From Forest Nursery Notes, Winter 2012

**180. A root drench in unsaturated hydrogel solution reduced stress in transplanted *Eucalyptus pilularis* cuttings but was ineffective for seedlings: a glasshouse experiments.** Thomas, D. S. and Heagney, G. A. Australian Forestry 74(2):133-140. 2011.

# A root drench in unsaturated hydrogel solution reduced stress in transplanted *Eucalyptus pilularis* cuttings but was ineffective for seedlings: a glasshouse experiment

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Revised manuscript received 20 September 2010

## Summary

Available soil moisture and quality of planting material are two important criteria affecting survival during plantation establishment. It has been observed that in northern NSW most seedling deaths occur within the first four weeks of planting. Reducing the rate that plants become stressed is important as less-stressed plants are more capable of exploiting available soil moisture required for survival beyond this four-week period. The health (leaf gas exchange, visual symptoms of leaf and stem wilt) and survival of *Eucalyptus pilularis* Smith seedlings and cuttings were examined following the application of water in the form of either a hydrogel solution or as irrigation. The main findings were that the rate at which stress developed was slower for cuttings than for seedlings; and that supplying more water, either as hydrogel or irrigation, reduced transplant stress and prolonged survival. Differences in morphology between seedlings and cuttings may explain why cuttings developed stress more slowly than did seedlings. Compared with seedlings, cuttings had reduced leaf area, an increased root : shoot ratio and lower leaf area : root dry mass ratio, all of which are traits that enhance water uptake and reduce water loss. The most effective treatments for reducing stress of seedlings and cuttings were either removing individual seedlings or cuttings from nursery trays and dipping the root ball into a 100% saturated hydrogel solution which coated it with a layer of saturated hydrogel, or supplying the equivalent volume of water as irrigation when transplanting the plants. Drenching nursery trays in 25% and 50% unsaturated hydrogel solutions prior to the removal of the plants delayed stress of transplanted cuttings to a similar extent as the 100% saturated hydrogel solution, but these solutions were ineffective in delaying stress in seedlings. It is thought the more open structure of the soil medium used for cuttings allowed the unsaturated hydrogel solutions to enter the root-ball during root drenching, and because the hydrogel solutions are more viscous than water the drainage of the solutions after removing the nursery trays from the root drench was reduced.

*Keywords:* seedlings; cuttings; transplanting; shock; stress; survival; hydrophilic polymers; *Eucalyptus pilularis*

## Introduction

Economically viable plantations require more than 85% survival of planted stock. Seedling mortality after transplanting in field conditions can be caused by a range of plant morphological and environmental factors, although water stress is a common factor (Burdett 1990; Close *et al.* 2005; Grossnickle 2005). Essentially conditions that improve supply of moisture or reduce evaporative loss from leaves will reduce death (Grossnickle 2005). Plant morphological traits such as lower leaf area that limit dehydration, or higher root : shoot ratios that promote water absorption, are thought to be advantageous for seedling survival (Burdett 1990; Close and Davidson 2002; Close *et al.* 2005). Enhanced drought tolerance is correlated with lower specific leaf area and greater leaf thickness (Li and Wang 2003; Warren *et al.* 2005), possibly as thicker leaves would be expected to have higher photosynthetic rates and greater water-use efficiency (Wright *et al.* 2001). Enhanced carbon capture would then supplement carbohydrate reserves that are required to produce the new roots needed to quickly exploit the moisture and nutrients within the bulk soil that provides long-term sustenance (Burdett 1990; Maillard *et al.* 2004). As many plant morphological characteristics are relatively malleable and therefore able to be influenced by nursery practice, it is important to consider these plant characteristics when exploring responses to other parameters.

In NSW both seedlings and vegetative cuttings are used to establish plantations. Seedlings are more common; vegetative cuttings from genetically superior material are used for some selected species (M. Henson, Forests NSW, *pers. comm.*, 2008). The two plant types differ not only in morphological traits such as leaf size and thickness that may affect evaporative water loss, but also in the volume of water held within the root ball of the plant. The soil medium used for the production of cuttings has less water-holding capacity than that used for seedlings. This could influence the success of establishment (or re-establishment), as water held within the root ball is the water most readily available to the transplanted seedling. While it is known that the addition of water either by rain or by irrigation will reduce

transplant shock (Close and Davidson 2002; Viero *et al.* 2002), these additions can be unpredictable or prohibitively costly. An alternative to irrigation is the use of a soil ameliorant such as hydrophilic polymers (hydrogels) which usually promote but do not guarantee 100% survival (e.g. Davies *et al.* 1987; Save *et al.* 1995; Hutterman *et al.* 1999; Viero *et al.* 2002; Sarvas 2003; Rowe *et al.* 2005; Viero and Little 2006). These products retain many times their own mass of water and release that water to the seedling's roots, thereby reducing potential water stress after planting. Hydrogels have the capacity to make water available to plant roots independently of the weather, evaporation and drainage (Specht and Harvey-Jones 1998).

