Differential freezing resistance and photoprotection in C₃ and C₄ eudicots and grasses

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Abstract

Globally, C₄ plants dominate hot, open environments, but this general pattern is underpinned by important differences in the biogeography of C₄ lineages. In particular, the species richness of C₄ Poaceae (grasses) increases strongly with increasing temperature, whereas that of the major C₄ eudicot group Chenopodiaceae correlates positively with aridity. Freezing tolerance is a crucial determinant of biogeographical relationships with temperature and is mediated by photodamage and cellular disruption by desiccation, but little is known about differences between C₄ families. This study hypothesized that there is a greater risk of freezing damage via these mechanisms in C₄ Poaceae than Chenopodiaceae, that freezing protection differs between the taxonomic groups, and that freezing tolerance of species is linked to arid habitat preference. Chlorophyll fluorescence, water relations, and freezing injury were compared in four C₃ and six C₄ species of Poaceae and Chenopodiaceae from the same Mongolian flora. Contrary to expectations, freezing-induced leaf mortality and photodamage were lower in Poaceae than Chenopodiaceae species, and unrelated to photosynthetic pathway. The freezing resistance of Poaceae species resulted from constitutive protection and cold acclimation and an ability to protect the photosynthetic apparatus from photodamage. Freezing protection was associated with low osmotic potential and low tissue elasticity, and freezing damage was accompanied by electrolyte leakage, consistent with cell-membrane disruption by ice. Both Chenopodiaceae and Poaceae had the potential to develop cold acclimation and withstand freezing during the growing season, which conflicted with the hypothesis. Instead, freezing tolerance was more closely associated with life history and ecological preference in these Mongolian species.

Key words: C₃ photosynthesis, C₄ photosynthesis, Chenopodiaceae, cold acclimation, freezing tolerance, photodamage, Poaceae, water relations.

Introduction

The CO₂-concentrating mechanism of C₄ plants gives them a competitive advantage over those with the C₃ photosynthetic pathway under high light and temperature and under CO₂ limitation caused by atmospheric CO₂ depletion or water deficits (Sage et al., 1999a). C₄ plants represent only 3% of terrestrial plant species, but dominate all tropical and subtropical grasslands, most warm temperate grasslands, deserts, and most disturbed landscapes in warmer regions of the world (Sage et al., 1999b). Together, these ecosystems contribute approximately 20% of terrestrial carbon fixation (Lloyd and Farquhar, 1994). The C₄ pathway is distributed across >60 lineages in 17 families, and about 7000–8000 species of flowering plants (Sage et al., 2011). About 6000 C₄ species are grasses and sedges, with only about 1200 C₄ eudicots. Within eudicots, the family Chenopodiaceae (chenopods) contains the largest number of C₄ species (Sage et al., 1999b). C₄ grasses dominate the North American prairies (Ehleringer et al., 1997), African savannas (Batanouny...
et al., 1988), and desert and semidesert regions in Australia (Hattersley, 1983), while C4 members of the Chenopodiaceae are infrequent. However across the vast Eurasian steppe region, exemplified by the Mongolian Plateau, the situation is quite different. Native Mongolian C4 plants from the Chenopodiaceae and Poaceae make up 50 and 30%, respectively, of the total C4 species. C4 grasses are most common in the steppe zones, with C4 chenopods found largely in the arid desert zone. Moreover, the species richness of these C4 lineages show contrasting associations with environmental variables (Pyankov et al., 2000).

The distributions of C4 Poaceae and Chenopodiaceae species across the Mongolian plateau follow patterns similar to those seen at the global scale (Ehleringer et al., 1997). The relative abundance of C4 grass species declines strongly with falling temperature, whilst the equivalent correlation for C4 chenopod species is weak (Pyankov et al., 2000). Indeed, C4 chenopods may survive at high altitudes close to the permanent frost line. Rather than being limited by low temperature, C4 chenopod abundance correlates most strongly with aridity, implying that drought and frost tolerance are linked in these species. In fact, frost and drought exert similar desiccating effects on leaf tissues because extracellular ice formation extracts water from cells, leaving behind high concentrations of solutes that damage cell membranes. Given this common mechanism of damage, drought-tolerant species should better tolerate freezing than species adapted to more mesic habitats. Constitutive protection mechanisms would be expected in any environment, whereas any drought acclimation responses would also need to be induced by low temperatures to protect plants from freezing.

