Germination Responses to Water Potential in Neotropical Pioneers Suggest Large-seeded Species Take More Risks

MATTHEW I. DAWS 1 , 2 , *, LORA M. CRABTREE 1 , JAMES W. DALLING 3 , CHRISTOPHER E. MULLINS 1 and DAVID F. R. P. BURSLEM 1

1 Institute of Biological and Environmental Sciences, University of Aberdeen, Cruickshank Building, St Machar Drive, Aberdeen AB24 3UU, UK; 2 Seed Conservation Department, Royal Botanic Gardens, Kew, Wakehurst Place, Ardingly, W. Sussex RH17 6TN, UK; and 3 Department of Plant Biology, University of Illinois, 265 Morrill-Hall, 505 S Goodwin Avenue, Urbana, IL 61801, USA

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• Background and Aims In neotropical forests, very small-seeded pioneer species (< 0.1 mg seed mass) recruit preferentially in small tree fall gaps and at gap edges, but large-seeded pioneers do not. Since water availability is related to gap size, these differences in microsite preference may reflect in part species-specific differences in germination at reduced water potentials.

• Methods For 14 neotropical pioneer species, the hypothesis is tested that small-seeded species, with shallow initial rooting depths, reduce the risks associated with desiccation by germinating more slowly and at higher water potentials than large-seeded species.

• Key Results Germination occurred both more quickly and at lower water potentials with increasing seed mass. For example, Ochroma pyramidale (seed mass 5.5 mg) had a time to 50% germination (T 50 ) of 2.8 d and a median base potential for germination ( משתה) of −1.8 MPa while Clidemia quinquenervia (seed mass 0.017 mg) had a T 50 of 17.6 d and a T 50 of −1.1 MPa.

• Conclusions These data suggest that small-seeded species germinate only in comparatively moist microsites, such as small canopy gaps, which may reduce the risk of drought-induced mortality. Conversely, large-seeded species are able to germinate in the drier environment of large gaps, where they benefit by enhanced seedling growth in a high irradiance environment. The positive association of seed size and canopy gap size for optimal seedling establishment is maintained by differential germination responses to soil water availability coupled with the scaling of radicle growth rate and seed size, which collectively confer greater drought tolerance on large-seeded species.

Key words: Germination, seed size, Panama, neotropical, pioneer, water potential.

INTRODUCTION

Seed size is a key variable for predicting patterns of plant regeneration. For example, in temperate herbaceous plant communities, seed persistence in the soil is associated with small seed size (Thompson, 1987; Thompson et al., 1993), whereas in neotropical forests long-term persistence of pioneer species is associated with relatively large-seeded species (Dalling and Burslem, 2005; Dalling and Brown, unpubl. res.). Across a range of ecosystems small-seeded species are also more likely to require light as a cue to germinate in canopy openings or gaps in leaf litter (Milberg et al., 2000; Pearson et al., 2002; Jankowska-Blaszczuk and Daws, 2007). However, the importance of seed mass for other aspects of germination, such as the response to water potential, has received little attention and yet is a likely determinate of successful establishment.

Among tropical shrubs and trees, a functional group labelled ‘pioneers’ has been identified that consists of fast-growing early successional species that need canopy gaps for establishment (Swaine and Whitmore, 1988). In central Panama, pioneers have seed sizes from approx. 0.02 mg to 100 mg (Daws et al., 2007a) and occur in canopy gaps of differing size. Along the understorey—gap continuum, the quantity of irradiance, and hence the amplitude of soil temperature fluctuations and the rate of soil surface drying, increase with increasing gap size (Denslow et al., 1998; Daws et al., 2002, 2007a; Pearson et al., 2002). For example, in large canopy gaps at the present study site in central Panama (Barro Colorado Island), irregular rainfall during the wet season can result in the soil matric potential at 10 mm depth falling to less than −1.5 MPa (the permanent wilting point) after just 6 d of drying (Engelbrecht et al., 2006; Daws et al., 2007a; Matthews et al., 2008). In some small gaps, water extraction by the roots of the surrounding trees results in surface soil drying up to but not beyond the wilting point, while litter-free soil in the centre of large gaps continues to dry beyond the wilting point (Matthews et al., 2008). This potential for rapid drying beyond the wilting point implies that the risk of mortality from desiccation for germinating seeds/establishing seedlings increases with gap size (Engelbrecht et al., 2006; Daws et al., 2007a, b).