The use of hydrogels applied as a fully hydrated slurry directly into the planting hole increased the survival of *Eucalyptus pilularis* Smith and *Eucalyptus citriodora* Hook. subsp. *variegata* seedlings, two important forestry species in sub-tropical Australia (G. Smith and D. Thomas, Forests NSW, unpublished data). The cost of application by this method, however, can be prohibitive. An alternative method of applying hydrogel, that of dipping root balls into a fully saturated, fine-grained hydrogel solution immediately prior to hand planting, was examined by Thomas (2008). This method coated the seedling's root ball with a thin layer of hydrogel that supplied a little additional water and therefore significantly enhanced survival compared with no application of hydrogel (Thomas 2008). This method was not favoured by planting crews, however, as individually dipping each root ball into the hydrogel immediately prior to planting was considered cumbersome and labour-intensive. Thus a refined method of applying hydrogel that was cheaper, supplied sufficient water to enhance survival and was also acceptable to planting crews was needed.

Standard practice during plantation establishment is to immerse nursery trays containing seedlings or cuttings in water immediately prior to transplanting. This process saturates the nursery soil medium; any water above field capacity drains from the soil before transplanting.

The aim of this experiment was to test if partially saturated hydrogel mixtures (mixtures more viscous than water) are able to enter an immersed root ball and be retained sufficiently to supply significant additional water to the seedling or cutting. Unlike earlier methods of applying hydrogel, the method used in this experiment replaces one operation with a similar operation—that is, immersing the nursery trays containing seedlings or cuttings in a partially saturated hydrogel solution instead of immersing them in plain water, minimising changes to standard planting operations.

## Materials and method

### Planting material

*Eucalyptus pilularis* seedlings and cuttings used in this experiment were produced by Forests NSW Grafton Nursery (29°38'S 152°58'E). Seeds were sown in germination trays of 6-cm$^3$ cells containing a soil medium of 90% composted pine bark (0–6 mm diameter) and 10% coir fibre. Seeds were covered with 2-mm vermiculite. The trays were placed on raised benches and received irrigation daily and fertiliser weekly using 3 g l$^{-1}$ liquid fertiliser 20.6:8.5:16.0 (N:P:K) at a rate of 5 l m$^{-2}$. Seedlings remained there for 10 weeks, when they had developed 1–2 pairs of leaves above the cotyledons, and were then transplanted into 93-cm$^3$ cells in 40-cell nursery trays. The soil medium was identical to that used in germination trays. Seedlings were then grown under the standard conditions employed by Forests NSW nurseries, receiving regular irrigation, pest and disease control, and fertiliser through irrigation until 27 weeks old.

Cuttings were produced by Forests NSW Grafton Research Nursery in 85-cm$^3$ pots contained in 40-cell nursery trays. Cuttings about 10 cm long were collected from apical material of *E. pilularis* seedlings and planted in a medium consisting of carbonised rice husks, vermiculite and perlite (1:1:1). These were raised in a glasshouse and received regular misting until roots had initiated, after when they were placed outside on raised beds and regularly received irrigation and fertiliser until they were ready for planting.

Thirty seedlings and twenty cuttings were randomly selected from unplanted material to determine their morphological characteristics. Plant height was measured from the soil surface to shoot apex. Stem diameter at the soil surface was recorded, and a stem sturdiness quotient calculated as height/stem diameter. The number of leaves on each seedling was counted and leaf area measured using a LiCor 3100 leaf area meter (LI-COR, Lincoln, Nebraska, USA). Roots were washed free of soil. Dry mass of leaves, stem and roots was then measured after oven drying at 70°C. Root : shoot ratio (g g$^{-1}$) and root : leaf area ratio (g cm$^{-2}$) were calculated from these data. Specific leaf area (m$^2$ kg$^{-1}$) was calculated as leaf area / leaf dry mass.

