

## Research Article

### SPECIAL ISSUE: *Phragmites australis* in North America and Europe

# Maximal stomatal conductance to water and plasticity in stomatal traits differ between native and invasive introduced lineages of *Phragmites australis* in North America

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**Abstract.** The fitness costs of reproduction by clonal growth can include a limited ability to adapt to environmental and temporal heterogeneity. Paradoxically, some facultatively clonal species are not only able to survive, but colonize, thrive and expand in heterogeneous environments. This is likely due to the capacity for acclimation (*sensu stricto*) that compensates for the fitness costs and complements the ecological advantages of clonality. Introduced *Phragmites australis* demonstrates great phenotypic plasticity in response to temperature, nutrient availability, geographic gradient, water depths, habitat fertility, atmospheric CO<sub>2</sub>, interspecific competition and intraspecific competition for light. However, no *in situ* comparative subspecies studies have explored the difference in plasticity between the non-invasive native lineage and the highly invasive introduced lineage. Clonality of the native and introduced lineages makes it possible to control for genetic variation, making *P. australis* a unique system for the comparative study of plasticity. Using previously identified clonal genotypes, we investigated differences in their phenotypic plasticity through measurements of the lengths and densities of stomata on both the abaxial (lower) and adaxial (upper) surfaces of leaves, and synthesized these measurements to estimate impacts on maximum stomatal conductance to water ( $g_{wmax}$ ). Results demonstrated that at three marsh sites, invasive lineages have consistently greater  $g_{wmax}$  than their native congeners, as a result of greater stomatal densities and smaller stomata. Our analysis also suggests that phenotypic plasticity, determined as within-genotype variation in  $g_{wmax}$ , of the invasive lineage is similar to, or exceeds, that shown by the native lineage.

**Keywords:** Clonal plant; invasive; *Phragmites*; plasticity; stomata.

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## Introduction

The capacity for clonal growth is often given as an explanation for the invasive character of many introduced species (Thompson et al. 1995). Clonal growth affords species a capacity for reproduction despite small initial population sizes. It also offers competitive advantages such as the ability to nurse new ramets (sprouts), share resources between ramets and avoid the costly risks involved in sexual reproduction. However, the fitness costs of reproduction by clonal growth can include a limited ability to adapt to environmental and temporal heterogeneity (Alpert and Simms 2002). Recombination of genetic material and associated natural selection are not available for the rapid innovation and trial of new genotypes in clones, suggesting that the range of habitats invaded by clonal lineages should be more limited than that inhabited by competitors exhibiting more frequent sexual reproduction. Paradoxically, some facultatively clonal species are not only able to survive, but colonize, thrive and expand in heterogeneous environments. What factors underlie the success of particularly invasive clonal lineages? We hypothesize that these lineages are able to compete with, and ultimately outcompete, species with more diverse gene pools, greater rates of recombination or longer history of local adaptation, through the process of acclimation (*sensu stricto*) and a potentially greater range of phenotypic plasticity, which compensates for the fitness costs and complements the ecological advantages of clonality.

*Phragmites australis* is a large stature clonal grass that is found in a wide range of wetland and marsh-like ecosystems and occurs on every continent but Antarctica. In North America, several lineages have been recognized, while two are most prevalent: *P. australis* (Trin. × Steud.) is an invasive lineage (introduced), and *P. australis* subspecies *americanus* (Saltonstall, PM Peterson and Soreng) is a native lineage (native) (Saltonstall et al. 2004). Both the native and introduced lineages have the capacity for extensive clonal growth (Duhovnikoff and Hazelton 2014). However, the introduced lineage is expanding its range and outcompeting many native species across a broad range of local conditions and wetland types throughout North America.

Introduced *P. australis* demonstrates great phenotypic plasticity in response to temperature and nutrient availability (Eller and Brix 2012), geographic gradient (Bastlova et al. 2004), water depths (Vretare et al. 2001), habitat fertility (Clevering 1999), atmospheric CO<sub>2</sub> (Mozdzer and Magonigal 2012), interspecific competition (Bellavance and Brisson 2010) and intraspecific competition for light (Bellavance and Brisson 2010). However, the majority of prior work focussed on common garden studies with

the European ancestral lineage, and not plants collected in North America. Further, no *in situ* comparative lineage studies have explored the difference in plasticity between the invasive introduced and non-invasive native lineages (reviewed in Mozdzer et al. 2013). Despite the obvious comparative potential, such closely related groups have rarely been examined with respect to the ecology of invasion. Among 93 comparative studies of plasticity in invasive plants identified by Palacio-López and Gianoli (2011), the closest shared taxon was at the genus level.

In addition to closely related (conspecific) lineages, the clonality of the native and introduced lineages make *P. australis* a unique system for the comparative study of phenotypic plasticity. Phenotype is a result of genetic (G) × environmental (E) interactions (Via and Lande 1985). Clonal plants are powerful model systems as they control for genetics (G). Assuming moderate mutation rates and developmental differences among compared groups, observed variation would largely be explained by plastic responses to environmental (E) conditions. Naturally occurring replicates (ramets) of a given genotype (genet) make it possible to measure and compare the reaction norms within and between genotypes permitting a better understanding of the role plasticity plays in plant ecology (Duhovnikoff and Dodd 2015) from the ramet to the lineage scale (Gianoli and Valladares 2012).

