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Phytocapping: Importance of Tree Selection and Soil Thickness

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Abstract An alternative landfill capping technique known as ‘Phytocapping’ (establishment of perennial plants on a layer of soil placed over the waste) was trailed in Rockhampton, Australia. In this technique, trees were used as ‘bio-pumps’ and ‘rainfall interceptors’ and soil cover as ‘storage’ of water. The environmental performance of the phytocapping system was measured based on its ability to minimise water percolation into the waste. The percolation rate was modelled using HYDRUS 1D for two different scenarios (with and without vegetation) for the thick and thin caps, respectively. Results from the modelling showed percolation rates of 16.7 mm year⁻¹ in thick cover and 23.8 mm year⁻¹ in thin cover, both of which are markedly lower than those expected from a clay cap. Results from monitoring and observations showed that 19 trees out of 21 tree species grew well in the harsh landfill environment. Top ten performing species have been identified and are recommended to be grown on phytocaps in the Central Queensland region.

Keywords Phytocapping · Sap flow · Biomass · Stem girth · Landfills · Canopy interception · HYDRUS 1D

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1 Introduction

Deposition of wastes in landfills has adverse environmental impacts such as leachate generation and methane emission (El-Fadel and Massoud 2000). To reduce the impact of landfills on the environment, various technologies such as leachate collection systems (Rittmann et al. 1998), compacted lay liners (Aliston et al. 1997), composite liners (Halse et al. 1990), geosynthetic clay liners (GCLs; Benson 2000), compacted clay covers (Khire et al. 1997) and composite covers (high density polyethylene, HDPE; Khire et al. 1997; Levin and Hammod 1990) have been introduced and practiced.

Landfill capping is a mandatory post-closure procedure to isolate the deposited wastes from outside environment, mainly water (Vasudevan et al. 2003). Landfill capping involves placing a barrier, which acts as a raincoat over filled landfill to minimise percolation of rainfall or surface water into the waste (Scott et al. 2005). In recent years, conventional capping systems made of compacted clay (Othman et al. 1994), GCL (Benson 2000), polyvinyl chloride (Levin and Hammond 1990) and HDPE (Simon and Muller 2004) have been used extensively in developed and many developing countries. Amongst these, the most popular practice in Australia has been the use of compacted clay caps. A typical compacted clay cap recommended in Queensland contains 200 to 300 mm of earthen cover at the bottom, followed by a 500-mm layer of low permeability clay ($K_s < 10^{-8}$ m/s;

where K_s is saturated hydraulic conductivity), 200 to 500 mm of subsoil base and 150 mm of top soil on the top to support mild vegetation (e.g. grasses; EPA 2005).

In Australia, the caps constructed on landfills should be sustainable for at least 30 years. However, recent studies have shown that clay caps have shorter lifespan (Vasudevan et al. 2003) and fail to prevent percolation of water due to cracking (Khire et al. 1997; Benson and Othman 1993; Melchior 1997; Albrecht and Benson 2001). Furthermore, clay caps do not allow optimal interaction of methane with oxygen, which is necessary for methane oxidation (Abichou et al. 2004).

Phytocaps, a new and alternative technology, have two major components, viz. the trees that act as 'bio-pumps' and 'rain interceptors' and the soil that acts as 'storage' (Fig. 1). The soil and trees together minimise percolation of water into the waste. This concept system has been well received by the US Environmental Protection Agency, but still is in its infancy in Australia. Thus, the trial conducted at Lakes Creek Landfill in Rockhampton, Australia is the first of its kind in Australia.

Fig. 1 Cross section of the Rockhampton phytocapping site showing various processes

In addition to minimising percolation, phytocaps offer other environmental benefits over conventional capping systems such as methane oxidation, providing park environment, timber production and biodiversity conservation. Although these benefits are not adequately tested, some studies have proved the ability of phytocaps to effectively minimise water percolation using lysimeters (Albright et al. 2004). A field trial was therefore undertaken at Lakes Creek Landfill in Rockhampton, Australia, to test the environmental performance of a phytocapping system. Studies in the past have demonstrated the effectiveness of phytocaps in comparison with other conventional capping systems using lysimeters, but the different components the type of trees to be grown in this system and the optimum thickness required to sustain plant growth and retain maximum soil moisture need to be determined. Soil and trees have a vital role to play in this system, but their performance, integrity and sustainability are barely understood and reported. Secondly, the ability of phytocaps to reduce methane emission has not been explored. For these reasons, performance of trees, soil thickness, methane emission and the characteristics of the individual trees to suit the system needs to be identified and addressed.