### Experimental design

This experiment examined the survival of *E. pilularis* seedlings and cuttings in response to the application of hydrogel and irrigation treatments at the time of planting. The experiment consisted of a 2×5 factorial in a randomised complete block design (Factor A = plant types and Factor B = irrigation/hydrogel applications), replicated six times. Five varying combinations of water and hydrogel were used on both seedlings (treatments 1–5) and cuttings (treatment 6–10) (Table 1).

In addition to survival we also measured leaf gas exchange shortly after planting. Because leaf gas exchange is affected by soil moisture and a range of atmospheric environmental conditions such as temperature, light and humidity that vary over a diurnal period, it was considered necessary to provide an additional treatment of plants receiving daily irrigation to ascertain if potential differences in leaf gas exchange of hydrogel treatments were affected by water availability or by the prevailing atmospheric environment. These additional treatments consisted of seedlings and cuttings planted in the same soil type and receiving regular (daily) irrigation to field capacity. These additional 'regular irrigation' treatments were used only to examine treatment effects on leaf gas exchange and not to compare survival or stress categories.

The 72 plots (60 used to assess survival and stress category, and 12 used for the regular irrigation treatments) consisted of 30-litre sealed containers filled with 25 kg of soil. The soil was a brown earth soil (Milford 1999) derived from late carboniferous siltstone, mudstone and conglomerate (Gilligan *et al.* 1992). It is a clay loam, well structured soil with a water-holding capacity of 41%. Soil moisture content in the plots (30-litre containers)

**Table 1.** The treatments used to assess survival

| Treatment | Material | Description |
|---|---|---|
| 1 and 6 | Seedlings and cuttings | Control: Immerse nursery tray containing seedlings or cuttings in water for 5 minutes prior to removal of plants and transplanting. |
| 2 and 7 | Seedlings and cuttings | 25% unsaturated hydrogel as a root drench: Immerse nursery tray containing seedlings or cuttings in 25% unsaturated hydrogel for 5 minutes prior to removal of plants and transplanting. |
| 3 and 8 | Seedlings and cuttings | 50% unsaturated hydrogel as a root drench: Immerse nursery tray containing seedlings or cuttings in 50% unsaturated hydrogel for 5 minutes prior to removal of plants and transplanting. |
| 4 and 9 | Seedlings and cuttings | 100% saturated hydrogel applied as a root dip: Control plant removed from nursery trays and dipped into a fully saturated (100%) hydrogel. |
| 5 and 10 | Seedlings and cuttings | Irrigation at planting: Control seedlings or cuttings, and 46 ml water applied to each seedling or 26 ml water applied to each cutting immediately after planting. |

was amended to 20.0% (±0.2)% at the start of the experiment. Soil moisture during the experiment was monitored using theta probes (Delta-T type 2, Hoddeston, UK) and readings converted to soil moisture content (Delta-T devices 1999).

The hydrogel (WaterSave—Type F, Polymer Innovations Pty Ltd, Singleton, NSW, Australia) had a particle size of less than 0.3 mm. The 100% saturated solution was made by mixing 2.5 g $l^{-1}$ hydrogel in water. Unsaturated hydrogel solutions of 50% and 25% solutions were made of 1.25 g $l^{-1}$ hydrogel in water and 0.625 g $l^{-1}$ hydrogel in water respectively. Although these unsaturated hydrogel solutions were more viscous than water we assumed they could enter the root media during soaking. Hydrogel solutions were prepared and mixed intermittently for 30 minutes to allow the hydrogel to adequately hydrate.

The control treatment for the seedlings and cuttings (Treatments 1 and 6 respectively) was applied by immersing nursery trays containing plants in water for 5 minutes (Table 1). The root-dip hydrogel treatments (Treatments 4 and 9) involved removing a soaked plant from its cell and dipping the root ball in a 100% saturated hydrogel solution immediately prior to planting. Treatments 2 and 7, and 3 and 8, involved immersing nursery trays for 5 minutes in 25% and 50% unsaturated hydrogel solutions respectively and then removing plants from cells and planting. After imposing treatments, eight seedlings or cuttings were planted in each plot using hand trowels so that the top of the root ball was 5 cm below the soil surface.

The weight of 48 representative plants (seedlings and cuttings) was determined immediately prior to planting to determine the volume of water that each treatment (Treatments 1–4 and 6–9) supplied. Seedlings dipped in 100% saturated hydrogel–water solution increased in weight by an average of 46 g $seedling^{-1}$ compared with control seedlings, showing that they had access to 46 ml additional water (the weight of the hydrogel in the saturated solution was not taken into account, but would have decreased the available water by 0.25%).