Large-seeded neotropical pioneer species generally have a distribution that is biased towards the ‘risky’ environment of larger sizes of canopy gap (Brokaw, 1987; Pearson et al., 2003a), although these studies did not invoke seed size to account for these differential distribution patterns (but see Dalling et al., 2004). In addition, germination requirements

* For correspondence. E-mail matthew.daws@ewlsciences.com.au

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of large-seeded pioneers typically appear to be ‘cued’ to large gap environments, i.e. they require either a high ratio of red: far red light (R:FR) or a large amplitude of diurnal temperature fluctuations for germination (Vázquez-Yanes and Orozco-Segovia, 1982; Daws et al., 2002; Pearson et al., 2002). The risk of desiccation-induced mortality may be lower for seedlings from large seeds since such seedlings can emerge from greater soil depths (Bond et al., 1999; Pearson et al., 2002) and have more rapid radicle growth rates (Daws et al., 2007a) than seedlings from small seeds. Consequently, it is hypothesized that large-seeded species may be better able to ‘cope’ with the risk associated with large canopy gaps. The high light environment of large gaps is likely to be advantageous for seedlings that can establish successfully, by facilitating rapid post-establishment growth, as long as this occurs in advance of the frequent dry spells in the early wet season. For these potentially ‘risk-taking’ species, the risk of rapid emergence may be tempered by a rapid radicle growth and hence access to soil water at depth (Daws et al., 2007a). However, for small-seeded species that can germinate only at shallow depths, where soil drying occurs rapidly, it is predicted that germination will occur more slowly. This response will limit germination either to large gaps in prolonged wet spells or to the less strongly drying environment of small gaps.

Soil water potential modulates seed germination, and species differ in the minimum water potential at which germination can occur (Kaufmann, 1969; Evans and Etherington, 1990; Choinski and Tuohy, 1991; Allen et al., 2000; Daws et al., 2002). For neotropical pioneer shrubs and trees, only four species from one genus have been characterized for their germination response to water availability (Daws et al., 2002). These congeners had a limited range of seed mass values and showed only modest differences in the base water potential for germination (Daws et al., 2002). Since large-seeded pioneers occur more frequently in large gap environments, it was predicted that they would germinate at lower matric potentials than small-seeded species. Such a response would potentially complement rapid germination in enabling rapid establishment in the unpredictable large gap environment.

Consequently, in this paper, the predictions that for pioneer species (a) large-seeded species germinate more rapidly than small-seeded species and (b) that large-seeded species are able to germinate under lower water potentials (drier conditions) than small-seeded species are tested. The results are discussed in the context of risk-spreading environments of unpredictable rainfall.

MATERIALS AND METHODS

Study site and species

Ripe fruits of the ten study species (Table 1) were collected between February and July 1999 from semi-deciduous forest on Barro Colorado Island (BCI; 9°09′N, 79°51′W), Republic of Panama. Mean annual rainfall at BCI is approx. 2700 mm with about 93% of the total occurring in the wet season between May and December (Croat, 1978). Fruits were collected from at least five individual plants per species and seeds extracted by mashing the fruits in water and decanting off the fruit pulp. Subsequently, seeds were air-dried in the dark, transported to Aberdeen, UK, and stored at room temperature prior to the start of germination experiments. In addition, seed mass and germination data for a further four pioneer species from BCI (Piper dilatatum, P. hispidum, P. margintatum and P. peltatum) were obtained from Daws et al. (2002).

Seed germination

Seeds were subjected to water potentials of approx. 0, –0.25, –0.5 and –1.0 MPa by placing three replicates of 25 seeds each on the surface of a wick connected to a reservoir of polyethylene glycol 8000 (PEG), at a concentration appropriate to the intended treatment (Michel and Kaufmann, 1973), following the method outlined by Daws et al. (2002). The PEG solution flowed over the wick, maintaining the seeds at a constant water potential.

