Compared with our results, Matthews et al. (2004) found an important total biomass reduction by zinc treatment at 0.7 mmol l\(^{-1}\) in *Juncus effusus*, a concentration considerably lower than those used in our experiment. Moreover, Stefani et al. (1991) found that initial growth of seedlings of *J. acutus* was strongly inhibited by Pb concentrations from 0.00195 mmol l\(^{-1}\) upwards, and by Cu and Cd concentration from 0.00012 mmol l\(^{-1}\), but these specific metal discrepancies could be attributed to different tolerance mechanisms.

On the other hand, tolerant plants could be classified into plants that tolerate a high uptake of metals in roots but avoid their transport to above-ground tissues, and plants that accumulate metals and preferentially transport metals to aerial parts (Pollard et al., 2002). In our glasshouse experiment, Zn levels were much higher in *J. acutus* subterranean structures than in the aerial structures, reaching values ca. 2500 mg Kg\(^{-1}\) in the roots. These results revealed that *J. acutus* could have the basic characteristics of a tolerant plant with high capacity for the phytostabilization of metal in its belowground structures. In accordance with this, Fitzgerald et al. (2003) found that the roots of marsh plants overall accumulate more metals than the above-ground biomass. The lower Zn concentration in tillers of *J. acutus* compared to that in roots could be related to the development of mechanisms such as compartmentation, which would control ion transport into tillers, thereby improving plant tolerance to heavy metals. This species may have accumulated most Zn in the roots to minimize Zn translocation to aboveground tissues. The sequestering of metals into tissue or cellular compartments,
which are less sensitive to such metals, has been described as a tolerance mechanism (Kabata-Pendias and Pendias, 2001; Weis and Weis, 2004) that entails restriction of both upward movement into shoots (avoidance mechanism) and translocation of excess metals into leaves (Verkleij and Schat, 1990). However, when Zn is present in an extremely high concentration in the nutrient solution, it can be translocated from the roots and accumulated within the shoots (Kabata-Pendias and Pendias, 2001), which could explain the Zn increase in the tops of *J. acutus*.

Metal hypertolerance in plants has been described as an ecophysiological adaptation to metalliferous environments (Evangelou et al., 2004). In our experiment, the analysis of physiological measurements of *J. acutus* corroborated this idea because neither WUEi, TWC, nor A were affected by Zn concentration, even when it was as high as 100 mmol l⁻¹. Vaillant et al. (2005) reported that the photosynthetic activity of four *Datura* species decreased at 2.5 mmol l⁻¹ Zn in nutrient solution. Mateos-Naranjo et al. (2008) and Cambrollé et al. (2013) reported that other marshes plants, such as *Spartina densiflora* and *Limoniastrum monopetalum*, showed reductions in A at external Zn concentrations of 10 and 60 mmol l⁻¹, respectively. Similarly, there were not any effects whatsoever of Zn on Gs and Ci. Although net photosynthetic rates depend on mesophyll conductance and carboxylation capacity of Rubisco apart from stomatal conductance (Flexas et al., 2008; Perez-Martín et al., 2009), the invariable A across the whole range of external Zn indicated that the photosynthetic apparatus of *J. acutus* could be able to accommodate to prolonged exposure to high external zinc concentration, this involving considerable physiologic plasticity. In fact, $F_v/F_m$ at dawn and midday did not change across the same range of external Zn, this ratio being commonly used to quantify photoinhibition (Maxwell and Johnson, 2000), a phenomenon that affects photosynthetic productivity and, consequently, plant growth (Melis, 1999). Therefore,
the long-term effects of the highest Zn concentration on the growth rate of *J. acutus* could be due to the different development of the photosynthetic area rather than to variations in net photosynthetic rate. Hence, similar rates of CO₂ assimilation could be more than compensated for by a greater photosynthetic area in low Zn concentration. This response might provide positive feedback, since larger photosynthetic areas would induce higher growth rates which would in turn induce more photosynthetic area, amplifying the difference between plants at different zinc concentrations over time. Thus, in our experiment, the largest differences in RGR were related to variations in the number of tillers, which might be related to differences in photosynthetic area and hence to reduction in light interception. In line with our results, Delperee and Lutts (2008) also found that growth inhibition was not correlated with CO₂ assimilation rate for *Solanum lycopersicum* under cadmium stress conditions. This was explained by the presence of several mechanism of tolerance related with oxidative stress control and the protection of photosystems. It is possible that *J. acutus* used the same protection system. In this respect, the hypertolerance of *J. acutus* to Zn stress was also reflected in the integrity and functionality of its photochemical apparatus. Several studies have reported a direct effect of zinc on the photosynthetic electron transport chain (Vaillant et al., 2005; Mateos-Naranjo et al., 2008), which may be associated with a substantial stress response. Our data showed that *Fv/Fm* values were always lower at midday than at dawn, a fact that indicated that *J. acutus* experienced some degree of dynamic photoinhibition at the higher light flux. Several authors have defined dynamic photoinhibition as a reversible mechanism controlling the dissipation of excess luminous energy by means of thermal dissipation (NPQ), which is in agreement with the greater NPQ at midday than at dawn in our data. This was supported by the lower Φ<sub>PSII</sub> at dawn than at midday, a decrease due to the increase in NPQ, which indicates
that the plants dissipate light as heat, thereby protecting the leaf from light-induced
damage (Maxwell and Johnson, 2000). Dawn values of $F_v/F_m$ were close to optimal
values for unstressed plants (approximately 0.84; Bjorkman and Demmig, 1987), this
fact revealing no presence of chronic and irreversible photoinhibition.