The size and spacing of stomata on leaves are simple measurements that provide a strong framework within which to explore phenotypic plasticity linked with physiological performance (Hetherington and Woodward 2003). Stomata permit and regulate gas exchange between the inner plant and the atmosphere, facilitating the exchange of gases necessary for photosynthesis and transpiration. In moving air, stomatal conductance is the principal control over leaf gas exchange with direct consequences for both leaf metabolism and energy balance (Schulze et al. 1994). Stomatal morphometrics provide an accurate representation of the capacity for leaf gas exchange through the calculation of maximal conductance ( $g_{\max}$ , Dow et al. 2014), which incorporates the influences of stomatal pore area and pore depth (Brown and Escombe 1900). The multi-dimensional framework for the assessment of stomatal variation provided by  $g_{\max}$  has been used to demonstrate both heritable variation and environmental plasticity (Franks et al. 2009; Fanourakis et al. 2015). Differences in stomatal morphometrics have previously been identified for *P. australis* lineages (Hansen et al. 2007; Saltonstall et al. 2007). Differences in plasticity of stomatal morphology could further permit a single genotype to acclimate to a range of conditions, making it a strong competitor in heterogeneous environments such as tidal wetlands.

Introduced *Phragmites* produces biomass more quickly, metabolizes carbon and nitrogen more quickly, and it is suspected that the introduced lineage has a photosynthetic advantage over its native conspecific (Mozdzer et al. 2013). Using previously identified clonal genotypes (Duhovnikoff and Hazelton 2014), we took advantage of the  $g_{\max}$  framework to investigate variation in stomatal conductance and its dependence on stomatal morphometrics within and between *P. australis* lineages, stands and genets. We quantified maximum stomatal conductance to water,  $g_{w\max}$ , and its plasticity, through measurements of the lengths and densities of stomata on the abaxial (lower) and adaxial (upper) surfaces of leaves. We tested the hypotheses that (i) there are genetic effects on  $g_{w\max}$  differentiating native and introduced *P. australis* lineages and genotypes and (ii) variation in  $g_{w\max}$  in response to local site conditions is greater in clones of introduced *P. australis*, indicating greater physiological plasticity that may contribute to the invasive character of this lineage.

## Methods

### Site description

Three marshes in Southern Maine were systematically surveyed for stand scale *P. australis* clonal structure, which was mapped on a 5 × 5 m grid (Duhovnikoff and Hazelton 2014). Marsh sites were Libby (70.310W, 43.563N), Spurwink (70.250W, 43.589N) and the more distant Webhannet (70.585W, 43.286N). Maximum and minimum marsh-to-marsh distances were 43.2 and 5.6 km, respectively. The marshes are back barrier dune systems, and are well suited for comparisons of lineages among stands within the respective marshes; both native and introduced *P. australis* were present, in proximity to each other, at all sites. In the case of the Libby marsh, the introduced and native stands abut each other and overlap in some areas (E. L. G. Hazelton, pers. obs.). The most developed of these sites is the Webhannet marsh, the Spurwink marsh abuts agricultural land and the Libby marsh occupies a watershed with relatively little development or agriculture.

### Sample collection and DNA extraction

Samples were collected in the summer of 2011. The most apical fully expanded leaves were collected from the nearest stem to each sample grid point. Earlier work had determined that the 5 × 5 m sampling grid was ideal for the efficient mapping of genotypic diversity at the sites (Duhovnikoff and Hazelton 2014). Lineages were differentiated by morphological characteristics (Swearingen and Saltonstall 2010), and microsatellite markers (Saltonstall 2003) were used to establish

clonal identities (detailed methods in Duhovnikoff and Hazelton 2014).

### Stomatal morphometrics and $g_{w\max}$

Leaf material was stored at  $-20^{\circ}\text{C}$  prior to analysis. Epidermal impressions were made using clear nail polish (ethyl acetate) applied directly to the leaf surface, and were mounted on slides. Preliminary measurements indicated that stomatal traits varied systematically along the length of leaves, so middle-adaxial and middle-abaxial leaf surfaces were sampled for consistency. Slides were viewed on Olympus BX-51 microscopes and stomatal morphometrics were determined from images captured at ×400 total magnification using QCapture software (QImaging). ImageJ software (Abramoff et al. 2004) was used to count the total number of stomata and measure the lengths of five randomly chosen stomata within a standardized 200 × 200 μm area within each image.