Table 1. Summary information of seeds used in this study

<table>
<thead>
<tr>
<th>Species</th>
<th>Family*</th>
<th>Habitat information</th>
<th>Seed mass (mg)</th>
<th>T_{50} (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apeiba tiborbou</td>
<td>Malvaceae-Tiliaceae</td>
<td>Abandoned farms, road edges, canopy gaps (^{1})</td>
<td>5.6</td>
<td>7.1</td>
</tr>
<tr>
<td>Cecropia insignis</td>
<td>Moraceae</td>
<td>Canopy gaps (^{1})</td>
<td>0.68</td>
<td>5.6</td>
</tr>
<tr>
<td>Cecropia longipes</td>
<td>Moraceae</td>
<td>Canopy gaps (^{1}), open areas (^{4})</td>
<td>1.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Cecropia obovifolia</td>
<td>Moraceae</td>
<td>Tree fall areas (^{4})</td>
<td>0.58</td>
<td>5.9</td>
</tr>
<tr>
<td>Cecropia peltata</td>
<td>Moraceae</td>
<td>Tree fall areas (^{4})</td>
<td>0.59</td>
<td>14.0</td>
</tr>
<tr>
<td>Clidemia octona</td>
<td>Malastomataceae</td>
<td>Forest edge (^{4})</td>
<td>0.015</td>
<td>21.4</td>
</tr>
<tr>
<td>Clidemia quinquenervia</td>
<td>Malastomataceae</td>
<td>Edge of clearings (^{4})</td>
<td>0.017</td>
<td>17.6</td>
</tr>
<tr>
<td>Luehea seemanii</td>
<td>Malvaceae-Tiliaceae</td>
<td>Along roads, canopy gaps (^{4})</td>
<td>1.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Miconia argentea</td>
<td>Malastomataceae</td>
<td>Along roads, canopy gaps (^{4})</td>
<td>0.076</td>
<td>11.3</td>
</tr>
<tr>
<td>Ochroma pyramidale</td>
<td>Malvaceae-Bombacaceae</td>
<td>Large clearings (^{4}), Disturbed areas (^{4})</td>
<td>5.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

\(^{1}\) From APG II (2003).

\(^{2}\) From CTS (2004).

\(^{3}\) From Wüthrich et al. (1998).

\(^{4}\) From Croat (1978).
Sub-samples of the wicks were removed after the experiment had been running for 20 d, and their actual water potential determined using an SC-10A Richards thermocouple psychrometer (Decagon Devices, Pullman, WA, USA). Measured rather than nominal values of water potential were used in all analyses; measured values were all within 20% of the target values and had standard deviations <15% of the mean value.

Seeds of *Ochroma pyramidale* and *Apeiba tibourbou* require a dormancy-breaking treatment. Consequently, to ensure germination in the water potential treatments, seeds of *A. tibourbou* and *O. pyramidale* were treated with hot water at 80 °C and 90 °C, respectively, for 2 min (Açúña and Garwood, 1987; Daws et al., 2006).

The germination system was housed in transparent polyethylene boxes and placed in a growth chamber at 26 °C, with a 12-h photoperiod. Although for some species base potential has been shown to be dependent on temperature (Dahal et al., 1993; Kebreab and Murdoch, 1999), a single temperature (26 °C) was used. Even though soil surface temperatures in large gaps are elevated close to mid-day, time-courses of temperature at 1-cm depth suggest that values for both small and large gaps are within 1 °C of 26 °C for a mean of 87.5% and 67.4%, respectively, each day (Daws et al., 2002). Irradiance inside the transparent boxes averaged 5 μmol m⁻² s⁻¹, the R:FR was approx. 2:0. Seeds were scored daily for germination up to 50 d with germination defined as visible radicle emergence.

**Data analysis**

Time to 50% of maximum germination (*T₅₀*) at 0 MPa (water) was determined for each species from plots of germination against time.

The effect of water potential on time to germination has been described by the hydrotme model of germination (Bradford, 1990). In this model seeds germinate only when they have accumulated sufficient hydrotme (*tₜ*). At and below a base water potential (*ψ_b*) seeds do not start to germinate. Above this potential, seeds accumulate hydrotme. Within seed lots a normal distribution of base potentials is typically observed (Bradford, 1990; Dahal and Bradford, 1990; Gummerson, 1996) while the hydrotme constant, *tₜ*, is the length of time seeds have accumulated sufficient hydrotme when they have accumulated sufficient hydrotme (*OH*).

The unknown *ψ_b* can be estimated iteratively (Bradford, 1990). If the value of *tₜ* is repeatedly changed until the best fit (i.e. the value with minimal residual variation) is obtained when a single least squares regression line is fitted to the data for the range of water potentials, then *ψ₅₀* corresponds to the base potential when germination is 50% of the maximum observed germination level and the reciprocal of the slope of the regression line is the standard deviation of the base potential (*σ_b*).