Soaking seedlings in 50% or 25% unsaturated hydrogel solutions added less than 5 g, or the equivalent of 5 ml water $seedling^{-1}$. Cuttings dipped in 100% saturated hydrogel, or immersed in 50% and 25% unsaturated hydrogel solution added only 24 g, 16 g and 11 g respectively compared with control cuttings. We assumed the 100% hydrogel solutions would be most effective, but in order to ascertain if these findings would be due to the additional water or to the hydrogel per se, it was necessary to supply the same amount of additional water applied by the 100% saturated hydrogel treatments as irrigation after planting to seedlings (Treatment 5) or to cuttings (Treatment 10). Consequently 46 ml $seedling^{-1}$ of water was applied as irrigation when planting seedlings and 26 ml water $cutting^{-1}$ was applied as irrigation when planting cuttings.

The planting containers (i.e. plots) were placed in a glasshouse at Coffs Harbour (30°19'S, 153°07'E). Four household fans were positioned in the glasshouse, and glasshouse air vents were left open to facilitate air flow during the experiment. Air temperature and relative humidity (RH) inside the glasshouse were recorded at seedling height using Gemini data loggers (Tinytag Extra TGX-3580). Climate within the glasshouse during the daylight hours averaged 30(±0.6)°C maximum daily temperature (±standard error) with 54(±1.7)% RH. Within the experimental period (52 days), seven days had maximum daily temperatures greater than 35°C and one day was hotter than 40°C.

### Assessment of plant stress and leaf gas exchange

The stress of each plant was visually assessed using a five-point scale (Table 2), with 1 representing a healthy plant and 5 repre-

**Table 2.** Description of stress categories

| Stress category | Leaf wilting symptom | Stem apex symptom |
|---|---|---|
| 1 (Unstressed or healthy) | Less than 25% | Apices erect |
| 2 | Between 25% and 50% | Minor drooping of apices |
| 3 (Very stressed but not dead) | More than 50% but petioles above horizontal | Pronounced drooping of all apices, but apices above horizontal |
| 4 | More than 50% but petioles below horizontal | Pronounced drooping of all apices; apices below horizontal |
| 5 (Dead) | Leaf abscission and discoloured | Stem dehydrated |

senting a dead plant. Assessments were made every second day until 16 days after planting after when assessments were made at 20, 23, 26, 30, 35, 39, 47 and 52 days after planting. All seedlings and cuttings were considered dead 52 days after planting. The experiment was terminated at this point.

Leaf gas exchange was measured on the youngest fully expanded leaf from two plants per plot at 2, 4 and 8 days after planting using a LI-6400 (LI-COR, Lincoln, Nebraska) portable gas exchange system equipped with a light source (6400-02B LED, LiCor). Plants from all ten treatments used to assess survival and the plants that received regular irrigation were measured. Measurements were made in the morning (09:00–12:00 EST). Light levels were maintained at 1000 $\mu$mol $m^{-2}$ $s^{-1}$. During measurements, leaf temperature was controlled by maintaining the LI-6400 block temperature at 25°C. Ambient humidity of the incoming air to the leaf chamber was left at that of the external glasshouse environment. Reference $CO_2$ concentration was maintained at of 375 $\mu$mol $CO_2$ $mol^{-1}$ air.

### Statistical analysis

All seedlings or cuttings progressively moved from a minimal stress category (at planting) to eventual mortality. The proportion of seedlings that met or exceeded a particular category was calculated for each sampling date. Kaplin–Meier estimates for the proportion of failure of a particular stress category as a function of days after planting were generated. The influence of treatments on this non-censored data was analysed using log-rank non-parametric survival analysis comparing paired collections of treatments. Treatments that were not significantly different ($P > 0.05$) were classified as belonging to the same statistical group. Repeated continuous data such as soil moisture and leaf gas exchange data were analysed by repeated analysis of variance. Plant morphological characteristics between seedlings and cuttings and moisture (as hydrogel) added by treatments were analysed using two-way analysis of variance. All data was analysed using Genstat 9.1 (Lawes Agricultural Trust) with the level of significance set to 0.05.