2 Materials and Methods

Details of establishing the phytocapping trial and parameters used in HYDRUS 1D simulation are provided in Venkatraman and Ashwath (2007) and Venkatraman et al. (2008). In summary, a 5,000-m² trial plot was established at Lakes Creek Landfill in Rockhampton, which constituted two soil treatments, viz. a thin cap (700 mm) and a thick cap (1,400 mm; Fig. 2).

The environmental performance of the phytocapped site was measured by evaluating the tree species with regards to their growth (height, stem girth, above-ground biomass), transpiration rates and canopy interception potential.

Height was measured using a calibrated 8-m high collapsible stick (Snowdon et al. 2002). Five trees of each species in each plot were selected, and their respective heights were determined. Height measurements were taken twice a year at 6 months interval. Stem diameter, a good predictor of growth (King et al. 2005), was measured using digital vernier caliper that

Fig. 2 Thin (700 mm) and thick (1,400 mm) soil caps placed on the landfill

can record measurements up to 200 mm manufactured by Cooper Hand Tools, Australia. These trees were also monitored for their stem diameter at 50 cm from the ground (D_{50}). D_{50} was determined twice a year along with height. Diameter at breast height (DBH) of 1.37 m was also measured once every year.

Above-ground biomass produced by various tree species was estimated by direct harvest method (Poorter and Garnier 1996; Snowdon et al. 2002). Biomass was estimated for 19 tree species on two different occasions: (1) after 2 years of planting and (2) after 3.5 years of planting. Biomass produced after 3.5 years of planting is only discussed in this paper.

In the first instance, alternate trees from each plot (nine trees) of individual species from different treatments were harvested after 2 years of plantation. Out of nine trees harvested from 18, three were studied for their above-ground biomass, and the other six were harvested and measured for their D_{50} , DBH, sapwood depth and height. The three trees harvested were separated into three components, namely stem, leaves and branches. Stem was further chopped into small bits using a chainsaw for easy weighing. Each of these components was weighed using a balance and the samples were gathered in a paper bag and labelled. The samples were then oven-dried at 70°C for 48 h as suggested by Salisbury and Ross (1991) and were not taken out of the oven till they attained a constant weight. This ensured the loss of entire moisture content from the leaves. Once dried, the samples were taken out and weighed. The difference in weight gave the moisture content in different parts of the tree. Similar procedure was followed during the next harvest in 2007. Out of nine trees per species per plot, three trees (representative the entire stand) were selected and studied for their above-ground biomass, and the rest were measured for their height D_{50} , DBH and sapwood depth. The same three trees harvested were also studied for their root biomass (not discussed).

Transpiration rates of different tree species were determined using thermal dissipation probes (TDP). The TDP sensors were preferred over other probes due to their simplicity, low energy demand, accuracy and low cost (Braun and Schmid 1999). Installation of TDP sensors requires the use of trees with a minimum stem diameter of 50 mm. Thus, only 14 of the 21 tree species were monitored using TDP sensors. A dynagauge (collar type sensor) was used to measure the sap flow in bamboo due to its hollow stem.

Throughfall and stem flow were measured in individual trees over a 2-year period with the rainfall ranging from 0.60 to 80 mm. Throughfall was determined using a standard rain gauge (4 cm wide and 51 cm high). Three randomly selected plants within each species (amongst 18 plants) were monitored by placing the rain gauges under the canopy at 30, 40 and 50 cm from the main stem. The tree species were established on thick and thin capping systems. Trees from one replication of each capping system were monitored by placing a total of 324 rain gauges in thick and thin capping treatments. Additional 20 rain gauges were placed all around the experimental plot in an open area to record the total rainfall at the site. The rain gauge readings were recorded for almost all rainfall events during a 24-month period (50 rainfall events).

In order to measure stem flow, a split plastic hose was stapled using galvanised staple pins around the tree with one of its ends tapering downwards (Crockford and Richardson 2000) to discharge water into a graduated jar. The gaps between the hose and the bark were sealed with neutral silicon sealant and left to dry for 24 h before measurement. Once dried completely, tapering end was inserted into the jar through the lid. The measuring jar was kept closed and anchored to the stem to restrict movement and to prevent evaporation respectively. The stem flow collars were tested for their performance before taking the actual measurements. During rain events, the

Fig. 3 Height of 19 tree species grown on a phytocap (39 months after planting)

water flowing through the stem entered the cup shaped split hose and ran through the tapering end into the jar. Three such stem flow gauges were installed per species in each of the thick and thin capping systems 24 months, and the measurements were taken over 50 rainfall events over a year.