Maximum stomatal conductance to water vapour ( $\text{mol m}^{-2} \text{s}^{-1}$ ) was calculated using the formula of Brown and Escombe (1900, see also Weyers and Meidner 1990; Franks and Farquhar 2006) parameterized for grass stomata (Taylor et al. 2012). Briefly,  $g_{w\max}$  for each leaf is the sum of maximum conductance values for leaf surfaces ( $g_{w\max,i}$ , where  $i$  is abaxial or adaxial), calculated as:

$$g_{w\max,i} = \frac{d}{v} \times D \times \frac{a_{\max}}{l + (\pi/2)\sqrt{a_{\max}/\pi}}$$

The diffusivity of water in air ( $d, \text{m}^2 \text{s}^{-1}$ , at  $25^{\circ}\text{C}$ ), the molar volume of air ( $v, \text{m}^3 \text{mol}^{-1}$ , at  $25^{\circ}\text{C}$ ) and  $\pi$  are physical and geometric constants. Stomatal density ( $D, \text{m}^{-2}$ ) and stomatal length ( $L, \text{m}$ ) were determined from our measurements and used to derive (i) stomatal size ( $S, \text{m}^2$ ), as  $0.25L^2$  (stomatal width =  $0.25L$ , Taylor et al. (2012)); (ii) depth of stomatal pores ( $l, \text{m}$ ), as  $0.125L$  (equal to guard cell width, Franks et al. 2009) and (iii) the maximum stomatal pore area ( $a_{\max}, \text{m}^2$ ), as  $0.4S$  (an empirical relationship for grass stomata determined by Taylor et al. 2012). Calculations were made using R Language and Environment (version 3.1.3, R Development Core Team 2015).

### Statistical analysis

We  $\log_e$  transformed  $g_{w\max}$  prior to statistical analysis. We employed standard approaches for an unbalanced nested 2 × 2 analysis of variance, using the R Language and Environment (version 3.1.3, R Development Core Team 2015), as follows. We performed a Type III conditioning procedure (Fox 2008), initially testing for interactions between the two putative fixed effects, site and lineage, holding the clones as random effects. We detected no significant

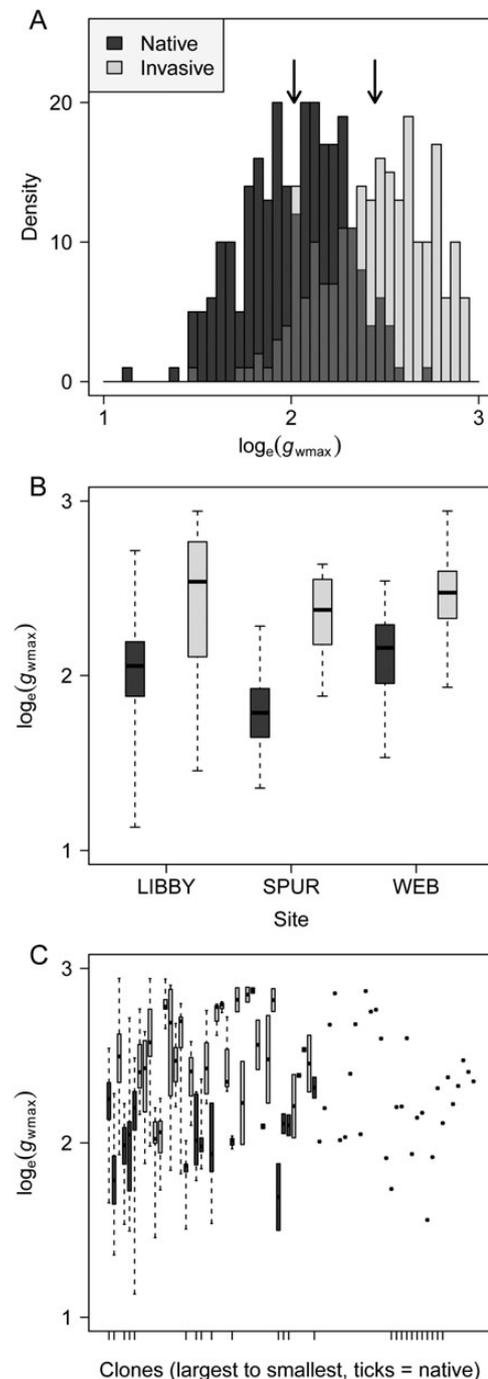
interactions in the complete data set, though we did find weak but statistically significant interactions when several highly variable clones were excluded from the data. We inferred the significant effects using the complete data set, employing a Type II procedure to ensure full power to determine effects (Langsrud 2003): all factors (site, lineage and clone) exhibited effects with  $P$ -values  $< 10^{-16}$ . We also employed a more advanced model selection machinery available to Bayesian approaches to calculate the Bayes factors across a wide variety of possible analytic frameworks (Rouder et al. 2012), garnering additional support for our choice of analysis. For clones with  $N > 11$  ramets, robust estimates of within-clone spatial variation, mean and standard deviation (SD) in  $\log_e(g_{wmax})$  were made using a permutation test that preserved the variation intrinsic to the data accounting for the variable number of ramets within each clone. This test proceeds by generating two distributions of statistics, a null distribution reflecting the correlation expected under no spatial effect but accounting for unevenness in the underlying spatial distribution of ramets and a corresponding distribution reflecting the correlation observed within the data. The first was generated by randomly permuting which  $g_{wmax}$  values associate with which  $(x,y)$  position pair for a given ramet, and repeating 10 000 times; for each permutation, a subset of size 10 was taken and a simple Spearman (rank order) correlation was calculated between the pairwise distance between ramets and the difference in their  $g_{wmax}$  values. The latter distribution was generated to represent the observed data by sampling 10 000 size 10 subsets and again calculating the Spearman correlation. A  $P$ -value was calculated by finding the fraction of replicates in the observed distribution that were more extreme than all values in the null distribution. While similar in concept to a Mantel test, this permutation approach is significantly more conservative in its  $P$ -value calculation while still sensitive to even mild (correlation values of 0.1) levels of spatial structure. To ensure that the results were independent of coordinate frame, the test was repeated having rotated the axes by  $45^\circ$ .