## Results

### Morphology of planting material

Seedlings were taller than cuttings and had a larger leaf area, but their leaves were thinner (Table 3). Plant total dry mass and root dry mass were similar for seedlings and cuttings, with the seedlings having a slightly lower leaf dry mass than cuttings. Seedlings had higher leaf area : root mass ratio and a lower root : shoot mass ratio than cuttings. This suggested a reduced potential for water absorption (smaller root) compared with the potential for water loss (greater leaf area) in seedlings than cuttings.

### Growth conditions

Soil moisture content progressively declined from 20.0(±0.2)% at the start of the experiment but was not affected by plant type, and minimal differences existed between treatments. Soil moisture content 12 days after planting was 13(±0.2)% in plots that received either a soil drench at planting or the 100% saturated hydrogel treatments but 11(±0.1)% in other treatments, including bare soil, suggesting much of the moisture loss was due to evaporation from the soil rather than plant transpiration. Soil moisture content 30 and 52 days after planting in all treatments had declined to 9(±0.9)% and to 5(±0.6)% respectively.

### Stress and survival of planted material

Seedlings behaved differently from cuttings. When seedlings and cuttings received similar hydrogel or water treatments, the cuttings significantly ($P < 0.001$) retained a lower stress category and delayed moving to higher stress categories compared with the seedlings (Fig. 1). All hydrogel treatments (100%, 50%, 25%) and the irrigation treatment performed similarly and all these treatments delayed the movement from stress category 1 to 5 compared with the control treatment (Fig. 1). In contrast, for seedlings, the 100% saturated hydrogel and water root drench treatments significantly ($P < 0.05$) delayed movement from stress category 1 to 5 compared with 50%, 25% unsaturated hydrogel

**Table 3.** Morphological characteristics of seedlings and cuttings at commencement of the experiment. Mean data for 30 seedlings and 20 cuttings. Numbers in parenthesis are standard errors. Similar letters for a particular plant characteristic denote means for seedlings and cuttings were not significantly different ($P > 0.05$).

| Descriptor of morphology | Seedlings | Cuttings |
|---|---|---|
| Plant height (cm) | 34.2 (1.1) a | 18.2 (0.5) b |
| Stem collar diameter (mm) | 2.75 (0.08) a | 2.58 (0.7) a |
| Stem sturdiness quotient (cm $cm^{-1}$) | 125.8 (4.3) a | 71.4 (2.4) b |
| Number of leaves | 9.2 (0.4) a | 8.7 (0.3) a |
| Leaf area ($cm^2$) | 97.9 (5.3) a | 56.7 (3.0) b |
| Specific leaf area ($m^2$ $kg^{-1}$) | 19.8 (0.4) a | 10.8 (0.2) b |
| Leaf chlorophyll (SPAD units) | 31.5 (0.7) a | 27.7 (0.7) b |
| Leaf dry mass (g $plant^{-1}$) | 0.59 (0.04) a | 0.64 (0.04) a |
| Stem dry mass (g $plant^{-1}$) | 0.36 (0.03) a | 0.22 (0.01) b |
| Root dry mass (g $plant^{-1}$) | 0.24 (0.02) a | 0.29 (0.02) a |
| Pant dry mass (g $plant^{-1}$) | 1.19 (0.08) a | 1.15 (0.06) a |
| Root:shoot ratio | 0.26 (0.01) a | 0.34 (0.01) b |
| Leaf area : root dry mass ($cm^2$ $g^{-1}$) | 502.6 (25.6) a | 244.5 (8.5) b |

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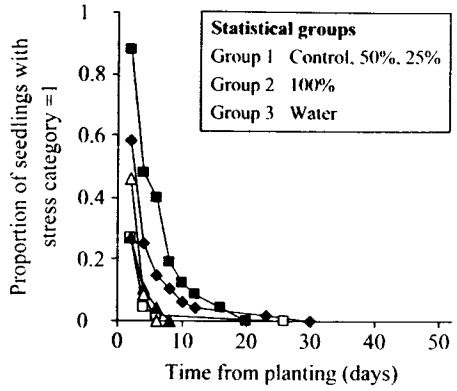
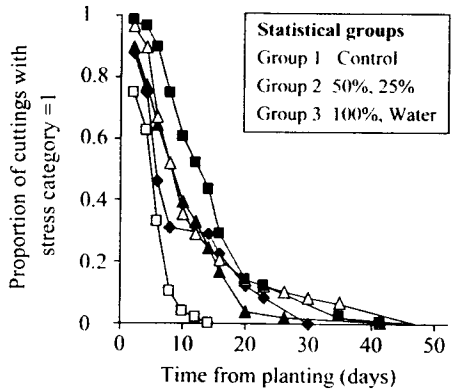
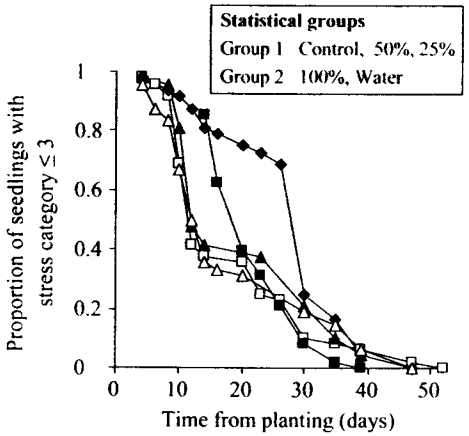


