The effect of substrate compaction on plant water use and the implications for phytocap design specifications

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Abstract

There is little experimental evidence to guide the design of substrate compaction for the optimal plant water use performance of a landfill phytocap. A glasshouse study was undertaken to address this with aim to evaluate the effect of substrate compaction on the water use of a phytocap plant community. Four levels of relative compaction (RC), i.e. the ratio of dry bulk density over the standard maximum dry bulk density, (72%, 77%, 82%, and 87 %) were considered. The native tree and grass species selected were typical of an Australian phytocap plant community: *Themeda triandra*, *Microlaena stipoides*, *Eucalyptus camaldulensis*, *Eucalyptus cladocalyx*, *Acacia mearnsii* and *Allocasuarina verticillata*. Plant water use was measured by weight as the difference between planted and unplanted cores over 5 drying periods occurring through the first 6 months of plant establishment traversing winter, spring and summer. Plant water use was optimal for all species at low-intermediate RC (72%, 77% and 82%), and all species except *Themeda triandra*, were most negatively impacted by the highest RC of 87%. The best linear model based on Akaike's Information Criterion included a second-order term for the continuous fixed factor 'relative compaction' and the categorical fixed factor 'species'. This model showed plant water use to be optimum at a RC of 76.5% and highlighted a wide range of RC's (70 – 83%), for which plant water use is not less than 90% of this optimum. It also highlighted increasing plant water use-sensitivity to RC's beyond these ranges, with a RC > 86% and a RC < 67% leading to reductions in plant water use of 20% or more. Substrate specifications are recommended to optimize phytocap plant water use within achievable RC ranges. These can be generalized beyond application to a single species or substrate texture to inform the design and quality assurance of substrate placement for future landfill phytocaps.

Keywords: landfill capping; phytocap; plant water use; soil compaction; evapotranspiration; Australian native plants; ET covers; land rehabilitation; soil bulk density; water balance; glasshouse study, store-and-release cover; *Themeda triandra*; *Microlaena stipoides*; *Eucalyptus camaldulensis*; *Eucalyptus cladocalyx*; *Acacia mearnsii*; *Allocasuarina verticillata*.

1 Introduction

Phytocaps are constructed ecosystems used to cap landfill and mine wastes. They consist of one or more layers of substrate comprised of soil, sub-soil or compost, planted with deep-rooted plant species such as perennial grasses, shrubs and trees. The specific characteristics of the substrate influence its ability to store water, maintain slope stability and provide the water and nutrients essential for the growth and survival of the phytocap plant community. Plant transpiration together with evaporation (evapotranspiration) typically accounts for more than 60% of the precipitation that falls on vegetated landfill caps (Apiwantragoon et al., 2015) and is essential for preventing deep drainage into the waste mass as a key objective and indicator of phytocap performance. Evapotranspiration will vary depending on the vegetation type planted but has been estimated to account for 60-93% of precipitation (woodland plantings) or 44-88% (grassland only plantings) (Yunusa et al., 2010). Interception is also a crucial water balance component, for instance, tree species on landfill may intercept greater than 30% of the precipitation and transpire 1-2 mmday^{-1} (Venkatraman and Ashwath, 2010). Plants, especially the ground cover provided by grasses, also armor the cap against erosion and are crucial on slopes and in vulnerable high-rainfall areas. Plant roots provide geo-mechanical reinforcement and the dewatering effect of PWU increases the stability of slopes by reducing pore water pressure (Chirico et al., 2013). As phytocaps include deep-rooted plants as part of their design, they are well-placed to take advantage of these bioengineering benefits, yet these have not been the focus of phytocap studies to date. Phytocaps are attractive to landfill operators as they are affordable to construct due to their use of locally sourced substrates (Albright et al., 2010) and their simplicity makes them an accessible option for landfills located in rural areas and in developing countries

(Rawlinson et al., 2004; Yuen et al., 2010). Their capacity to support a mature ecosystem that includes trees also offers obvious rehabilitation advantages. To fully capitalize on the benefits offered by phytocaps, it is essential to develop clear, evidence-based, design guidance to inform choices such as substrate thickness and placement compaction.

Thicker phytocap substrate has the advantage of greater water storage, depth for root establishment and buffering between the potentially deleterious impacts of landfill gases and the developing plant community (Dobson and Moffat, 1995; Flower et al., 1981). Landfill gas impacts on plant growth occur due to the exclusion of air from soil voids, reducing the supply of oxygen to roots for respiration, and also due to the toxic effects of elevated carbon dioxide (Chan et al., 1991; Marchiol et al., 2000; Wong and Yu, 1989). However, thicker substrate is more expensive and requires more commercially valuable air space (i.e. landfill capacity) than a thinner substrate from the same source. Thickness is commonly determined through sensitivity-based hydrological simulations or other calculations based on soil properties (Benson and Chen, 2003) or prescribed as minimum in environmental regulations. For example, a total cap thickness of no less than 1.5m is required in the State of Victoria, Australia (Environment Protection Authority Victoria, 2015). Substrate placement involves the placement of a thickness of soil or soil-like materials typically in layers or 'lifts' using large machinery. This results in substrate *compaction*, which is "the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing bulk density" (Soil Science Society of America, 2008). Increasing levels of compaction cause a decline in macroporosity and an increase in microporosity that leads to an increase in penetration resistance, a decrease in the water held at field capacity and a reduction in aeration at high water content (Chen et al., 2014). This has implications for civil and ecological engineering compaction objectives: higher compaction generally improves slope stability, whereas lower compaction generally improves water storage, root growth depth and plant nutrition (Goldsmith et al., 2001). It is also relevant to consider the negative impacts of high substrate compaction on plant morphology and physiology (primarily reduced root elongation and leaf expansion that impacts the plants ability to transport nutrients and water) and the exacerbation of these effects when the substrate is drying (Bengough et al., 2011; Bingham, 2001). PWU can be limited at low substrate compactions by poor root-to-substrate contact which impacts water and nutrient uptake, and at higher compactions by high mechanical impedance and low porosity which reduces root exploration and aeration (Håkansson and Lipiec, 2000; Kooistra et al., 1992; Veen et al., 1992). Further, for a constant substrate compaction, the strength of the substrate increases nonlinearly as moisture content decreases (Smith et al., 2001).