Freezing is an important abiotic factor limiting the geographical distribution and growth of plants in many regions of the world (Levitt, 1980). Cold acclimation or freezing resistance via osmotic adjustment is induced by exposure to chilling temperatures in the range 0–15°C (Larcher, 2003; Liu and Osborne, 2008), with failure to develop freezing resistance allowing ice to damage cellular membranes. The combination of water relations and electrolyte leakage therefore provides a good means of describing freezing resistance in plants (Neuner and Bannister, 1993; Pearce, 2001). Chilling and freezing temperatures also limit enzymic processes and the capacity of the photosynthetic apparatus for dissipating absorbed energy through photochemistry (Demming-Adams and Adams, 1992). If excess energy is not dissipated, the photosynthetic machinery can be damaged, resulting in impaired PSII activity (Huner et al., 1993). Therefore, protection of the photosynthetic apparatus in plant leaves is considered to be critical for low temperature tolerance.

Despite this general understanding of the physiological basis of cold tolerance, the mechanisms underpinning the differential geographical distributions of C4 grasses and chenopods are not well understood. This study hypothesized that the observed differences in biogeography are associated with differences in known mechanisms of chilling and freezing resistance, including the protection of the photosynthetic pathway at low temperatures. By comparing Mongolian grass and chenopod species, four questions were addressed (1) Does freezing cause greater damage in Poaceae than Chenopodiaceae? (2) Is the freezing damage greater in C4 than C3 species? (3) Does the protection mechanism differ between Poaceae and Chenopodiaceae? (4) Given the known involvement of desiccation in freezing damage, do species originating from more arid habitats show greater freezing resistance?

Materials and methods

Plant materials and environmental conditions

Plant species of Poaceae and Chenopodiaceae used in this experiment were from Inner Mongolia in the south of the Mongolian Plateau (39° 6’–49° 48’ N 101° 36’–122° 24’ E). Seeds of Haloxylon ammophila were collected from the desert ecosystem at Dengkou Xian (40° 57’ N 106° 26’ E, altitude 1037 m) (Table 1). Meteorological data from this area (1960–2010) show a desert climate, with mean annual temperature and average January and July temperatures of 7.8, –11.6, and 26.6°C, respectively. The frost-free period is about 168 days, and mean annual precipitation is 103 mm. Seeds of the other nine species were collected from steppe vegetation at Zhengliao Qi (43° 56’ N, 116° 08’ E, altitude 1103 m) (Table 1). Meteorological data from this region (1960–2010) show a temperate arid and semiarid climate, with mean annual temperature and average January and July temperatures of 1.8, –17.9, and 18.7°C, respectively. The frost-free period is about 120 days, and mean annual precipitation is 378 mm. The main habitats in this ecosystem are shifting dunefixed dune, lowland meadow, and wetland.

Collected seeds were germinated in sterile nutrient agar for 1 week, and 16 plants of each species were transferred to pots (height × diameter, 18 × 13 cm) containing four parts high nutrient compost (Levington M3, Scotts UK Professional, Suffolk, UK) to one part sand (Play Sand, William Sinclair Horticulture, Lincoln, UK) and one part Perlite (Esoteric Hydroponics, Guildford, UK). The plants were grown in a controlled environment chamber and watered daily with a 40% solution of Long Ashton solution to maintain a moist, nutrient-rich soil continuously throughout the experiment. Plants were maintained under a 14/10 h light/dark cycle with a photosynthetic photon flux density (PPFD) of 600 μmol m−2 s−1 measured at plant height, day/night temperatures of 25/15°C, and 60/80% relative humidity. These control conditions were maintained for 14 weeks. At the initiation of the experiment, eight plants of each species were transferred to an identical growth chamber with a day/night temperature of 15/5°C for 20 d (chilling pre-treatment), and the other half were maintained under pre-treatment, control conditions. The transfer of plants was staggered, so that one replicate of two species was transferred each day. Plants were exchanged between cabinets mid-way through the experiment, so that any effect of cabinet was not confounded directly with treatment. The design meant that, on average overall, half the replicates for each species received the chilling treatment in one cabinet and half in the other.