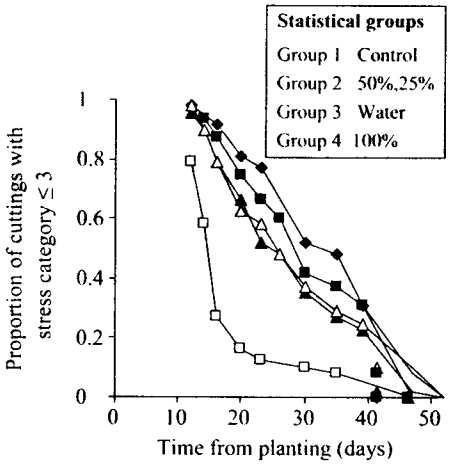

(a) Proportion of seedlings with stress category =1



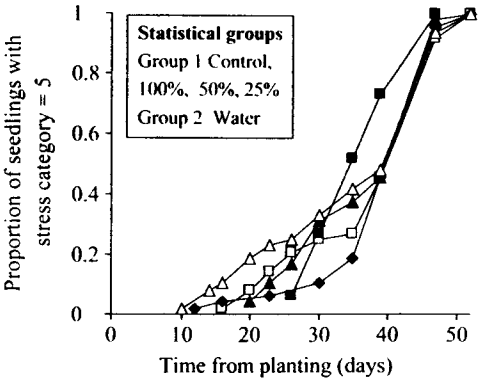

(b) Proportion of cuttings with stress category =1



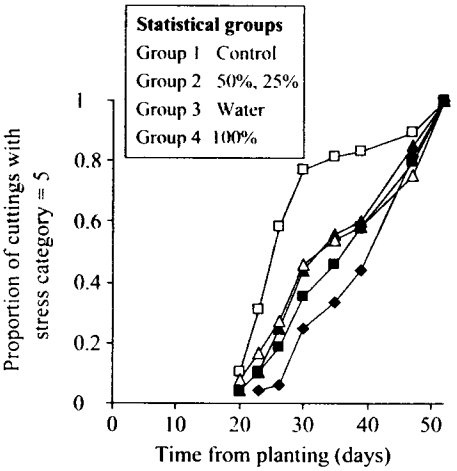

(c) Proportion of seedlings with stress category ≤ 3




(d) Proportion of cuttings with stress category ≤ 3




(e) Proportion of seedlings with stress category = 5




(f) Proportion of cuttings with stress category = 5

**Figure 1.** The stress of seedlings (a, c, e) and cuttings (b, d, f) as a function of time after planting. = Control; △ = 25% unsaturated hydrogel (25%); ▲ = 50% unsaturated hydrogel; ◆ = 100% saturated hydrogel applied as a root dip (100%) and ■ = irrigation at planting (water). (a), (b) = Proportion of seedlings or cuttings with stress category = 1 (i.e. unstressed or healthy) (c), (d) = Proportion of seedlings or cuttings with stress category ≤ 3 (i.e. very stressed) (e), (f) = proportion of seedlings or cuttings with stress category = 5 (i.e. dead). Treatments not significantly different ($P > 0.05$) as measured by log-rank non-parametric survival analysis are classified as belonging to the same statistical group.

treatments and the control (Fig. 1). Applying water either as 100% hydrogel or as a root drench at planting therefore delayed the onset of plant stress compared with the control, but applying water to seedlings in the form of a root drench of either a 25% or a 50% unsaturated hydrogel did not significantly alter the movement of seedlings from stress category 1 to 5 compared with the control treatment (Fig. 1). Seedlings remained in stress category 1 (i.e. unstressed) longer when water was applied as irrigation than when the same quantity of water was applied as 100% hydrogel, but seedlings survived for longer (i.e. movement to stress category 5 was delayed) when water was applied as 100% saturated hydrogel compared with when water was applied as irrigation.