For phytocaps, compaction can be expressed as absolute dry bulk density (dry soil mass/soil volume), g/cm^3, or as a percentage of a reference maximum dry bulk density. Relative compaction (RC) is the ratio of field dry bulk density to the maximum dry bulk density determined in the laboratory at the optimum moisture content (OMC) for compaction using standard compactive effort of 596 kJm^{-3} (Standards Australia, 2017). RC has the advantage of allowing compactions to be compared irrespective of soil texture and is used throughout this paper as the measure of compaction. Phytocaps are typically specified at RC levels between 80-90% at moisture contents drier than OMC (Albright et al, 2010), with RC targets $\geq$ 85% being most common (Benson et al., 2007). Examples of studies with specifications falling within these ranges include (Abichou et al., 2012; ACAP, 2005; McGuire et al., 2009; Schnabel et al., 2012; Wong et al., 2007). It is also important to discuss the practical achievement of substrate compactions in the field alongside design specifications given for phytocap field trials. Butler (2004) described a 10% RC range (i.e. 80-90%) as an achievable or “workable” specification based on their experience of full-scale substrate placement and the difficulties associated with achieving a narrower RC range of 5% (i.e. 83-88%). Similarly, McGuire et al (2009) reported difficulties with managing the variability of substrate compaction in the field, achieving a RC range of 78–97% with a mean of 86%, while aiming to achieve ≤80%.

The literature related to bioengineering of slopes, where slopes need to be geotechnically stable and not limiting to plant growth, is of relevance to landfill phytocap specification. Daddow and Warrington (1983) coined the growth limiting bulk density (GLBD) which refers to a threshold value specific to each soil texture beyond which roots can no longer penetrate due to high mechanical impedance. Through review of the GLBD’s of 80 different soil textures, GLBD isodensity lines were overlaid across the USDA soil texture triangle. Goldsmith et al (2001) converted Daddow and Warrington’s GLBD’s to RC’s and found them to vary between 82 and 91% but was of the opinion nonetheless that a RC specification of 80-85%, close to (or overlapping) these limits was most practical for bioengineering slopes. Phytocap specifications have generally been derived from operational experience at a single site and/or the measurement of the surrounding native soils. Considering the needs of the plant community, Kiel et al. (2002) built an intentionally low-compaction phytocap achieving a RC range of 75-82% and recommended a slightly expanded RC specification of 75-85% based on their measurement of the native soils at a RC of 85%. McGuire et al. (2006) measured the RC of the native soils surrounding their site and found them to be closer to 75%, and set a RC specification of ≤ 80% on that basis.

Cropping studies have shown that ameliorating compaction via deep ripping of the soil moderately increases evapotranspiration, but substantially reduces the ratio between evaporation and evapotranspiration, and importantly (from a phytocap perspective) reduces the frequency and rate of drainage below the crop root zone (Sadras et al., 2005). In the context of turf management, a 20% reduction in PWU was measured due to compaction over a 4 month study of the grass species *Poa pratensis* (O'Neil and Carrow, 1982) with subsequent studies showing compaction reduced both total water use and moisture extraction in the deeper zones (Agnew and Carrow, 1985). However, little is known about the specific effect of selected substrate RC targets/ranges on the performance of a designed phytocap, especially on the PWU of the phytocap plant community which is a large component of the overall water balance. The aim of this study is to improve landfill phytocap performance outcomes through greater consideration of the phytocap plant community in the specification of substrate RC. The specific hypothesis is that an ideal RC range can be identified that will enable optimal (or maximum) PWU performance to be realized for a landfill phytocap. The first objective is to quantify relative PWU for a range of species under field-relevant experimental conditions at different levels of RC. A controlled glasshouse study was carried out to measure the PWU of six plant species in tall cylinders of substrate at four levels of RC over the crucial first six months of plant establishment. As phytocaps are rarely irrigated and decreasing moisture content exacerbates the effect of RC (by increasing substrate strength), plants were subjected to five extended drying periods through winter, spring and summer. The second objective is to develop the relationship between RC and PWU. A set of multiple linear regression models were applied to the observed PWU for different species at different levels of RC. The third objective is to recommend RC specifications for the placement of landfill phytocap substrate. Operationally-achievable RC ranges are recommended that can be used to specify phytocap substrate for optimal PWU performance.

2 Materials and methods

2.1 Substrate

Substrate was sourced from a commercial landfill facility in Victoria, Australia (Wollert landfill: 37°35’S, 145°2’E) referred to in this paper as the ‘site’. The substrate was a gravel-sand-clay mixture, GC, according to the United Soil Classification Scheme, comprising: 43% gravel (2 - 20mm), 40% sand (50 - 2000µm), 16% clay (<2µm), and a relative <1% gap grading of silt (2µm - 50µm) determined by AS 1289.3.6.1-2009 (Standards Australia, 2009). The standard maximum dry bulk density of the substrate was 2.02 g/cm^3 at an optimum moisture content (OMC) of 12.7 w/w% determined by AS 1289.5.1.1:2017 (Standards Australia, 2017) and was used to calculate relative compaction (RC) as a percentage. Moist substrate was collected from phytocap pilot trials at the site in 10 kg polythene bags and equilibrated for 48 hrs without need for further moisture conditioning as the field moisture content was close to OMC.