By rearranging eqn (2) in terms of base potential:

\[
ψ₅₀ = ψ_w - (tₜ/τₚ)
\]

**RESULTS**

**Effect of water potential on germination**

For all ten species, germination percentage and rate of germination decreased as water potential became more negative. Thus, germination was most rapid and reached the highest percentage at 0 MPa (water) and was lowest at 1-0 MPa. In addition, the negative effect of −0.25 and −0.5 MPa was relatively minor for most species, with a greater impact of −1.0 MPa (data not shown).

Plotting germination (in probits) against base potential indicated that the median base water potential (the base potential when germination in probits is 5; *ψ₅₀*) ranged from −1.07 to −2.06 MPa (*Clidemia quinquenervia* and *Apeiba tibourbou*, respectively; Fig. 1). On Fig. 1 each point represents an observation from the four germination progress curves with values of base potential determined after iteration of the hydrotme constant, *tₜ*, in the expression \[ψ_w - (tₜ/τₚ)\] to maximize the fit of the linear regression. Therefore species that take longer to germinate have more observations per germination progress curve, which is reflected in a greater number of points on the corresponding graphs.

For the ten study species and four additional species from Daws et al. (2002), there was a significant negative relationship between the median base water potential and seed mass (linear regression, \(R^2 = 0.457\), d.f. = 12, \(P = 0.008\): small-seeded species were less able to germinate at low water potentials (Fig. 2A).

**Time to 50% germination and seed mass**

Time to 50% germination (*T₅₀*) in the 0-MPa (water) treatment for the 14 species was significantly negatively related to seed mass (linear regression, \(R^2 = 0.684\), d.f. = 12, \(P < 0.001\); Fig. 2B). For example, *Ochroma pyramidale* (seed mass = 5.5 mg) reached 50% of maximum germination in 2.8 d while *Clidemia octona* (seed mass = 0.015 mg) took 21.4 d. In addition, *T₅₀* and *ψ₅₀* were significantly correlated, i.e. the faster-germinating species
Fig. 1. Plots of germination, on a probit scale (a probit value of 5 corresponds to 50% germination), against the median base water potential for germination ($\psi_{50}$) for the ten study species. Species (A–J) are ranked in order of increasing seed mass.
could germinate at more negative water potentials (Pearson’s correlation coefficient, \( r = 0.573 \), d.f. = 12, \( P < 0.05 \)).

**DISCUSSION**

There were substantial differences in the germination responses of BCI pioneer species in both \( T_{50} \) and \( \psi_{50} \) that were related to seed size. The low base potential and rapid germination (low \( T_{50} \)) of large-seeded species suggests a ‘risky’ germination strategy that has the potential to enable germination in large gaps and result in microsite pre-emption in advance of slower-germinating species. However, smaller-seeded species are more ‘conservative’, germinating slowly and at less-negative water potentials, which may reduce the likelihood of seedling mortality by ensuring germination occurs primarily in either small gaps or large gaps during prolonged wet periods. For the 14 species examined here and by Daws *et al.* (2002) seed size differences are confounded by phylogenetic contrasts at the family level, and there were no relationships between \( T_{50} \) or \( \psi_{50} \) and seed size within any of the four families (Fig. 2). Consequently, phylogenetic effects independent of seed size may also be important: data from a larger sample of species and families would help to clarify this issue.

**Base water potential and germination microsite**

The 14 species exhibited differences of >1 MPa in \( \psi_{50} \). Species with more negative values of \( \psi_{50} \) (e.g. *Ochroma pyramidale*, \(-1.8\) MPa) can progress towards germination under drier conditions, which may facilitate germination in large (drier) gaps. In contrast, a higher \( \psi_{50} \) will limit germination to small gaps and potentially also to large gaps during extended wet periods. A wide range of \( \psi_{50} \) values has also been reported for other species. For example, Allen *et al.* (2000) report values for 24 desert species ranging from \(-5.92\) to \(-0.07\) MPa, although most values were clustered in the range \(-1.8\) to \(-0.07\) MPa. Similarly, Evans and Etherington (1990) found that among 15 British plant species there was a wide range of responses to water potential with differences between species partly corresponding to habitat type. Thus, the three species with germination most sensitive to decreasing water potentials were all wet-land species (e.g. *Juncus articulatus*). However, among the remaining species there was little clear pattern in sensitivity to water potential in relation to habitat type.