## Results

### Site, lineage and clone as factors influencing $g_{wmax}$

Our model of  $\log_e(g_{wmax})$  identified significant additive effects of site, lineage and clone (clones having been identified as unique to each site, i.e. completely nested;  $F$  values 48.06, 495.70 and 4.50 with  $df = 2, 1$  and 68, respectively,  $P < 10^{-16}$  for all). At the three sites, *P. australis* showed greater mean  $\log_e(g_{wmax})$  at Webhannet (2.28) and Libby (2.26) than at Spurwink (1.93). When grand means for the native and introduced lineages were compared,  $\log_e(g_{wmax})$  of the introduced lineage was 21 % greater than the native

lineage (Fig. 1A), equivalent to an increase of 54 % when back-transformed to the original scale (mean (2.5–97.5 % quantile): native, 7.5 (4.5–12.1)  $\text{mol m}^{-2} \text{s}^{-1}$ ; introduced,



**Figure 1.** (A) Native and invasive lineages of *P. australis* show significantly different  $g_{wmax}$  determined on the basis of stomatal morphometrics. (B) Differences in  $g_{wmax}$  between native and invasive lineages of *P. australis* are consistent between marsh sites in Maine, and are substantially greater than differences in  $g_{wmax}$  between sites. (C) When comparing unique clones of *P. australis* across three marsh sites in Maine,  $g_{wmax}$  differentiates clones belonging to native and invasive lineages.

11.5 (6.7–18.1) mol m<sup>-2</sup> s<sup>-1</sup>). This substantial difference between the lineages was relatively consistent across the three sites (16–31 % increase on log<sub>e</sub> scale depending on site; Fig. 1B). When clones were treated as independent of their classification by site and lineage, and when lineage was excluded from consideration, among-clone variation explained the majority of variance in log<sub>e</sub>(g<sub>wmax</sub>) (55 %). Differences among clones were, however, strongly structured by contrasts between native and introduced lineages and sites (Fig. 1C).

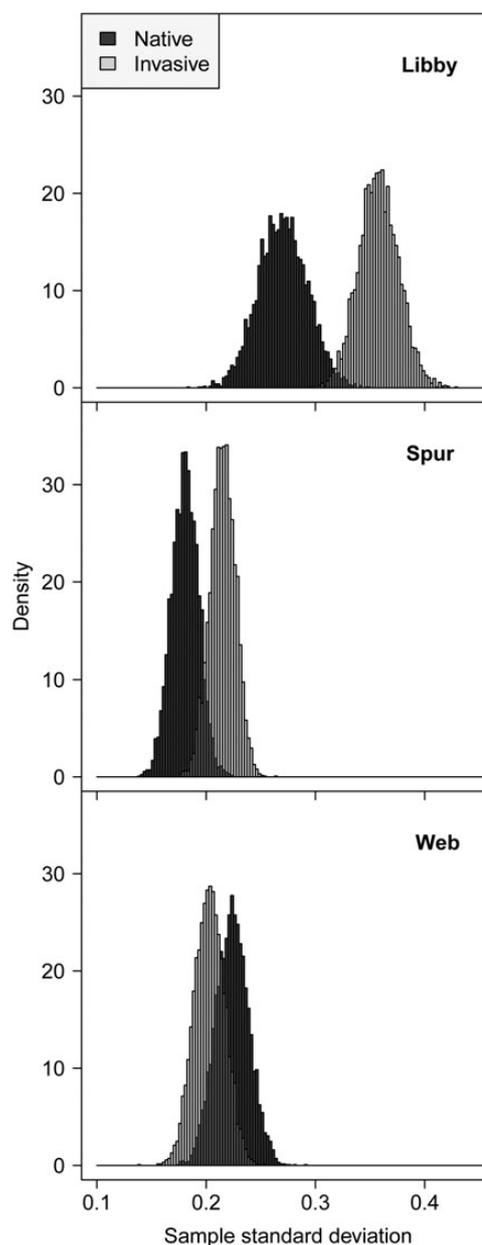
### Plasticity (within-clone variation) in g<sub>wmax</sub>

Using our entire data set, plasticity in log<sub>e</sub>(g<sub>wmax</sub>), determined as the SD of log<sub>e</sub>(g<sub>wmax</sub>) conditioned for clone identity (Fig. 2), was greater within the introduced lineage at the Libby (SD: introduced, 0.36; native, 0.27) and Spurwink (SD: introduced, 0.22; native, 0.18) marshes. At the Webhannet marsh, the opposite was true (Fig. 2), but the lineages were also more similar (SD: introduced, 0.20; native, 0.22).