Maximum quantum efficiency of PSII

On the 20th day of the chilling pre-treatment, chlorophyll fluorescence was measured using an integrated open gas-exchange and chlorophyll fluorescence system (LI-6400–40, LI-COR Biosciences, Lincoln, NE, USA). After 15 min of dark adaptation, the leaves were exposed to a weak modulated beam to determine the zero fluorescence level (F0), and then a saturating pulse to obtain the maximum fluorescence level (Fm). Variable fluorescence (Fv) is the difference between Fm and F0, which was used to calculate Fv/Fm, the maximum quantum efficiency of PSII.

Pressure and volume measurements

Pressure/volume curves were generated for four individuals per species from each treatment at the end of the 20-d pre-treatments using...
Table 1. Species involved in current experiments: A, annual; F, forb; G, grass; P, perennial; S, shrub.

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Abbreviation used in figures</th>
<th>Photosynthetic pathway</th>
<th>Life history and life form</th>
<th>Common habitats on the Mongolian Plateau</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chenopodiaceae</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ceratoides arborescens (Losina-Losinskaja) C. P. Tsien and C. G. Ma.</td>
<td>Ca</td>
<td>C₃</td>
<td>P, S</td>
<td>Sandy steppe, sandy slopes</td>
</tr>
<tr>
<td>Conspernum heptapotamicum Iljin</td>
<td>Ch</td>
<td>C₃</td>
<td>A, F</td>
<td>Shifting and semi-shifting sand dunes in sandy grassland</td>
</tr>
<tr>
<td>Haloxylon ammodendron (C. A. Mey) Bunge Schrad.</td>
<td>Ha</td>
<td>C₄</td>
<td>P, S</td>
<td>Desert, in saline sands</td>
</tr>
<tr>
<td>Kochia prostrata (Linn.)</td>
<td>Kp</td>
<td>C₄</td>
<td>P, S</td>
<td>Sandy grassland, especially in sandy and loamy soils or stony soils</td>
</tr>
<tr>
<td>Salsola collina Pall. Poaceae</td>
<td>Sc</td>
<td>C₄</td>
<td>A, F</td>
<td>Disturbed land</td>
</tr>
<tr>
<td>Chloris gayana Kunth.</td>
<td>Cg</td>
<td>C₄</td>
<td>P, G</td>
<td>Naturalized exotic species, grown in pastures</td>
</tr>
<tr>
<td>Pennisetum clandestinum Hochst. ex Chiov.</td>
<td>Pc</td>
<td>C₄</td>
<td>P, G</td>
<td>Naturalized exotic species, grown in pastures</td>
</tr>
<tr>
<td>Cleistogenes squarrosa (Trin.) Keng</td>
<td>Cs</td>
<td>C₄</td>
<td>P, G</td>
<td>Desert steppe, especially in sandy and loamy soils; also found scattered in rocky habitats</td>
</tr>
<tr>
<td>Leymus chinensis (Trin.) Tzvel.</td>
<td>Lc</td>
<td>C₃</td>
<td>P, G</td>
<td>Steppe, in saline meadows, sand beds of river valleys</td>
</tr>
</tbody>
</table>

where $\Delta P$ is the change in turgor pressure and $\Delta RWC$ is the change in RWC. The maximum value of $\varepsilon$ across the observed values of $1 - RWC$ was taken as $\varepsilon_{\text{max}}$.

High-light freezing treatment and chlorophyll fluorescence measurement

After pressure/volume curve measurements, all plants were exposed to a high-light freezing treatment to test for constitutive freezing resistance (control pre-treatment plants) and to investigate whether cold acclimation had developed (chilling pre-treatment plants). The freezing treatment was designed to simulate a frost during the growing season in the natural environment on the Mongolian Plateau and was applied using a walk-in controlled environment cabinet (BDW 40, Conviron Controlled Environments). The treatment was applied to a single block of plants (one of each species × pre-treatment combination = 16 plants), and replicated on five consecutive days.