2.2 Preparation of substrate

The substrate was packed into 0.5m tall polycarbonate cylinders (150mm in diameter, 1.5mm wall thickness) at 4 levels of RC: 72% (1.45gcm^{-1}), 77% (1.55gcm^{-1}), 82% (1.65gcm^{-1}), and 87% (1.75gcm^{-1}); with the required level of RC achieved in 110mm layers using a 75 mm diameter hydraulically lowered metal stage of an Instron Model 1122 with a 5000 N load cell. During packing, a steel plate was fitting inside the cylinder walls to evenly distribute the applied force across the layer surface and a rigid PVC sleeve was used to prevent side-splitting. Compacted substrate layers were scarified to 5 mm to ensure continuity at the layer boundaries, with the bottom layer of the cylinder contained with 1 mm grade plastic mesh. Tolerances were set to allow acceptable variation in the target RC during packing (equivalent to a RC range of 2%). Layers of lower RC were recompacted and layers of higher RC were scooped out and discarded, resulting in 0.02-0.74% variation in RC between individual layers and 0.05-0.06% variation within RC treatments.

2.3 Plant species and glasshouse arrangement

Six plant species were chosen as a representative sub-set of plants selected for a full-scale pilot trial at the site (Michael et al., 2007) and sourced from an indigenous plant nursery as sun-hardened seedlings in 125mm tall forestry tubes to reflect commercial practice. These included two grass species of differing photosynthetic pathways (C3 weeping grass, *Microlaena stipoides* and C4 kangaroo grass, *Themeda triandra*); late successional trees, (river red gum, *Eucalyptus camaldulensis* and sugar gum, *Eucalyptus cladocalyx*); and pioneer nitrogen-fixing species (weeping she-oak, *Allocasuarina verticillata* and black wattle, *Acacia mearnsii*).

The full-factorial design comprised 120 planted cores (6 plant species x 4 levels of relative compaction x 5 replicates) with 6 additional unplanted cores for evaporation measurement (with 1-2 replicates for each RC treatment). Cylinders of compacted substrate (referred to as cores) were planted with a single seedling into pre-prepared holes 80mm high and 50mm in diameter (a small amount of potting mix was removed under running water to achieve a snug fit flush with the substrate surface) containing 5g of 6-month slow release *Osmocote* fertilizer (NPK ratio 17:1.6:8.7). Initial heights of the approximately 6-month old plants ranged from about 20cm (grasses) to about 80cm (eucalypts). Any variability in plant height was evenly distributed across RC treatments for each species. The cores were wrapped in black polythene to exclude light and underlain by pre-drilled plastic dishes to allow free drainage and facilitate weekly re-arrangement across mesh glasshouse benches without damage (Figure 1).

Figure 1 – Examples of glasshouse experimental arrangement (a) planted cores viewed from above (b) planted cores viewed from the side with weighing scales for plant water use (PWU) measurement; and (c) an unplanted core nested among planted cores for evaporation measurement.

2.4 Plant water use measurements and calculations

Plants were subjected to a sequence of 5 extended periods of substrate drying and increasing substrate strength as is common in the field between rainfall events. After a 2 month establishment period, cores were observed and weighed weekly using an internally calibrated 40kg capacity balance to 0.1 g. Monitoring commencing mid-winter (July) in 2006 and ran through to mid-summer (January) 2007 with a two month break between periods 3 and 4 where some species required more frequent watering and care due to insect attack (Figure 2). The glasshouse was not heated but cooled using louvers and evaporative cooling when temperatures exceeded 25°C and relative humidity was maintained between 30-60%. Both planted and unplanted cores were irrigated with the same amount of water (1000-1500 mL) when planted cores showed visible signs of water stress.

Total water use (TWU) from planted cores, and evaporation (E) from unplanted cores were calculated as:

$$\text{TWU} = W_{i(\text{planted})} - W_{f(\text{planted})}$$

and,

$$E = W_{i(\text{unplanted})} - W_{f(\text{unplanted})}$$

where W_i is the weight (g) of the core at the beginning of the time period > 5 days after watering, and W_f is the weight (g) of the core at the end of the time period, before the next watering event. Plant water use (PWU) in mm/week was calculated from the difference between TWU and E as:

$$\text{PWU} = \frac{\text{TWU} - \text{E}}{\rho_w A \Delta t}$$

where A is the known cross-sectional area of the core (17,900 mm^2), ρ_w density of water (0.001g/mm^3), and Δt the duration of the time period (weeks).

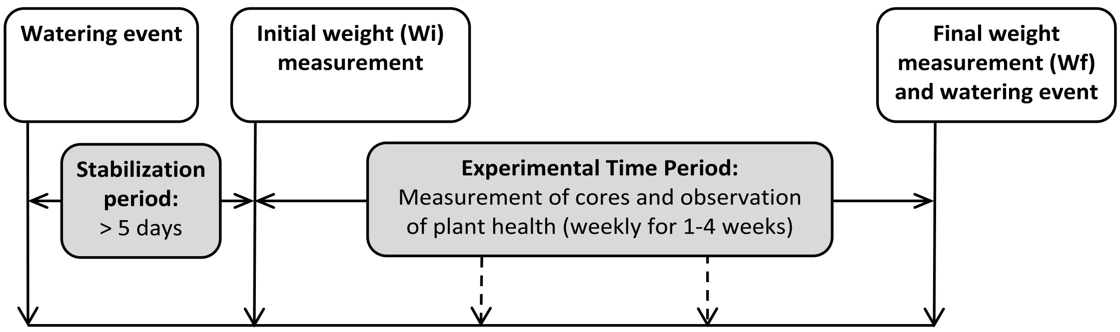

Figure 2 – Experimental sequence of plant water use (PWU) measurement. After watering, cores were stabilized for a period > 5 days to ensure no drainage. Cores were then weighed at the beginning (W_i) and the end (W_f) of the experimental time period, and plant health was observed weekly throughout. The experimental sequence was repeated five times.