HYDRUS 1D was used in this study to predict site water balance. HYDRUS 1D uses soil hydraulic parameters and various tree parameters such as transpiration rate, root depth and climate data (rainfall and evaporation). Final simulations were completed using the average values obtained for the selected ten tree species grown in the phytocapping system (Venkatraman et al. 2008). Two scenarios, namely (1) without vegetation and (2) with vegetation, were

considered while simulating the site water balance (Venkatraman et al. 2008).

3 Results and Discussion

Out of the 21 tree species grown on the phytocaps, all the tree species survived well except the *Populus* sp. and *Salix* sp. On an average, the species grew 4.7 m tall (Fig. 3) with an average stem girth of 84 mm (Fig. 4).

As anticipated, the patterns of height growth differed between the species is related to genetic differences between the species (Fig. 3). It is interesting to note the differences between thick and thin caps. For many species, the differences between

Fig. 4 Stem diameter of 19 trees species after 3 years of planting

Fig. 5 Total shoot biomass produced by 19 species after 3.5 years of planting (includes litter biomass)

thick and the thin caps have been very marginal, although the fast-growing species such as *Eucalyptus grandis*, *Eucalyptus raveretiana*, *Eucalyptus tereticornis*, *Acacia mangium* and *Casuarina cunninghamiana* grew more rapidly in the thick cap than in the thin cap (Fig. 3). Trees do change their growth rates from juvenile stage to mature stage, and as a result, their requirements for water and nutrients would also differ. Consequently, it is possible that the differences between the two caps are likely to increase with the maturity of plants. Since the thick cap is capable of holding more water than the thin cap, it is possible that the plants established in this treatment would grow larger than those grown in the thin cap.

Stem diameter increments are known to reflect growth rates of plants (Yokozawa and Hara 1995). Six

randomly selected plants were monitored in each plot for stem girth. The trends in stem diameter increments followed were similar to that observed in stem height, with most species in thick cap having larger diameter than those grown in thin cap. Overall, the differences between thick and thin caps were much smaller for stem diameter than for stem height (Fig. 4).

Biomass is a prominent parameter used to study growth which directly correlates to water uptake via its root growth (Singh and Bhati 2003). *Hibiscus tiliaceus*, *Dendrocalamus latiflorus* and *A. mangium* produced very high quantities of biomass, with *H. tiliaceus* producing 80 kg of shoots per plant (Fig. 5). This is equivalent to 200 tons/ha of shoot biomass in just over 3 years, which is a remarkable growth. The *D. latiflorus* and *A. mangium* produced ca. 130 and 100 tons/ha, respectively.

Fig. 6 Total leaf biomass produced by 19 species after 3.5 years of planting

Fig. 7 Total stem biomass produced by 19 species after 3.5 years of planting

The *Pongamia pinnata* showed large variation between seedlings, and hence, all these recorded very low biomass accumulation (<10 tons/ha; Fig. 5). Generally, these species grow well in other situations. Hence, their performance on this landfill could be ignored or they be not used in landfill phytocapping unless these inherent problems are resolved, as they will not contribute greatly to site water balance. The growth of *E. grandis* (50 tons/ha) in thick and thin phytocaps (Fig. 5) matched well with that reported for an effluent-irrigated plantation in Yeppoon (65 tons/ha; Sharma 2008). These results demonstrate that most species established on the thick and thin phytocaps were growing to their maximum potential despite the soil being saline in the thin cap.

Leaf weight was the highest in *D. latiflorus* and *H. tiliaceus* as they produced large number of leaves

compared to other species of the same size (Fig. 6). *P. pinnata* and *Callistemon viminalis* recorded the lowest amounts of leaves. Overall, the stem weight also showed similar patterns between species (Fig. 7).

The pattern of accumulation of biomass differed amongst the species, particularly between *H. tiliaceus* and other species. *H. tiliaceus* accumulated a large proportion of the biomass in branches, unlike most other species which used stem as their major source (Fig. 8). Likewise, the biomass distribution patterns differ markedly between *D. latiflorus* and other species, as the former accumulated significant proportion of biomass in roots (rhizomes) than the latter.