The protocol for each freezing event followed Osborne et al. (2008). Briefly, the root system of each plant was prevented from freezing by wrapping each pot in polythene, and immersing it in a water bath held at 15 °C. The plants were put into the cabinet at 14:00 h and exposed to 15 °C at a PPFD of 600 μmol m⁻² s⁻¹ until 19:00 h. The lights were then turned off, and the temperature was lowered gradually overnight at a rate of 4 °C per hour until 0 °C, after which the temperature was lowered more slowly to reach a minimum of −5 °C at 07:00 h, before dawn. The temperature was held constant at this level for 1 h, then the lights were turned on at 08:00 h to deliver a PPFD of 400 μmol m⁻² s⁻¹, and both temperature and PPFD were then ramped gradually upwards to reach 15 °C and 1200 μmol m⁻² s⁻¹ at 13:30 h.

After the high-light freezing treatment, three leaves for each plant were dark adapted for 15 min, before making $F'_m / F_m$ measurements.

### Key tissue water relations parameters were determined from plots of $-1/\Psi_{\text{leaf}}$ versus RWC, using a curve-fitting routine based on the template of Schulte and Hinckley (1985). A straight line was fitted via the stepwise addition of points from the lowest RWC to higher RWC to obtain the linear response of osmotic potential to RWC.

This permitted calculation of osmotic potential at full turgor ($\Psi_{\text{osm max}}$, MPa) by extending the regression line back to the $-1/\Psi$ axis. Relative water content and leaf water potential at the turgor-loss point ($\text{RWC*} 1$, MPa) were obtained at the intersection of the plots describing $-1/\Psi_{\text{leaf}}$ versus RWC and osmotic potential versus RWC (Turner, 1981).

Turgor pressures across the observed range of $1 - RWC$ were estimated from the difference between values of $\Psi_{\text{leaf}}$, on the non-linear curve and fitted data on the linear $1/\Psi$ versus $1 - \text{RWC}$ plot.Bulk modulus of elasticity ($\varepsilon_{\text{max}}$, MPa) was estimated from the slope of the linear regression of turgor pressure and symplastic relative water content ($R_s$) over the full range of positive turgor pressures (Tyree and Jarvis, 1982) using:

$$
\varepsilon = \Delta P/\Delta RWC^*(R_s)
$$

where $\Delta P$ is the change in turgor pressure and $\Delta RWC$ is the change in RWC. The maximum value of $\varepsilon$ across the observed values of $1 - RWC$ was taken as $\varepsilon_{\text{max}}$.
using an integrated open gas-exchange and chlorophyll fluorescence system, as already described.

Electrolyte leakage

Leaf injury caused by freezing was also assessed by the electrolyte leakage method described by Colombo et al. (1984). After the high-light freezing treatment, 15 freshly cut leaf discs (0.5 cm² each) were rinsed three times (2–3 min) with demineralized water and subsequently floated on 10 ml demineralized water. Electrical conductivity of the water after the freezing treatment (Cf) was measured after 24 h at room temperature using a conductivity meter (PCM1, Jenway Products, Leeds, UK). Before each measurement, the test tube was shaken vigorously. Total conductivity (Ct) was obtained after keeping the flasks in an oven (90 °C) for 2 h to kill the leaves. The temperature was then gradually lowered to 20 °C and held overnight. The electrolyte leakage of heat-killed leaves was then measured. The degree of freezing damage to leaves was assessed using relative conductivity (R = Cf/Ct).

Leaf freezing mortality

After the freezing treatment, the extent of leaf injury within the canopy was assessed for all plants exposed to the high-light freezing treatment. All dead leaves were cut off prior to the treatment, and the plants were returned to the control growth conditions after freezing. Over the subsequent 1–3 d, the total numbers of dead (>2/3 necrotic) and green leaves were counted. Leaf mortality was calculated as the number of dead leaves divided by the total number of leaves. For H. ammodendron, leaves are reduced to scales which cover the stem and here the succulent green stems serve a photosynthetic function. In this species, the visual assessment of freezing damage was based on colour changes of stems, by dividing the length of necrotic stem by the total stem length.