2.4.1 Statistical and data analysis

We explored the relationship between PWU and RC using multiple linear regression. A set of competing PWU models were constructed using R (R Core Team, 2018) by progressively adding fixed factors to an intercept term and competing models were evaluated using AIC (Akaike, 1974). Factors added included *RC* and *species* and the interaction of these main effects. Non-linearity in the relationship between PWU and RC was accommodated using orthogonal polynomial transformations of the RC term. Quadratic and cubic polynomials were evaluated. A random effect term on the intercept was initially added to each PWU model (mixed model approach) using the function 'lmer' in the R library 'lme4' by Bates et al. (2015) to account for the repeated measurement of each individual core over the 5 experimental periods. This term was considered redundant as the random effect had no influence in the AIC-best models. The AIC-best linear model was used to predict PWU performance at the four RC treatments (72%, 77%, 82%, and 87%) and to derive RC ranges as the basis for substrate placement specifications for adequate PWU performance. Graphical presentation of the AIC-best model fit include ±standard error calculated using the 'predict' call in the 'stats' package (R Core Team, 2018) and the 'allEffects' call in the 'effects' package (Fox, 2003). PWU for each RC treatment were also compared using pair-wise Student t-tests with an assigned significance level of $p<0.05$. Residual plots were inspected to verify homoscedasticity and normality.

3 Results

3.1 Experimental conditions

As plants established and grew in height and number of leaves (observed not measured) over the six-month experimental period, they used more water and required more frequent watering over the experiment. This resulted in a general increase in PWU as a proportion of total water use (TWU) and a decrease in time period from 3 weeks to 1 week ().

Table 1).

Table 1 – Water use measurements over the experiment. Plant water use (PWU) was calculated by subtracting evaporation (E, weight of unplanted cores) from the total water use (TWU, weight of planted cores) for each of the 5 experimental periods. Air temperature (minimum and maximum), and solar radiation (average and maximum) were collected external to the glasshouse (outdoors) and are only indicative of glasshouse conditions.

Period	Duration (days)	Mean TWU±SD (mm/week)	Mean Evap±SD (mm/week)	Mean PWU±SD (mm/week)	PWU/ TWU (%)	Air temp (min °C, max °C)	Solar Radiation (Ave Wm^{-2}, Max Wm^{-2})
1	21	10.6±2.4	5.9±0.9	4.7±2.4	44%	-0.5, 17	74, 566
2	31	11.3±2.5	5.8±0.5	5.5±2.5	48%	1.3, 23.2	116, 795
3	18	11.6±5.0	5.7±1.1	5.9±5.0	51%	1.4, 28.2	219, 1079
4	13	10.9±4.2	4.0±0.5	7.0±4.2	64%	4.7, 37	271,1310
5	7	18.1±6.7	5.7±1.3	12.4±6.7	68%	8.5, 36.3	297, 1443

The mean TWU across the 5 periods was 12.5mm/week partitioned into 57% (7.1mm/week) PWU and 43% (5.4mm/week) evaporation (E). There were no significant differences in water used from the six unplanted (E only) cores at different levels of RC ($p>0.05$ for all, by t-test). Considering cumulative PWU over the five periods, plants at RC 77% used the most water (45% more than an RC of 87%), and plants at RC 72% and 82% used a similar amount of water (33-35% more than an RC of 87%) (Figure 3).