Our investigation of both spatial variation and phenotypic variation in log<sub>e</sub>(g<sub>wmax</sub>) within the 10 clones having N > 11 ramets found no evidence for significant within-clone spatial structure (permutation test null distribution construction described in Methods with 9999 degrees of freedom, P > 0.291). The test used does not rule out spatial autocorrelation as a determinant of finer-scale patterns. Distributions of SDs for log<sub>e</sub>(g<sub>wmax</sub>) within large clones at the Libby site, in particular, were multimodal (Fig. 3). The permutation distributions shown in Fig. 3 were realized for each clone by holding the number of ramets to 10 and resampling from the full collection of observed values with replacement: for each clone, 1000 resamplings were made, with the sample mean and sample SD calculated for each sample. This analysis indicates that within these large, genetically homogeneous clones, subsets of ramets showed uniquely identifiable levels of plasticity, perhaps linked by epi-genotype.

### Lineage differences in stomatal morphometrics underpinning g<sub>wmax</sub>

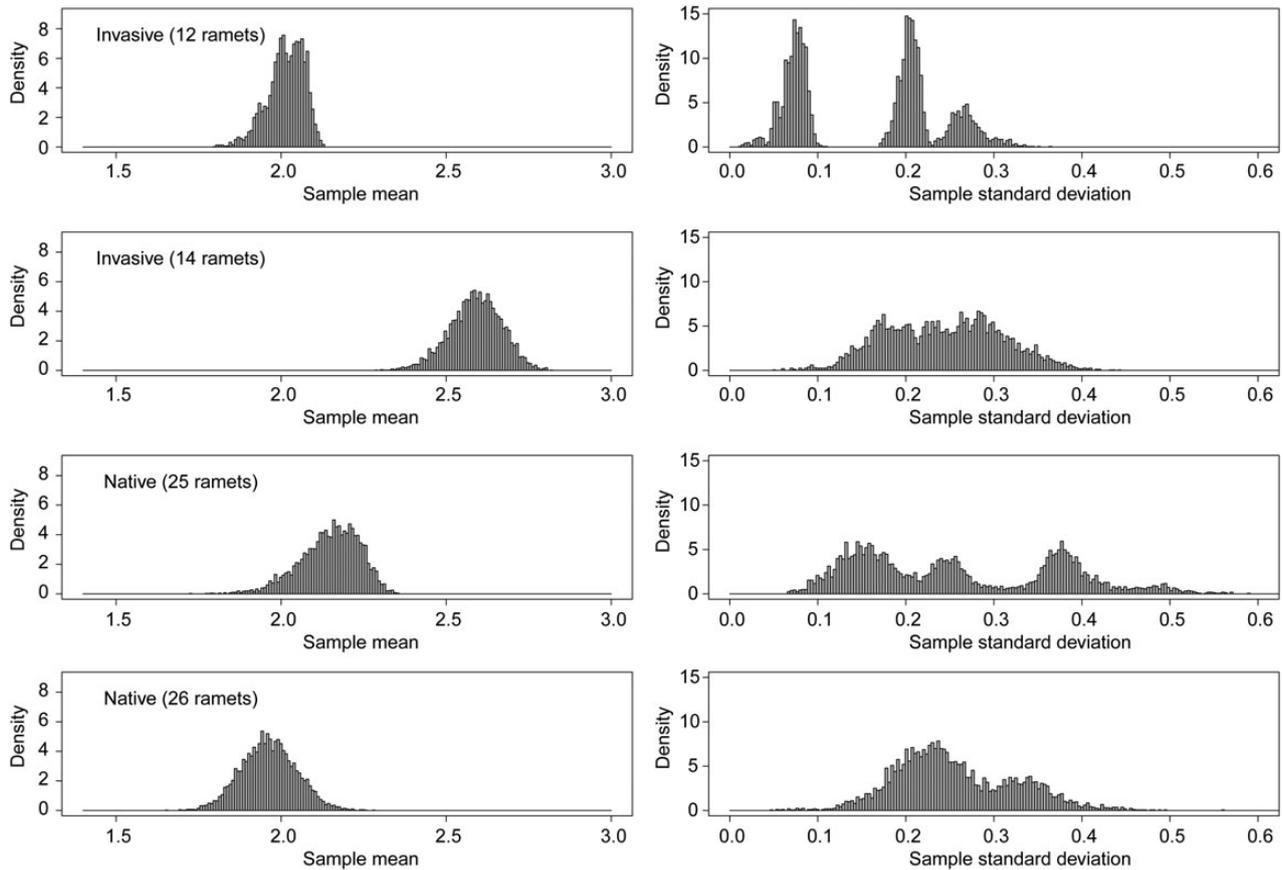
The consistently greater g<sub>wmax</sub> of introduced lineages of *Phragmites* was a result of increases in both adaxial and abaxial g<sub>wmax</sub> (Fig. 4A). Size (S)–density (D) plots indicated that differences in S and D between the lineages were broadly consistent with a size–density trade-off: the introduced lineage had relatively smaller and more abundant stomata than the native lineage (Fig. 4B and C). Shifts in S and D among native ramets resulted in conservation of g<sub>wmax</sub> (data for native ramets fall along g<sub>wmax</sub> isoclines in Fig. 4B and C). Among ramets of the introduced lineage, variation in g<sub>wmax</sub> arose from variation in D that was not matched by shifts in S (Fig. 4B and C).



**Figure 2.** Plasticity (SD) in g<sub>wmax</sub> within the invasive lineage of *P. australis* is similar to, or exceeds, plasticity measured within the native lineage at Libby, Spurwink and Webhannet marshes, in Maine.