### Leaf gas exchange

Leaf gas exchange of seedlings was significantly greater ($P < 0.05$) than that of cuttings two days after planting but not at any subsequent time (Table 4; only days 2 and 4 shown). All hydrogel treatments had no effect on leaf gas exchange (Table 4). Seedlings and cuttings that received water once as irrigation immediately after planting had higher rates of net photosynthesis, stomatal conductance and transpiration at the first measurement time two days after planting. By four days after planting, however, and at subsequent measurement times, all seedlings or cuttings not receiving regular irrigation had negligible rates of leaf gas exchange and were not significantly different from each other (Table 4). Rates of net photosynthesis, stomatal conductance and transpiration were higher at all measurement times in regularly irrigated treatments than in other treatments.

## Discussion

In situations of limited water availability, hydrogels were able to reduce the initial period of transplant shock in *E. pilularis* plantations, therefore positioning transplants to continue the normal growth (particularly root growth) required for successful establishment. From a management perspective, the use of hydrogels in plantation forestry may be viewed as a method to reduce stress of transplanted material until newly formed roots penetrate the bulk soil or until rain provides moisture to newly planted seedlings. The hydrogels are effective because less stressed plants are more likely to be able to exploit rainfall to a greater extent. Whilst prolonging survival is the ultimate goal, an important intermediate goal is to reduce the rate at which plants become stressed.

The application of a hydrogel at planting decreased the rate of wilting and prolonged the survival of *E. pilularis* seedlings and cuttings. The most appropriate treatment differed for different planting materials (Fig. 1). While health and survival of cuttings were enhanced following the immersion of nursery trays in an unsaturated solution of hydrogel, this method was ineffective for seedlings. The most effective method of applying a hydrogel to seedlings for planting was by dipping individual root balls into a 100% saturated hydrated mixture.

The observed differences between cuttings and seedlings were possibly related to the different types of soil medium used. Cuttings are grown in an open, free-draining growth medium to reduce soil pathogens and facilitate initiation of roots, while seedlings are grown in a more compact growth medium. It appears that the more open and free-draining structure of the medium used for cuttings allows the unsaturated hydrogel solutions to move into the root ball. Then, as unsaturated hydrogel is more viscous than water, drainage of the root balls may be retarded after the nursery trays have been immersed.

**Table 4.** Rates of net photosynthesis, stomatal conductance and transpiration measured two and four days after planting. Planting material (seedling and cutting) was significantly different only at two days after planting. 'SED material' and 'SED hydrogel' respectively denote standard error of difference in means of material (seedling or cutting) and hydrogel treatments. Similar letters (x, y, z) within a planting material denote means for treatments not significantly different ($P > 0.05$). Similar letters (a, b) within a treatment denote means for the planting material not significantly different ($P > 0.05$).

| Days after planting | Treatment | Net photosynthesis ($\mu$mol $m^{-2}$ $s^{-1}$) | | Stomatal conductance (mmol $m^{-2}$ $s^{-1}$) | | Leaf transpiration (mmol $m^{-2}$ $s^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | Seedlings | Cuttings | Seedlings | Cuttings | Seedlings | Cuttings |
| 2 | 1 and 6. Control | 3.30 ax | 1.49 bx | 73 ax | 33 bx | 0.83 ax | 0.43 bx |
| 2 | 2 and 7. 25% unsaturated hydrogel | 4.94 ax | 1.73 bx | 113 ax | 34 bx | 1.28 ax | 0.47 bx |
| 2 | 3 and 8. 50% unsaturated hydrogel | 3.81 ax | 1.62 bx | 51 ax | 24 bx | 0.73 ax | 0.36 bx |
| 2 | 4 and 9. 100% saturated hydrogel as a root dip | 4.82 ax | 2.78 bx | 155 ax | 62 bx | 1.43 ax | 0.81 bx |
| 2 | 5 and 10. Irrigation at planting | 7.09 axy | 2.47 bx | 190 ay | 54 bx | 1.84 ay | 0.71 bx |
| 2 | Regular irrigation after planting | 10.58 ay | 8.70 ay | 312 az | 268 ay | 2.94 az | 2.45 ay |
| 2 | SED material | 0.76 | | 25 | | 0.21 | |
| 2 | SED hydrogel | 1.32 | | 44 | | 0.37 | |
| | | Seedlings or cuttings | | Seedlings or cuttings | | Seedlings or cuttings | |
| 4 | 1 and 6. Control | 0.83 x | | 4 x | | 0.05 x | |
| 4 | 2 and 7. 25% unsaturated hydrogel | 0.45 x | | 13 x | | 0.08 x | |
| 4 | 3 and 8. 50% unsaturated hydrogel | 0.68 x | | 7 x | | 0.06 x | |
| 4 | 4 and 9. 100% saturated hydrogel as a root dip | 0.80 x | | 14 x | | 0.05 x | |
| 4 | 5 and 10. Irrigation at planting | 1.74 x | | 11 x | | 0.03 x | |
| 4 | Regular irrigation after planting | 10.52 y | | 135 y | | 1.66 y | |
| 4 | SED hydrogel | 0.94 | | 16 | | 0.20 | |