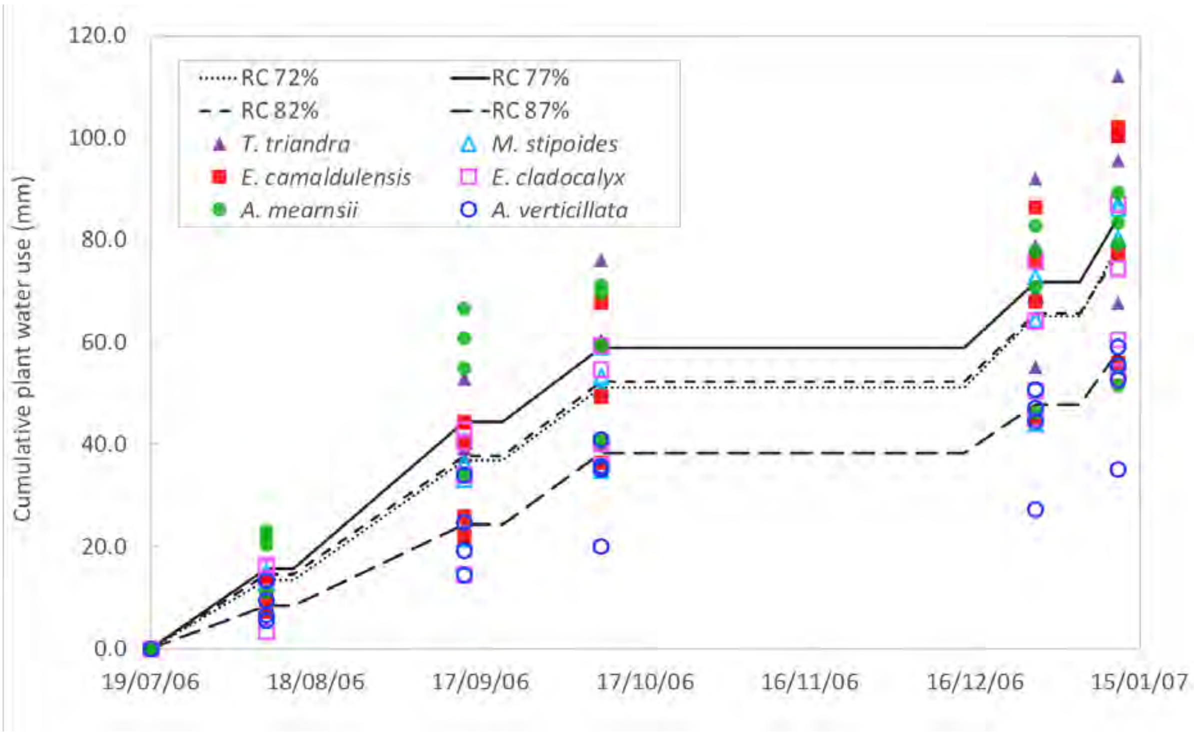

Figure 3 – Cumulative PWU for each RC treatment (72%, 77%, 82% and 87%) including the range for each species (*Eucalyptus camaldulensis, Eucalyptus cladocalyx, Microlaena stipoides, Themeda triandra, Allocasuarina verticillata, Acacia mearnsii*) averaged for 5 replicates. Flat sections of the lines represent

the time between experimental drying periods where PWU was not measured. Evaporation from unplanted cores is averaged across RC treatments.

Destructive observation after the experiment did not reveal any obvious negative effects of plant confinement such as the planted cores being root bound.

3.1.1 Evaluation of plant water use models

Linear models for PWU incorporating the main effects of *RC* and plant *species* are presented in Table 2. The AIC-best PWU model is the second-order *RC + species* model (df = 9) where *RC* is transformed to a quadratic orthogonal polynomial form and *species* is added as a categorical variable. This model includes no interaction: the parabolic curve has a fixed shape and is adjusted up and down in the y-dimension to account for between-species variation in PWU. The AIC-second best model is the *RC x species* interaction model (df = 13) where RC is fitted in both the x and y-dimension as a linear term. The remaining competing models had little support compared to these two AIC-best models as ΔAIC $\geq$ 2.0 (Burnham and Anderson, 2003).

Table 2 – Linear model structures for plant water use (PWU) incorporating factors of relative compaction ($\boldsymbol{RC}$) and Species ($\boldsymbol{Sp}$), ranked using Akaike's Information Criterion (AIC)

Model name	PWU Model	df	R^2	logLik	AIC	ΔAIC	Rank
RC + species (second order)	$\beta_0 + \beta_1 RC + \beta_2 RC^2 + \beta_3 sp + \varepsilon$	9	0.10	-1795.1	3608.1	0	1
RC x species (first order)	$\beta_0 + \beta_1 RC + \beta_2 sp + \beta_3 RCsp + \varepsilon$	13	0.11	-1791.2	3608.4	0.3	2
RC + species (third order)	$\beta_0 + \beta_1 RC + \beta_2 RC^2 + \beta_3 RC^3 + \beta_4 sp + \varepsilon$	10	0.10	-1795.1	3610.1	2.0	3
RC + species (first order)	$\beta_0 + \beta_1 RC + \beta_2 sp + \varepsilon$	8	0.10	-1797.4	3610.8	2.7	4
RC x species (second order)	$\beta_0 + \beta_1 RC + \beta_2 RC^2 + \beta_3 sp + \beta_4 RCsp + \beta_5 RC^2 sp + \varepsilon$	19	0.13	-1786.5	3611.0	2.9	5

3.1.2 Species-specific effect of relative compaction on plant water use

Individual species relationships between PWU and RC are presented in Figure 4, with measured experimental data overlaid on the AIC-best model fit. The *highest* PWU occurred at low-intermediate RC (72%, 77%, and 82%) for all species; whereas the *lowest* PWU occurred at the highest RC of 87% for all species, except for *T. triandra* where it occurred at the lowest RC of 72%. Two species showed significant negative impacts of increasing RC on PWU: *E. camaldulensis* used ~70% more water at intermediate RC, and *A. mearnsii* used 40-60% more water at low-intermediate RC, compared with the highest RC treatment of RC 87% ($p<0.05$, by t-test). *T. triandra* on the other hand, showed a significant negative impact of the lowest RC treatment: using 40-80% more water at intermediate RC compared with RC of 72% ($p<0.05$, by t-test). Other species-specific comparisons were non-significant ($p>0.05$, by t-test).