**Role of seed size in germination**

Brokaw (1987) inferred gap partitioning among the pioneer species *Miconia argentea*, *Cecropia insignis* and *Trema micrantha*, based on the observation that plants of these species grow to maturity in gaps larger than 102, 215 and 376 m², respectively, on BCI. While these differences have been related to a trade-off between growth-rate in high light and survival in the shade (Brokaw, 1987), seed size also increases in the same order in these three species: *Miconia argentea* < *Cecropia insignis* < *Trema micrantha*. Similarly, large-seeded species such as *Ochroma pyramidale* and *Cecropia obtusifolia* also occur preferentially in larger gaps sizes (Croat, 1978; Pearson *et al.*, 2003a). On the other hand, the small-seeded *Clidemia octona* and *Clidemia quinquenervia* occur preferentially in small gaps or the edges of large gaps (Croat, 1978). A role for seed mass in contributing to observed gap size preferences is supported by the correlation between \( \psi_{50} \) and seed mass: small-seeded species germinate less well at low water potentials and hence are less able to germinate in the drier environment of large gaps.

Successful establishment in large gaps may necessitate rapid germination to enable emergence in advance of potentially rapid soil drying (at least close to the soil surface), which is supported by the rapid germination of the larger-seeded species (Fig. 1B). Large seed size may also facilitate germination and establishment in large gaps by enabling emergence from greater soil depths (Bond *et al.*, 1999; Pearson *et al.*, 2002) where soil drying will be less rapid. However, even for shallowly buried large seeds, the risk of seedling mortality may be lower than for small-seeded species since the rate of radicle extension is allometrically related to seed mass; radicle growth of seedlings from large seeds may progress faster than the soil drying front in the event of a post-germination dry spell (Daws *et al.*, 2007a). Indeed, several studies have reported that seedlings

![Graph](image.png)
from small seeds have higher mortality under water stress than those from large seeds (Buckley, 1982; Leishman and Westoby, 1994). Thus, for these pioneer species it is proposed that for small-seeded species, a combination of rapid germination and germination at low water potentials is unlikely since it would result in extremely high seedling mortality in the event of a post-germination dry spell. Similarly, Doussi and Thanos (2002) suggested that slow germination of Mediterranean species was an adaptation to unpredictable water availability since this strategy ensures that germination only occurs with the onset of reliable winter rainfall (i.e. it prevents germination occurring following sporadic early autumn/winter rainfall).

However, the mechanism(s) resulting in slow germination in the small-seeded species is unclear. Small seeds have a faster water absorption capacity than large seeds resulting from a larger surface area to mass ratio (Kikuzawa and Koyama, 1999), suggesting that the opposite pattern might be expected. Alternatively, the mechanical restraint provided by the seed coat might contribute to delaying germination. However, Daws et al. (2007a) found no relationship between seed mass and the proportion of seed mass that constituted seed coat, which suggests that this may not contribute to the differences in $T_{50}$. Consequently, further studies are needed to understand the physiological basis of these differences in germination timing.

The present data for neo-tropical pioneers suggest a continuum between large-seeded ‘risk-takers’, with rapid germination and a low $\psi_{50}$, and small-seeded ‘risk-averse’ species with slow germination and a high $\psi_{50}$. This trend is further supported by the pattern of response in germination observed in relation to seed mass and $R:FR$ for pioneer taxa on BCI. Thus, Pearson et al. (2003b) reported that among species with photoblastic germination, large-seeded species require a higher $R:FR$ to trigger germination than small seeds. In this scenario, large-seeded species only germinate in the higher risk environment of large gaps, while the small-seeded species can germinate in all gap sizes. However, these kinds of patterns are not evident in the data of Allen et al. (2000) for 24 desert species where no relationship between $\psi_{50}$ and germination speed was observed. One explanation for this discrepancy is that the analysis of Allen et al. (2000) was potentially confounded by the inclusion of species belonging to various functional groupings (halophytes, psammophytes and generalists) while the present study is based on species from one functional group collected from the same location. Clearly, further studies are needed to test the generality of seed mass, germination rate and $\psi_{50}$ relationships using co-occurring species from additional habitat types that span a range of seed masses and that belong to the same functional group.

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LITERATURE CITED