In contrast, the more compact soil medium used in production of seedlings did not facilitate movement of the partially saturated hydrogel mixture into this medium. This is indicated by the negligible weight gain (< 5 g seedling$^{-1}$) when seedlings were immersed in unsaturated hydrogel solutions compared with when they were immersed in water. These data suggest that seedlings should be prepared for hand planting by immersing entire nursery trays of seedlings in water to saturate the soil medium, and then dipping individual seedling in a solution of fully hydrated hydrogel prior to planting. In contrast, entire nursery trays of cuttings may be immersed in an unsaturated solution of hydrogel (rather than in water) before planting.

It is apparent that an increased supply of water reduced stress and prolonged survival (Fig. 1). This is in agreement with other studies (e.g. Huttermann *et al.* 1999; Close and Davidson 2002; Viero *et al.* 2002), but it is also apparent that plant type, that is, seedlings or cuttings, behaved differently—cuttings maintained a less-stressed status longer after planting than did seedlings, although time to stress category 5 (i.e. dead) was similar (Fig. 1). Differences in plant morphology may explain these different responses. Plant morphological traits that limit dehydration such as lower leaf area, or promote water absorption such as higher root : shoot ratios, are thought to be advantageous to seedling survival (Burdett 1990; Close and Davidson 2002; Close *et al.* 2005). Cuttings had less leaf area and a proportionally larger root dry mass than seedlings, equating to a higher root : shoot ratio and lower leaf area : root dry mass ratio (Table 3).

The morphological trait of thicker leaves, as was observed in cuttings, would be expected to correspond to increased photosynthetic rates and greater water-use efficiency (Wright *et al.* 2001; Sefton *et al.* 2002). This was not observed, however—carbon capture by photosynthesis quickly declined due to insufficient water (Table 4). This was evidenced as the leaf gas exchange of regularly irrigated plants was maintained following planting, whereas leaf gas exchange of seedlings and cuttings supplied with water or hydrogel only at planting quickly declined (Table 4). It appears that the thicker leaves of the cuttings may have been related to a more severe nutritional and water deficit 'hardening' period in the weeks before the experiment. Reducing irrigation in the later stages of growth is commonly employed as a means of hardening seedlings or cuttings in anticipation of harsher conditions in the field than in the nursery (Royo *et al.* 2001; Guarnaschelli *et al.* 2003; Villar-Salvadore *et al.* 2004; Thomas 2009).

In conclusion, the most practical method of applying hydrogels was influenced by the type of planting material used. Dipping individual root balls into a 100% saturated hydrated hydrogel after their removal from nursery trays was most effective for seedlings, whereas vegetative cuttings benefited not only from this method but also from the alternative of immersing entire nursery trays into 25% or 50% unsaturated hydrogel mixtures. The more open soil medium used in the production of cuttings compared with seedlings probably allowed the partially-unsaturated hydrogel to enter the soil medium during the root drenching procedure and, unlike immersing in water, the more viscous nature of hydrogel resulted in greater retention of the hydrogel–water mixture near the root zone.

**Acknowledgements**

This project was achieved due to the willing assistance and technical support of Piers Harper and Darrel Johnstone, and the personnel of Forests NSW Grafton Commercial Nursery and Grafton Research Nursery. The polymer hydrogel was supplied by Polymer Innovations, NSW. Jann Conroy, University of Western Sydney, generously loaned the Li-Cor 6400 portable photosynthesis system used in this project. The authors would like to thank all reviewers, particularly P. Viero, whose comments greatly improved this manuscript.

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