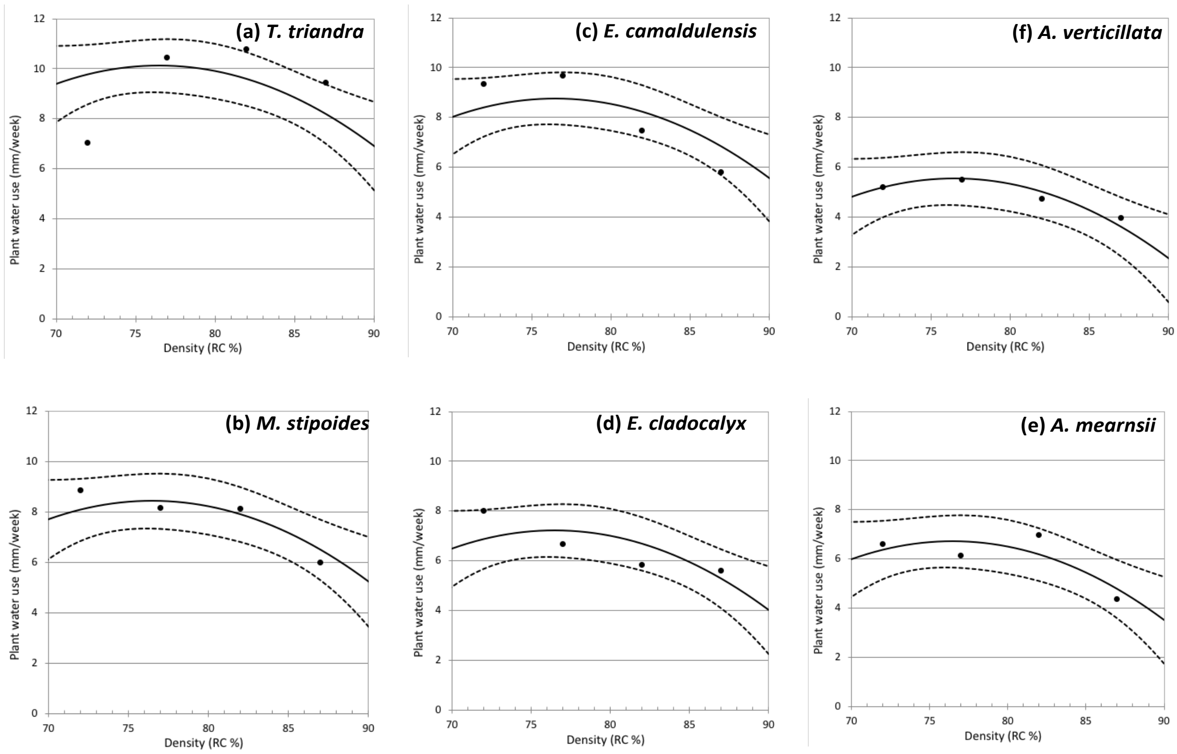

Figure 4 – The effect of substrate relative compaction (RC) on plant water use (PWU) for six plant *species*: (a) *T. triandra* (b) *M. stipoides*, (c) *E. camaldulensis,* (d) *E. cladocalyx,* (e) *A. mearnsii* and (f) *A. verticillata*. (•) are mean PWU at 72%, 77%, 82% and 87% RC measured over 5 experimental time periods. The AIC-best second-order *RC + species* model fit (solid line) flanked by ±standard error (dashed lines) was calculated using R software using the predict call in the stats package.

3.1.3 General effect of relative compaction on phytocap plant water use

Overall, PWU was 20-30% lower for the highest RC of 87% compared with the low-intermediate RC treatments (72%, 77%, and 82%), and this was highly significant ($p<0.001$); whereas PWU at the low-intermediate RC treatments (72%, 77%, and 82%) were not significantly different from one another ($p>0.05$, by t-test). The generalized relationship between RC and PWU for the phytocap plant community, the mean of all six species, is presented in Figure 5.

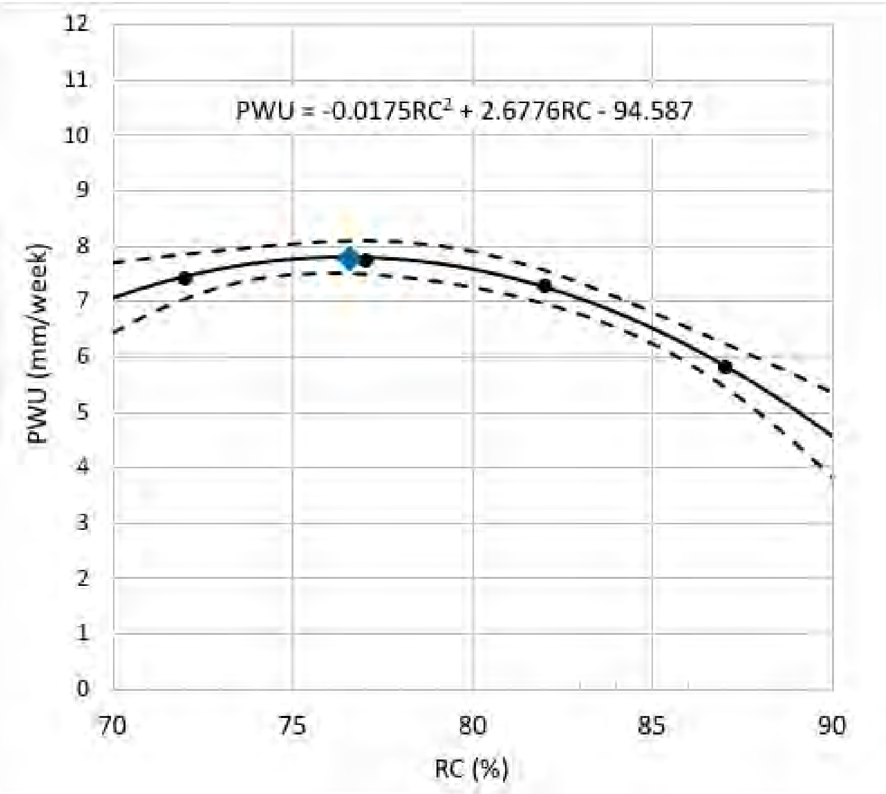

Figure 5 – Generalized relationship between substrate relative compaction (RC) and plant water use (PWU) for a six-species phytocap plant community. (•) is mean PWU at RC treatment levels of 72%, 77%, 82% and 87% measured over 5 experimental time periods. (♦) is the RC_{PWU_opt} of 76.5%. The AIC-best *RC + species* model fit (solid line) flanked by ±standard error (dashed lines) was calculated with R software using the allEffects call in the effects package.