Statistical analysis

Mixed linear regression models (SPSS 16.0, Chicago, IL, USA) were fitted using photosynthetic type, chilling pre-treatment, family, and the interactions of chilling pre-treatment × photosynthetic type and chilling pre-treatment × family as fixed factors, and species as a random effect. The models were used to test whether values of leaf water status traits (DMC, ψ₀, εₘₐₓ, ψₑ), Fv/Fm, and leaf freezing injury (Rₑ and leaf mortality) differed between chilling and control (chilling pre-treatment), C₁ and C₄ species (photosynthetic type), and Poaceae and Chenopodiaceae (family). For freezing injury, the data from each replicate were transformed by taking their natural logarithms to stabilize heterogeneous variances.

Results

Maximum quantum efficiency of PSII

Fv/Fm was used to measure photodamage after 20 days of the chilling pre-treatment, but before the high-light freezing treatment. Values of Fv/Fm for the control plants were 0.79–0.85, indicating the presence of a fully functioning photosynthetic apparatus (Fig. 1A). There were no statistically significant decreases in Fv/Fm for the chilling pre-treatment or differences between families and photosynthetic types (Table 2). There were no considerable differences in the Fv/Fm of chilling pre-treatment plants among species, because the values of Fv/Fm for most species were above 0.78, suggesting no damage to PSII (Fig. 1A). Exceptional values of Fv/Fm for the chilling pre-treatment and the control Salsola collina plants were 0.74 and 0.76, respectively, with only a small difference between treatments (Fig. 1A). Neither chlorosis nor other leaf discoloration was observed in any species during exposure to chilling.

After the high-light freezing treatment, the values of Fv/Fm displayed different patterns, with statistically significant effects of family and chilling pre-treatment (P < 0.05) (Fig. 1B; Table 2). For Chenopodiaceae species, the freezing treatment caused a smaller decrease in Fv/Fm in the plants exposed to the chilling treatment (4–22%), than in the control plants (9–45%), relative to the values before freezing (Fig. 1B). The equivalent values for grasses were 6–11% for the chilling pre-treatment and 8–23% for the controls (Fig. 1B). These patterns suggested that: first, the chilling pre-treatment protected PSII against the damaging effects of freezing; and secondly, this effect was most pronounced in the Chenopodiaceae, as evidenced by a statistically significant family × pre-treatment interaction for Fv/Fm after freezing, relative to the value before freezing (Table 2). Generally, PSII showed a higher degree of constitutive protection against freezing in the Poaceae, irrespective of whether there was a
There was no significant overall effect of photosynthetic pathway, nor an interaction with the chilling treatment (Table 2).

Pressure/volume curve traits

In leaves exposed to the chilling pre-treatment, osmotic potential at full turgor ($\psi_p$) decreased significantly to more negative values for all species, irrespective of photosynthetic pathway or family ($P < 0.01$) (Table 2, Fig. 2A). However, on average, across all species, $\psi_p$ was only -0.1 MPa lower after the chilling pre-treatment than in control plants (Fig. 2A). There were no differences in $\psi_p$ between families and photosynthetic types (Table 2). Leaf water potential at the turgor loss point ($\psi_{tlp}$) showed similar patterns to $\psi_p$, with an average decrease of -0.1 MPa ($P < 0.01$) in the chilling pre-treatment (Table 2, Fig. 2B). Patterns of bulk modulus of elasticity ($\epsilon_{max}$) were significantly affected by the chilling pre-treatment ($P < 0.01$) and family ($P < 0.05$) (Table 2, Fig. 2C), but there was no effect of photosynthetic type and there were no interactions (Table 2). Average values of $\epsilon_{max}$ for Chenopodiaceae and Poaceae were 13.5 and 16.6 MPa in control plants but 10.5