On the other hand, the reduction in the absorption of essential mineral elements
has been described as one of the effects of heavy metals on plants (Chaney, 1993;
Kabata-Pendias and Pendias, 2001). In this regard, our mineral nutrient analyses
indicated that the presence of zinc in nutrient solution did not generate large nutritional
imbalance in $J. \text{ acutus}$ plants, especially in tillers tissues, although root and tillers Ca
and Mg concentrations were lower at the highest zinc level. The interactions Zn-Ca and
Zn-Mg have been previously described by several authors (Kabata-Pendias and Pendias,
2001). Thus, the reduction in Mg concentration in tillers could be linked with a
decrease in chlorophyll content recorded in this experiment, since the most familiar role
of Mg in photosynthesis is as the central atom of the chlorophyll molecule (Shaul,
2002). Finally, Na concentration for tillers and roots increased with external Zn
concentration. Redondo-Gómez et al. (2011) determined that the accumulation of Na in
the tissues of $\text{Spartina densiflora}$ favored recovery of the photosynthetic apparatus of
this species against zinc excess. This result is linked with the high integrity showed by
photosynthetic apparatus of $J. \text{ acutus}$ to Zn stress.

5. Conclusions

$J. \text{ acutus}$ shows a high tolerance to zinc-induced stress, as proved the fact that all
plants were able to survive and did not show any visible Zn toxicity symptoms, such as
chlorosis, necrosis or a strong growth inhibition at concentrations up to 100 mmol l$^{-1}$
Zn. Likewise, unaffected photosynthesis and efficiency of PSII photochemistry apparatus might indicate that *J. acutus* is not experiencing metal toxicity, despite the fact that Zn concentrations recorded in its tillers tissues (> 500 mg Kg⁻¹) were greater than toxicity thresholds recorded for plants. Furthermore, Zn excess did not affect water relations of this species and overall absorption of essential mineral elements. All these results suggest that *J. acutus* is a hypertolerant species to zinc. Moreover, the capacity of this species to accumulate great amount of Zn in its roots (> 2500 mg Kg⁻¹ Zn) could be accounted for by the development of such mechanisms as compartmentation, which could control the ion transport into tillers, thereby improving its tolerance to Zn.