## Discussion

Previous demonstrations that g<sub>wmax</sub> is reliably linked with gas exchange performance (Dow et al. 2014) and demonstrates both heritable variation and environmental plasticity (Franks et al. 2009; Fanourakis et al. 2015) suggested that simple measurements of the size and spacing of stomata on leaves would provide a strong framework within which to explore phenotypic plasticity in *P. australis*. Our results confirm this expectation; we were able to characterize plasticity in stomatal morphometrics that



**Figure 3.** Permutation analysis demonstrates that unimodal distributions for means of  $g_{wmax}$  within clones of *P. australis* (left column) are linked with multimodal distributions for SDs (right column); clusters of ramets within each genet show unique levels of variability. Results shown are for invasive (BI24, BI51) and native (BN11, BN8) clones at the Libby marsh.

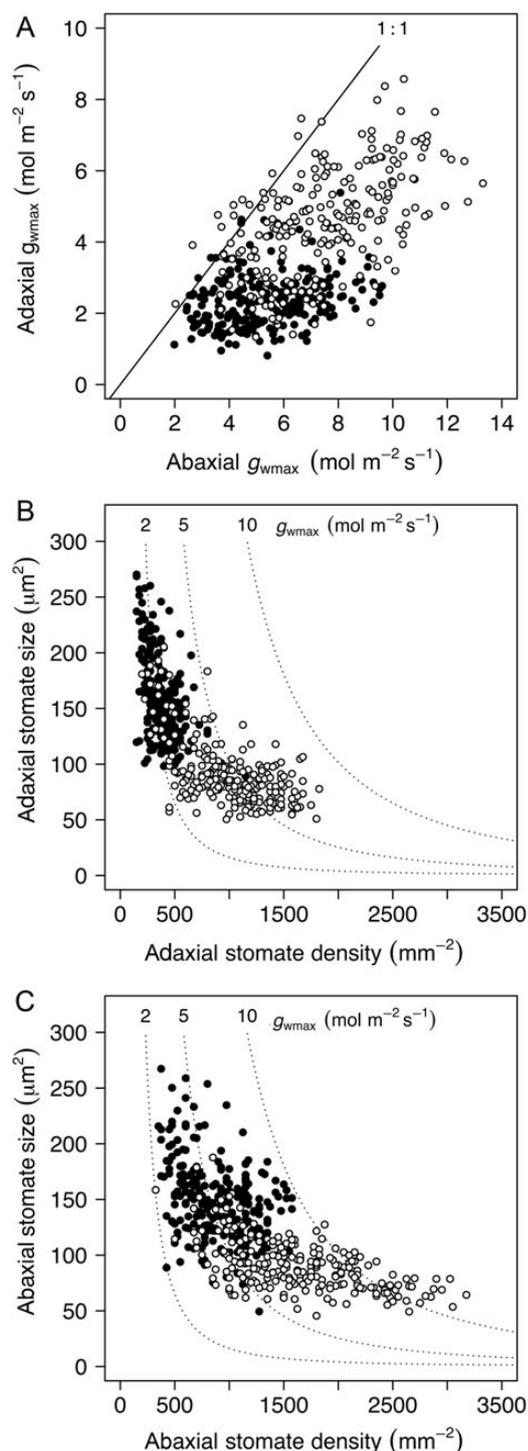
contributed to differences in  $g_{wmax}$  between native and invasive lineages. We found that at three marsh sites separated by as much as 43 km, introduced lineages have consistently greater  $g_{wmax}$  than their native congeners. Thus,  $g_{wmax}$  can be added to an already extensive list of functional traits that distinguish these genetic variants (stem densities, heights, above ground biomass, leaf area, leaf nitrogen and chlorophyll content, rates of photosynthesis, relative growth rates (RGR) and carbon fixation; reviewed in [Mozdzer et al. 2013](#)). Our analysis also indicates that plasticity of the introduced lineage, determined as within-genotype variation in  $g_{wmax}$ , is similar to or exceeds that shown by the native lineage. These results provide insights that scale up from stomatal morphometrics to community dynamics.

### Phenotypic variation in stomatal morphometrics

We observed inverse relationships between stomatal size and density, as have been commonly reported in the literature for multiple taxa ([Kawamitsu et al. 1996](#); [Hetherington and Woodward 2003](#); [Franks et al. 2009](#)). The derivation of  $g_{wmax}$  based on the work of [Brown and Escombe \(1900\)](#)

suggests that a trade-off between stomate size and density will be broadly linked with conservation of  $g_{wmax}$ ; decreases in stomatal size without a compensatory increase in density should result in decreases in  $g_{wmax}$  (the relative effect of decreased stomatal size on  $g_{wmax}$  is smaller when stomata are large because while pore resistance is increased by declines in pore area, parallel decreases in pore depth act to decrease pore resistance; see discussion by [Franks et al. 2009](#)). We interpret our results as pointing to size–density trade-offs linked with conservation of  $g_{wmax}$  among leaves from native *P. australis*. Meanwhile, plasticity in  $g_{wmax}$  among ramets of introduced *P. australis* was linked with greater plasticity in densities of stomata and was sometimes greater than for native clones.