![Fig. 2. Osmotic potential at full turgor ($\psi_p$) (A), water potential at the turgor loss point ($\psi_{tlp}$) (B), maximum bulk modulus of elasticity ($\epsilon_{max}$) (C) and dry matter content (DMC) (D) in response to 20 d chilling (filled bars) and control (open bars) pre-treatments in leaves of C$_3$ and C$_4$ Chenopodiaceae and Poaceae species. Abbreviations for species names are defined in Table 1. Values are mean ± SE for five individual plants.](https://academic.oup.com/jxb/article-abstract/64/8/2183/644116)
and 13.9 MPa after the chilling pre-treatment, with 17 and 22% reductions in Chenopodiaceae and Poaceae, respectively, in the chilled plants relative to the control ones. (Fig. 2C). The chilling pre-treatment decreased values of ε_{max}, and this is consistent with an increase in cell-wall elasticity under low temperature conditions (Fig. 2C). DMC was also significantly decreased by the chilling pre-treatment (Table 2; Fig. 2D). DMC was 7–33% and 1–14% less in Chenopodiaceae and Poaceae species in chilling pre-treatment plants compared to the control ones (Fig. 2D).

Leaf freezing injury

The high-light freezing treatment caused high leaf mortality in two C₃ species of Chenopodiaceae, *Agriophyllum pungens* and *Ceratoides arborescens*, killing 100 and 60% of the leaves, respectively, and in a C₄ species of Chenopodiaceae, *S. collina*, killing 75% of the leaf canopy (Fig. 3). For *Corispermum hep-tapotamicum*, a C₃ species of Chenopodiaceae, leaf mortality was 48 and 73% for chilling pre-treatment and control plants, respectively, displaying a cold acclimation effect (Fig. 3). By contrast, the C₄ Chenopodiaceae species *H. ammodendron* and *Kochia prostrata* and all of the C₄ Poaceae species exhibited significant resistance to the freezing treatment in both chilling pre-treated and control plants, with leaf mortality of 16–47%. The C₄ Poaceae species *Pennisetum clandestinum* and *Cleistogenes squarrosa* showed cold acclimation responses, with leaf mortality in the chilling pre-treatment 35% less than that in the controls. The C₃ Poaceae species *Leymus chinensis* displayed the lowest freezing leaf mortality in either chilling or control plants, at about 16% (Fig. 3). There were statistically significant effects of the chilling pre-treatment and family on leaf mortality, but no effect of photosynthetic type, and no interactions between factors (Table 2).

Electrolyte leakage rates (Rₑ) provided quantitative evidence of freezing injury to leaf cellular membranes when leaves were frozen to -5 °C in both chilling and control plants. If the photosynthetic type was ignored, there was a positive correlation between leaf freezing injury and Rₑ in Chenopodiaceae and Poaceae species across both the control and chilling treatments, with Rₑ explaining 61% of the variance in freezing leaf mortality (Fig. 4A). There was a strong correspondence between the visual assessments of leaf freezing injury and F_v/F_m measured immediately after freezing for all species across both the control and chilling pre-treatments, with F_v/F_m after freezing explaining 70% of the variance in freezing mortality (Fig. 4B).

The correspondence between cellular membrane damage and leaf mortality indicated that membrane damage was a critical element of leaf canopy injury. The correlation between Rₑ and ψ_{tip} was also close for all species in both the control and chilling pre-treatments, with ψ_{tip} explaining 57% of the variation in electrolyte leakage rates (P < 0.01) (Fig. 5). Overall, there was a significant effect of the chilling pre-treatment on Rₑ, but none of the other effects were statistically significant (Table 2).

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**Fig. 3.** Freezing leaf mortality of C₃ and C₄ plants after 20 d of chilling (filled bars) or control (open bars) pre-treatments followed by high-light –5 °C freezing events. Abbreviations for species names are defined in Table 1. Values are mean ± SE for eight individual plants.