From this general relationship it can be seen that optimum PWU (PWU_{opt}) occurs at a RC of 76.5% (RC_{PWU_opt}), half a percentage point less than the intermediate RC of 77% (Figure 4). RC levels within an intermediate range close to RC_{PWU_opt}, have little effect on PWU

(Table 3). For example, losses to PWU for substrate specified at RC in the range of 72 – 81% (RC_{PWU_opt} ± 4.5%), are no more than 5% of PWU_{opt}. However, as the RC range widens further from RC_{PWU_opt}, the potential PWU losses are greater for each unit change in RC. For example, substrate specified at a RC range of 70 – 83% (RC_{PWU_opt} ± 6.5%) can be expected to result in PWU losses up to 10% compared with PWU_{opt}. The general relationship shows that PWU is more severely affected by RC < 67% or > 86%. At these ranges, small changes in RC can be expected to result in PWU losses of 20% or more compared with PWU_{opt}.

Table 3 – Example phytocap substrate relative compaction (RC) specification ranges with expected effect on plant water use (PWU) compared with optimum plant water use (PWU_{opt}).

RC Specification	PWU
RC_{PWU_opt} = 76.5%	PWU_{opt} = 7.8 mm/week
72% < RC < 81%	95% PWU_{opt}
70% < RC < 83%	90% PWU_{opt}
67% < RC < 86%	80% PWU_{opt}
67% > RC > 86%	Reduction in PWU > 20%

4 Discussion

4.1 Experimental conditions

Often planted in poor soils with low organic matter and nutrients, on long barren slopes without provision for supplemental water; a phytocap plant community is subjected to a range of stresses between rainfall events that include increasing water deficit and substrate strength. We conducted a controlled glasshouse experiment that measured the plant water use (PWU) of six species in tall cylinders of substrate compacted to four known levels of relative compaction (RC). As distinct from other trials where cores are maintained under well-watered or constant conditions (Grzesiak et al., 2002; Zarehaghi et al., 2017), the planted and unplanted cores in this study were exposed to extended periods of substrate drying and increasing substrate strength. These drying periods commenced >5 days after watering to ensure vertical drainage was excluded and PWU measurements were conservative. The PWU experiment began in winter with newly planted tube stock that slowly dewatered the substrate over 3-5 weeks without watering; and concluded in summer with relatively mature plants that more rapidly dewatered the substrate and required watering every 1-2 weeks. The increases in PWU as a proportion of TWU reflected these experimental conditions and the intent of the experimental design to test the *relative* not absolute impacts of the RC treatments on PWU. Variations in plant maturity, season and the timing of water events created a field-relevant dataset, with weekly re-assignment of core locations ensuring the variability was consistently applied.

4.2 Evaluation of plant water use models

In constructing a general linear model to describe the effect of RC on PWU, two models emerged as AIC-best: the second-order *RC + species* model without interaction, and the first-order *RC x species* model with interaction. While both models are considered equally good at describing the overall data set, the former best met the objectives of this study as a tool for determining operationally-relevant RC specifications for landfill phytocapping. As this model did not include an interaction between RC and species, a generalized (or average) relationship between RC and PWU could be derived and applied to the plant community as a whole.

4.3 Species-specific effect of relative compaction on plant water use

The community of native plant species tested for this study were selected with the landfill phytocap context in mind: grasses for erosion control; nitrogen-fixing species to pioneer barren, nutrient-impoverished soils; and eucalypts as late successional species. Given the diversity of plant forms, it is remarkable that a general curve with the same parabolic shape and peak (albeit different magnitude) accommodated the data for the majority of species relatively well. *Themeda triandra* was the only exception in that it was more negatively impacted by low (72%) than high (87%) RC when compared with the intermediate (77% and 82%) RC treatments. It is worthwhile to note that *Themeda triandra* was the only species with a C4 photosynthetic pathway and was observed to have the most prolific root growth of the six species which is consistent with findings by Guo et al. (2005). This relative sensitivity for low RC and tolerance for higher RC may be helpful in considering options for rehabilitation of temperate grassy woodlands dominated by *Themeda triandra* that are critically endangered in South-east Australia due to land clearing and agriculture (Cole and Lunt, 2005; Cole et al., 2004) where soil compaction is a factor.

4.4 General effect of relative compaction on phytocap plant water use

This study met its objectives in describing a general relationship for the effect of RC on PWU that could be used to derive substrate placement specifications for the design and placement of landfill phytocap substrate. It's important to view these results as *relative* not absolute impacts of substrate density changes on the phytocap water balance, and as the establishing plants also did not outgrow the confines of their containers, there is no need to address scaling issues such as the translation of individual PWU to whole stand water use such as described by Eamus et al. (2006). The use of RC (%) rather than absolute dry bulk density (gcm^{-3}), and plants representative of Australian phytocap conditions (grasses, eucalypts and nitrogen-fixing species) strengthened the application of the general relationship beyond individual species or substrate texture, as did the similarities in the magnitude and pattern of PWU for individual species. The R^2 for the AIC-best model was 10%, indicating as one would expect, that other biologically relevant climate and substrate differences besides density and species are important in predicting the variability of PWU described in the model. For example, daily and seasonal climate variability, drying period length and localized variations in micro-topography, organic matter, phosphorus and particle size that in turn affect the variability of root growth, plant productivity and PWU foraging behavior (Biederman and Whisenant, 2009; Nie et al., 2008; Wilcox et al., 2004; Williamson and Neilsen, 2003). In addition, plant biomass or leaf area index (LAI) measurements are commonly used predictors of plant transpiration that could be included in future models.