Smaller stomata, as observed for the introduced lineage of *P. australis*, may improve water use efficiency. They are expected to be capable of opening and closing more rapidly ([Aasamaa et al. 2001](#); [Drake et al. 2013](#)); in combination with lower resistance offered by shorter diffusion paths through smaller pores, rapid adjustment should lead to tighter linkage between stomatal responses and the need to regulate transpiration ([Knapp 1993](#)). In the



**Figure 4.** Components of  $g_{wmax}$  for lineages of *P. australis* native (filled symbols), and invasive (open symbols), to North America. (A) Leaf  $g_{wmax}$  is the sum of  $g_{wmax}$  for the adaxial and abaxial leaf surfaces; higher leaf  $g_{wmax}$  among invasive lineages is a result of increases in both adaxial and abaxial  $g_{wmax}$ . Stomate size shows a negative relationship with stomate density on both the adaxial (B) and abaxial (C) leaf surfaces: higher  $g_{wmax}$  on abaxial surfaces are linked with greater stomate densities, and the higher stomate densities among invasive *P. australis* are linked with reduced stomate size compared with the native lineage.

case of *P. australis*, improvements in stomatal feedback could allow introduced lineage access to more exposed ground with less reliable water supply, contributing to their observed capacity to reduce soil moisture levels (by accretion, Rooth et al. 2003; by transpiration, Windham 2001; by Venturi Effect ventilation, Armstrong and Armstrong 1991). Detailed physiological work assessing the components of leaf gas exchange and hydraulics will be necessary to fully resolve whether differences in water use efficiency are mechanistically linked with stomatal morphometrics in these *Phragmites* lineages.

The  $g_{wmax}$  values we determined for *P. australis* in Maine, particularly the introduced lineage, were very high (Table 1). They exceeded measurements made by one of the authors in a previous pot-based greenhouse study (Taylor et al. 2012). A broad survey of other grass species (Kawamitsu et al. 1996) indicates that stomatal morphometrics of cultivated rice (*Oryza sativa*) were most similar to *P. australis*, but  $g_{wmax}$  values for *P. australis* were higher. This is despite the expectation that a hydrophytic habit and selection for high productivity in rice would be expected to have maximized  $g_{wmax}$ . The  $g_{wmax}$  values we determined are underpinned by similar stomatal morphometrics to those demonstrated in a previous study that addressed the potential for ploidy level variation of stomatal traits in field collected samples across north-eastern North America (Saltonstall et al. 2007; Table 1). Indeed, the stomatal traits reported by Saltonstall et al. (2007) suggest even more extreme values for  $g_{wmax}$  than in our sample (Table 1). Although our study is limited to three marshes in Maine, our results parallel those from a broader set of populations support differences in mean  $g_{wmax}$  between native and introduced lineages as a general feature of *P. australis*, at least across its north-eastern North American range. Comparison of our measurements, those made by Saltonstall et al. (2007), and material of a European origin (Table 1, Taylor et al. 2012) also suggests a strong conservation of between-lineage differences in stomatal size while density is more variable (Table 1): plastic responses of  $g_{wmax}$  in *P. australis* may depend strongly on variation in density of stomata.

*Phragmites australis* is a water-loving species characteristic of marshes and wetlands. Reliable availability of water can relax selection against increases in transpiration (Dudley 1996), allowing for improved net carbon gain or nutrient acquisition (Donovan et al. 2007). In hot environments, increased transpiration can improve photosynthetic efficiency and leaf survival by helping to decrease leaf temperatures (Lu et al. 1998). In the cool climate of New England, it seems likely that the principal advantage of high stomatal conductances would be to decrease resistance to  $CO_2$  diffusion into leaves and improve net carbon gain, consistent with observations

**Table 1.** *Phragmites australis* as a species show exceptionally high  $g_{wmax}$ . [1] Saltonstall et al. (2007), [2] Taylor et al. (2012) and [3] Kawamitsu et al. (1996). <sup>1</sup>Saltonstall et al. did not determine lengths of adaxial stomata for most populations, there being no significant difference between surfaces in a subset. <sup>2</sup>Most extreme among 41 cultivars.

Species/lineage	Mean length of stomata ( $\mu\text{m}$ )		Mean density of stomata ( $\text{mm}^{-2}$ )		$g_{wmax}$ ( $\text{mol m}^{-2} \text{s}^{-1}$ ) predicted from mean values	Location, data source
	Adaxial	Abaxial	Adaxial	Abaxial		
<i>P. australis</i> native	25	24	394	924	7.94	Maine, this study
<i>P. australis</i> invasive	19	19	1002	1635	12.42	
<i>P. australis</i> native	25 <sup>1</sup>	25	804	1147	12.09	Northeast USA and Canada [1]
<i>P. australis</i> invasive	19 <sup>1</sup>	19	1726	2167	18.34	
<i>P. australis</i>	19	19	419	510	4.38	Glasshouse, UK [2]
<i>Oryza sativa</i> cv. Raikei <sup>2</sup>	18	18	646	844	6.65	Japan [3]

that the introduced lineage shows greater productivity, responsiveness to carbon enrichment (Mozdzer and Magonigal 2012) and higher RGR, the latter being a proposed factor driving invasion (Mozdzer et al. 2013). More broadly, high rates of productivity and the capacity for local habitat modification, e.g. by drying, are traits common to many invasive plants (Cuddington and Hastings 2004); our demonstration that  $g_{wmax}$  values for introduced *Phragmites* stands exceed those for native stands fits with reports of local drying effects linked the introduced lineage, mediated by both evapotranspiration and sediment accretion (Rooth et al. 2003). Summarizing, advantages under a variety of field conditions could arise from increases in transpiration linked with higher  $g_{wmax}$  that would provide for increased conductance to  $\text{CO}_2$  and reduction in leaf temperature, or improved water use efficiency linked with decreases in stomatal size.