**Fig. 4.** Relationships of electrolyte leakage rates of leaf cellular membranes versus freezing leaf mortality (r² = 0.61; n = 20; P < 0.001) (A), and the F_v/F_m of leaves after the freezing treatment versus freezing leaf mortality (B) (r² = 0.70; n = 20; P < 0.001), for Chenopodiaceae and Poaceae species in the chilling compared with the control pre-treatment. Values are mean ± SE for eight individual plants.
Poaceae are all perennials.

The exposure of plants to a chilling treatment drove photoprotection responses, which reduced photodamage during a subsequent high-light freezing event. This acclimation response was evident in both Chenopodiaceae and Poaceae species, irrespective of their photosynthetic type. However, when plants were grown under warm conditions prior to freezing and were not allowed to develop cold acclimation, the species of the Poaceae showed a greater degree of constitutive photoprotection. Chilling-induced photoprotection was more important within Chenopodiaceae. These results are consistent with prior reports of the effects of cold-acclimation on freezing responses (Strand and Öquist, 1988; Dai et al., 2007). However, there were no differences between species using C3 and C4 pathways.

Leaf freezing mortality was also higher in the Chenopodiaceae than the Poaceae, but exposure to chilling conditions induced a cold acclimation response that protected leaves against the subsequent high-light freezing event. As with photodamage, there were no differences in freezing damage between species using C3 and C4 photosynthesis. This finding, and the observation of greater leaf damage in Chenopodiaceae than Poaceae, conflicts with this study’s a priori expectations. Rather, it supports an alternative hypothesis that freezing resistance in species is more closely related to their ecological preferences and life history. Notably, the two Chenopodiaceae species with greatest freezing resistance are both perennials of arid habitats and the Poaceae are all perennials.

Physiological mechanisms of freezing resistance

The strong association between visible damage to leaves and electrolyte leakage suggests that cellular damage caused by ice formation was the primary mechanism of freezing injury. Damage may be caused directly by the physical disruption of cellular membranes by intracellular ice crystals. Alternatively, it may be driven by the lower water potential over extracellular ice than water at the same temperature, which extracts symplastic water, causing cellular dehydration and (eventually) plasmolysis (Tao and Li, 1993; Mitchell et al., 2008). Consistent with this dehydration mechanism, the present study found a positive correlation of $\psi_{tlp}$ with electrolyte leakage after the subsequent frost (Fig. 5); i.e. species with a low $\psi_{tlp}$ suffered less freezing damage. Since osmotic potential is the major cause of interspecific variation in the turf-growth point (Bartlett et al., 2012), this result suggests that constitutive differences in leaf osmotic potential among species are important determinants of their differential freezing resistance.

Cold acclimation also involved adjustments to leaf water relations, manifested as a decrease in $\psi_{tlp}$ and associated with a lowering of $\psi_{s}$, $\epsilon_{\max}$, and DMC. However, these adjustments are unlikely to form a major component of the cold acclimation response, since full equilibration of apoplastic water with extracellular ice generates a water potential of approximately $-6$ MPa (Améglio et al., 2001), and the present study found an osmotic adjustment $<0.25$ MPa. Instead, alternative acclimation mechanisms such as changes to membrane composition, the accumulation of dehydrin and ice-interacting proteins, and the stabilization of membranes by fructans (in grasses) may be more important (Sandve et al., 2011). Osmotic adjustment associated with chilling has been reported in a previous experiment on Mongolian grasses (Liu and Osborne, 2008) and other studies (e.g. Roberts and Knoerr, 1977; Tyree et al., 1978; Grossnickle, 1992).

The high constitutive freezing resistance in the Poaceae and two Chenopodiaceae species ($H.$ ammodendron and $K.$ prostrata) was also associated with a high $\epsilon_{\max}$. High values of $\epsilon_{\max}$ mean low tissue elasticity, which leads to large changes in leaf water potential for only small changes in water content. In the situation where leaf water potential is driven downwards by extracellular ice formation, this maintains tissue hydration as water potential declines (the ‘cell water conservation hypothesis’; Valentini et al., 1990; Bartlett et al., 2012). Indeed, high $\epsilon_{\max}$ and low $\psi_{tlp}$ are considered key facets of desiccation tolerance (Bartlett et al., 2012). However, cell water conservation only protects leaves at water potentials above the $\psi_{tlp}$ and at temperatures close to the freezing point (Valentini et al., 1990).