High (> 86%) and low (< 67%) levels of RC were shown to negatively affect PWU performance by 20% or more compared with optimum RC levels, however, the raw comparisons between treatments showed only the negative impact of the higher end to be significant ($p<0.001$, by t-test). A 20% reduction in water use at high RC is consistent with turf-grass studies where a compacted state was created with 30 passes/week with a smooth power roller (O'Neil and Carrow, 1982). In reality, the reduction in water use at non-optimal compaction, relates to the complex interactions between soil water potential, aeration and mechanical impedance that varies depending on the moisture content and the distribution of micro and macroporosity at each RC (Chen et al, 2014). Previous work on the substrate showed total water storage to increase with RC (2.7mm/m for every % RC between 72 and 87%), but total available water (TAW) to show no consistent pattern with respect to RC (TAW range = 17-32 mm/m) (unpublished data). Therefore, we expect that it's high mechanical impedance at high RC and low root-substrate contact at low RC that predominate as restricting factors, rather than water availability.

Phytocaps are currently specified within RC ranges of 80-90% with RC targets of ≥ 85% being commonplace (Benson et al, 2007). These are at the upper-edge of the acceptable RC specification ranges derived in this study. PWU performance can be improved by specifying substrate at field-relevant ranges close to the RC_{PWUopt} of 76.5%. For example, for an RC range of 72-81%, PWU is expected to be 95-100% of PWU_{opt}; whereas for an RC range of 70-83%, PWU is expected to be 90-100% of PWU_{opt}. Currently there are few examples where phytocaps are specified at these lower RC ranges, except Kiel et al (2002) and McGuire et al (2009), and fewer examples that have reported on achieving them during construction.

4.5 Practicalities of full-scale substrate placement

Enhanced PWU at ranges closer to the RC_{PWUopt} of 76.5% has the benefit of depleting the soil-water reservoir and providing greater capacity for absorbing rainfall as is core to the function of a phytocap. Lower RC ranges however, have less shear strength than higher RC ranges at the same moisture content with potential implications for the design of slopes for earthen landfill caps. For phytocaps, decreases in shear strength due to lower RC are accompanied by plant-induced *increases* in shear strength. Plants increase shear strength by increasing soil water potential, and modelling has shown that this can be as much as 50% (Garg and Ng, 2015). Other factors increasing bank stability for a phytocap include the presence of roots (enhancing shear and tensile strength) (Barrett et al., 2006), canopy interception (reducing the amount of rainfall that hits the substrate surface) and the absence of a veneer plane between the substrate layer and the waste. These benefits are realized as the phytocap matures, and the first 6 months of early establishment remains crucial as plants are growing and their capacity to dewater the substrate is developing. Timing of planting to avoid seasons of heavy rainfall and selection of plant species that rapidly colonize and bind the substrate together can assist in progressing the phytocap through the vulnerabilities of early establishment. Careful planning of plant succession on slopes has also been shown to positively impact bank stability (Osman and Barakbah, 2011).

RC treatments in this study were created with an instron tensile testing machine and quality assured within a narrow range (target RC ± 2%). A broader range is more appropriate for full-scale construction with large (20+ tonne) earth-moving machinery. Kiel et al (2002) described a RC range of 13% as a “workable” substrate placement specification for the field, similar to the RC range of 70-83% recommended in this study. It is also important to ensure substrate placement specifications can be *consistently* met with full-scale equipment and techniques. For example, Michael et al (2007) tested a variety of placement methods using a D6 caterpillar bulldozer and achieved three RC scenarios: (i) *placed and levelled and ripped* = 77%, (ii) *placed and levelled* = 84% and (iii) *placed and levelled and track rolled one pass* = 92%. Scenario (i) was initially considered superior as the RC was close to the RC_{PWU_opt} of 76.5%. However, this scenario was created by retrospectively ripping a layer already compacted to a RC of 84%, resulting in a blocky macro-structure (compacted clods surrounded by larger pore spaces) that raised concerns for preferential flow (Michael et al, 2007). Kiel et al (2002) had similar concerns about using ripping to ameliorate over-compacted layers of substrate after observing the undulating gullies became areas where water ponded. These case studies highlight the importance of independent geotechnical supervision to verify the condition of the substrate macro-structure in addition to meeting the specified RC ranges. Ideally, pre-trials are conducted during the design process to verify the achievability of the RC specifications. Placement techniques that use non-standard or low ground pressure machinery, or changes to construction sequencing to minimize traffic, can assist with achieving a good result and also impact upon the cost of construction.

5 Conclusion

The selection of RC during design and substrate placement of a landfill phytocap will have an effect on the water use of selected plant species. This relationship can be generalized by a model and used to derive RC ranges that optimize PWU irrespective of substrate texture. This glasshouse study found PWU to be optimum at a RC of about 77% for a variety of native tree and grass species common to Australian landfill phytocaps. PWU was reduced by no less than 90% of this optimum within an operationally-achievable RC range of 70 – 83%. Beyond this range, PWU is more sensitive to changes in RC with levels > 86% or < 67% leading to reductions in PWU from optimum of 20% or more. Future work needs to concentrate on RC models that optimize both PWU and root growth to capitalize on the benefits for hydrology and slope stability.

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