### Community dynamics

High levels of plasticity in stomatal traits support the description of introduced *P. australis* as a ‘Jack-and-master’ of change (Mozdzer and Magonigal 2012; Mozdzer et al. 2013). Plasticity in stomatal morphology would be expected to permit a single genotype to acclimate to a range of conditions and make it a strong competitor in a heterogeneous environment. Marsh systems susceptible to *Phragmites* invasion are starkly heterogeneous in many factors, for example sharp gradients from waterline to bank in salinity, aeration, nutrient availability and water depth (reviewed in Engloner 2009). Comparing North American lineages, Holdredge et al. (2010) described a cline ranging from lower elevation associated with waterlogged soils up to higher elevation characterized by high levels of interspecific competition. A single clonal genotype of *P. australis* might span multiple microhabitat transitions in this setting. Genotypes with a plastic localized response at the scale of the ramet could minimize the risks, costs or

genetic resources associated with adaptation through sexual reproduction while best optimizing potential opportunities for resource sharing and economies of scale inherent in integrated clonality.

Indeed, ‘Theory predicts that plasticity in . . . morphologies of plants can transmit heterogeneity from the environment to the population or community’ (Callaway et al. 2003). Thus, we can predict that significant variation should be identifiable from the among-lineage down to the among-ramet scales dependent upon local conditions. The lack of spatial structure to our data suggests that drivers of heterogeneity in stands of *P. australis* operate at a scale smaller than the  $5 \times 5$  m scale measured here.

Plasticity is important for both lineages (Mozdzer and Magonigal 2012) and worth comparison against other non-clonal species. However, the lower levels of native plasticity suggest that there may be a cost involved. Net fitness, which synthesizes survival, growth and fecundity, does not necessarily benefit from plasticity (Palacio-López and Gianoli 2011; Pichancourt and Van Klinken 2012). In some circumstances, plasticity can be disadvantageous, for example, when there are costs of inappropriate specialized phenotypes, when environmental cues are unreliable, when the environment is not variable or when the plastic response lags too far behind environmental change (Vretare et al. 2001; Callaway et al. 2003). Thus, narrower plasticity in the native lineage may constrain optimal microhabitat range or reflect the more homogeneous sites it occupies.

A frequent assertion in invasive plant literature is that phenotypic plasticity is common in invasive species, making possible a broader ecological niche through the expression of site-specific advantageous phenotypes (Richards et al. 2006; Davidson et al. 2011). Previous work has shown that invading populations have the potential for rapid adaptive evolution (Dlugosch and Parker 2008),

which would select for a ‘general purpose genotype’ (Moroney et al. 2013). There is some evidence that introduced *P. australis* may be less plastic in its native range (Rolletschek et al. 1999) warranting further study of reaction norms in common gardens (e.g. Křiváčková-Suchá et al. 2007; Achenbach et al. 2012).

After within-genotype variation (plasticity), genetic variation (diversity) was the most important contributor to heterogeneity in phenotypes in this study, with relatively little variation being explained by among-site comparisons. Limited variation among sites may result from an emphasis on clonal reproduction, with limited sexual reproduction, natural selection and genetic drift. Initial models of *P. australis* establishment focussed on the transport of vegetative propagules and would lead to low genet richness at a given site (Bart et al. 2006); however, recent research indicates a greater role for sexual reproduction (McCormick et al. 2010) with clonal growth clearly important on a local scale (Kettenring and Mock 2012; Duhovnikoff and Hazelton 2014). Instead local genetic diversity can remain relatively high due to long lifespans and mechanisms such as remnant regional dynamics (Duhovnikoff and Hazelton 2014).

## Conclusions

Plasticity in the introduced lineage of *P. australis* is similar to or exceeds that of native stands, both in our results and other reports (Mozdzer and Megonigal 2012; Mozdzer et al. 2013). This suggests that capacity for greater plasticity may be a major driver in the introduced lineage’s invasiveness. Nonetheless, native *P. australis* does demonstrate considerable plasticity, which may underpin observations of long-term resistance to invasion, resilience and site consolidation. For example, the native lineage is well adapted to both low nutrient environments and exploitation of increasing nitrogen (sensu Hazelton et al. 2010). In contrast, the invader consistently outperforms the native in biomass production, nitrogen assimilation and various aspects of carbon metabolism (Mozdzer et al. 2013). These differences in physiological traits and trait plasticity may be indicators of different life-history strategies underpinning the ecological success and evolutionary maintenance of the two *P. australis* lineages in North America.

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## Contributions by the Authors

V.D. was involved in all stages of research execution, data analysis and manuscript preparation. J.O.B. and S.H.T.

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## Conflict of Interest Statement

None declared.

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