Ecology and photosynthetic pathway

Leaf freezing resistance for both C4 grasses and C4 Chenopodiaceae species fell within the range of C3 species across the two families, suggesting that the C4 pathway presented no inherent barrier to freezing resistance in either family. Despite the general finding of higher leaf freezing mortality in Chenopodiaceae than Poaceae species, some C3 Chenopodiaceae from the Mongolian Plateau ($H.$ ammodendron and $K.$ prostrata) had a high resistance to frost during the growing season. Since most species coexist in steppe
ecosystems at a similar latitude, differential freezing resistance cannot be attributed to climatic adaptation. Instead, two possible interpretations of these results may be put forward.

First, interspecific differences could represent differing ecological characteristics. The two Chenopodiaceae species with high freezing resistance were *H. ammodendron*, a perennial tree-like species distributed in the deserts of the Mongolian Plateau, especially in arid deserts with <100 mm annual precipitation (Pyankov et al., 2000), and *K. prostrata*, a perennial shrub-like species that naturally occupies sandy grassland or stony soils and has a high resistance to drought and salt. In contrast, the majority of remaining Chenopodiaceae species were annuals, which are opportunistic in ecosystems, taking advantage of pulses of water after rains or living in moist, disturbed habitats, and thus lack resistance to low water potentials.

Secondly, although cold acclimation is theoretically less effective in C₄ than C₃ plants due to the lower phenotypic plasticity of C₄ leaves (Sage and McKown, 2006), the present data have demonstrated that both C₄ Poaceae and Chenopodiaceae species can resist leaf freezing injury at temperatures of ~5 °C. This result is consistent with several previous field observations and controlled experiments that have documented the development of frost protection in some C₄ grass species during exposure to chilling (Rowley, 1976; Sage and Kubien, 2007; Liu and Osborne, 2008). Thus this study furthers understanding of the phenomenon by providing evidence for the mechanism of freezing resistance in eudicots, through an investigation of some C₄ Chenopodiaceae species from the Mongolian Plateau.

A striking feature of perennial C₄ plants in deserts and grasslands of the Mongolian Plateau is their presence in areas with large daily and annual temperature fluctuations and extremely low temperatures during winter (Pyankov et al., 2000). By contrast, the annual C₄ chenopod species *S. collina* is a succulent halophyte, occurring in saline and arid environments in steppe or disturbed land, which survives the winter as seeds (Liu et al., 2009). The successful protection of leaves from frost in the C₄ Chenopodiaceae species could therefore represent an adaptive response of above ground parts of plants to early frost in autumn or extremely cold winters in the steppe environment. The present findings suggest that this mechanism may reflect physiological plasticity and is an ecologically relevant strategy.

In conclusion, contrary to *a priori* expectations, leaf mortality and photodamage during a high-light freezing event were lower in Poaceae than Chenopodiaceae species and were unrelated to the photosynthetic pathway. The freezing resistance of C₄ Poaceae species was associated with a low turgor loss point, a low osmotic potential, and an ability to protect photosynthetic apparatus from damage by energy dissipation. However, despite this general difference between plant families, some C₄ Chenopodiaceae species originating from arid habitats also showed constitutive freezing tolerance. Freezing damage to leaves was mediated by electrolyte leakage consistent with intracellular ice formation and the desiccating effects of extracellular ice formation in tissues. Both freezing resistance and photoprotection were enhanced by cold acclimation, which involved only a slight lowering of the turgor loss point. In contrast, the leaves of species with constitutive resistance to freezing typically had a low tissue elasticity, which minimizes cellular water loss during extracellular ice formation. It is hypothesized that ecotypic differentiation between the Chenopodiaceae and Poaceae species with respect to chilling and freezing sensitivity may be interpreted in terms of physiological and ecological divergence among the families. This study demonstrated that responses to freezing events during the growing season are better explained by taxonomic and ecological factors than by the differential limitation of species with different photosynthetic pathways.

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