Consequently, the hypertolerance to zinc proved by these results, together with its ability to establish in a wide variety of ecosystems, reflect that this species is suitable as a phytostabilizer for revegetation of Zn-contaminated lands.
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References


**Figure captions**

**Fig. 1.** Growth analysis of *Juncus acutus* in response to treatment with a range of Zn concentrations for 50 d. Total dry mass (A); relative growth rate, RGR (B); number of tillers (C) and mean height of tillers (D). Values represent mean ± SE, n = 5. Different letters indicate means that are significantly different from each other (Tukey test, P < 0.05).

**Fig. 2.** Chlorophyll a, Chl a (A); Chlorophyll b, Chl b (B) and carotenoids, Cx+c (C) concentrations in randomly selected, fully developed photosynthetic tiller of *Juncus acutus* in response to treatment with a range of Zn concentrations for 50 d. Values represent mean ± SE, n = 5. Different letters indicate means that are significantly different from each other (Tukey test, P < 0.05).

**Fig. 3.** Maximum quantum efficiency of PSII photochemistry, $F_{v}/F_{m}$ (A); quantum efficiency of PSII, $\Phi_{PSII}$ (B) and non-photochemical quenching, NPQ (C) at dawn (○) and at midday (●) in randomly selected, fully developed photosynthetic tillers of *Juncus acutus* in response to treatment with a range of Zn concentrations for 50 d. Values represent mean ± SE, n = 10. Different letters indicate means that are significantly different from each other (Tukey test, P < 0.05).

**Fig. 4.** Concentration of Zn (A); calcium, Ca (B); sodium, Na (C); potassium, K (D); phosphorus, P (E) and magnesium, Mg (F) in tillers (○) and roots (●) of *Juncus acutus* in response to treatment with a range of Zn concentrations for 50 d. Values represent mean, n = 5. Different letters indicate means that are significantly different from each other (Tukey test, P < 0.05).

**Fig. 5.** C/N ratio for tillers (○) and roots (●) of *Juncus acutus* in response to treatment with a range of Zn concentrations for 50 d. Values represent mean, n = 5. Different
letters indicate means that are significantly different from each other (Tukey test, $P < 0.05$).
Fig. 1.

Growth analysis of *Atriplex halimus* in response to treatment with a range of Cu concentrations over 20 d. Total dry mass (above- and belowground biomass) (A), relative growth rate, RGR (B), total leaf area (C) and individual leaf area. Values represent mean±SE, n=6. Different letters indicate means that are significantly different from each other (Tukey test, p<0.05).
Net photosynthetic rate, AN (A), stomatal conductance, gs (B), intercellular CO2 concentration, Ci (C) and water use efficiency, WUE (D) in randomly selected, fully expanded leaves of Atriplex halimus in response to treatment with a range of Cu concentrations over 20 days. Values represent mean±SE, n=12. Different letters indicate means that are significantly different from each other (Tukey test, p<0.05).
Fig. 3.

Maximum quantum efficiency of PSII photochemistry, \( F_a/F_m \) (A), quantum efficiency of PSII, \( \Phi_{\text{PSII}} \) (B) and non-photochemical quenching (C) at midday (●) and at dawn (○) in randomly selected, fully expanded leaves of *Atriplex halimus* in response to treatment with a range of Cu concentrations over 20 days. Values represent mean±SE, \( n=10 \). Different letters indicate means that are significantly different from each other (Tukey test, \( p<0.05 \)).
Total, chronic and dynamic photoinhibition in randomly selected, fully expanded leaves of *Atriplex halimus* in response to treatment with a range of Cu concentration over 20 days. Values represent mean±SE, n=10.

Fig. 4.

Total copper, Cu (A), total sodium, Na (B), total potassium, K (C), total phosphorous, P (D), total magnesium, (E) and total nitrogen (F) concentrations on a dry weight basis for above- (○), and belowground biomass (●) of *Atriplex halimus* in response to treatment with a range of Cu concentrations over 20 days. Values represent mean, n=6. Different letters indicate means that are significantly different from each other (Tukey test, p<0.05).

Fig. 5.