The thick and thin capping systems had different soil depths, and their composition and structure were also variable. The plants established on these capping

Fig. 8 Total branch biomass produced by 19 species after 3.5 years of planting

Fig. 9 Water uptake by 14 species grown on a phytocap (48 observations)

systems may respond differently to these conditions. An examination of biomass accumulation patterns between the thick cap and the thin cap revealed that the plants grown in thick cap accumulated significantly higher quantities of stems and branches than those growing in thin capping system (Figs. 5 and 8). However, the leaf biomass did not show such a marked differences between the two capping system. In contrast, the coarse root weight was markedly higher in thin cap than in thick cap. The smaller differences between thick and thin capping systems for leaf weight and larger proportion of coarse roots (data not shown) in thin capping than in thick capping may have some implications for plant water use as the plant canopy matures, as these two components are directly responsible for transpiration losses leading to their influence on overall site water balance.

Sap flow measurements were recorded in *A. mangium*, *Acacia harpophylla*, *C. cunninghamiana*, *E. grandis*, *E. raveretiana*, *E. tereticornis*, *Ficus microcarpa*, *Ficus racemosa*, *Glochidion lobocarpum*, *H. tiliaceus*, *Melaleuca leucadendra*, *P. pinnata*, *Cupaniopsis anacardioides* and *Syzygium australis* on different occasions. Results from 48 observations showed that sap flow varied significantly among species. *E. raveretiana* showed maximum uptake capacity of 2.1 mm day⁻¹ while *A. harpophylla*, *G. lobocarpum* and *P. pinnata* could take up only 0.9 mm day⁻¹ (Fig. 9). The study also shows that the species grown on the phytocapping system have the capacity to draw more water during high rainfall period. These species could also withstand water stress conditions and can take up water as low as 300 ml day⁻¹ (data not shown). This shows the potential of the selected

Fig. 10 Canopy rainfall interception by 19 tree species grown on a phytocap in Rockhampton. Data are means of 50 events $\times$ 2 measurements over a 2-year period

Fig. 11 Simulated percolation of water in thin (*left*) and thick (*right*) phytocaps, in the absence of vegetation (cumulative of 15 years data; 1992 to 2006)

species to adapt to the seasonal variation, along with their ability to take up maximum water thereby reducing water percolation through the waste.

The canopy rainfall interception by the 3-year-old trees varied from 20% to 53%, with an average of 30% (all species and for thick and thin capping; Fig. 10). Seven of the 19 species intercepted more than 30% of the rain. The species amongst this group include *C. cunninghamiana*, *F. microcarpa*, *Melaleuca linariifolia*, *H. tiliaceus*, *E. grandis*, *Dendrocalamus maroochy*, *Lophostemon confertus*, *C. viminalis*, *P. pinnata*, *S. australis*, *E. raveretiana* and *A. mangium* (Fig. 10). Site water balance was simulated under two scenarios, viz. without and with vegetation.

Scenario 1 Percolation simulated for the thin cover (700 mm) and thick cover (1,400 mm) and without vegetation was 153 and 133 mm year⁻¹, respectively (Fig. 11). As expected, the difference between the two covers is due to soil depth which plays a vital role in retaining maximum amount of water (Warren et al. 1996). Detailed description of the simulated runoff and storage capacity has been previously mentioned in Venkatraman et al. (2008).

Scenario 2 In this scenario, percolation was simulated using the same parameters as in scenario 1, but an

additional component, vegetation, was introduced. In this simulation, average transpiration of 1.5 mm day⁻¹ was used. This average represented the measured values from the highest ten performing tree species grown in the experimental site. The average rainfall intercepted by the best ten tree species was 32%. Therefore, the actual incident daily rainfall was reduced by 32% during HYDRUS 1D simulation. This simulation showed a percolation of 23.8 mm year⁻¹ for the vegetated thin cover and 16.7 mm year⁻¹ for the vegetated thick cover (Fig. 12). Thus, the percolation rate in vegetated phytocaps is six to nine times less than that simulated for non-vegetated sites. This clearly demonstrates importance of vegetation in phytocapping, both via canopy rainfall interception and transpiration.

Results from the above simulation demonstrate that the phytocaps are very effective in reducing percolation of water into the waste. In this simulation, establishment of ten selected tree species using 1,400-mm layer of unconsolidated soil (thick phytocap) will allow a percolation rate of 251 mm in 15 years or 16.7 mm year⁻¹. This value is significantly lower than the percolation rate expected of a compacted clay cap (i.e. 78 mm/year⁻¹; Geoff Thompson, Maunsell, Brisbane, personal communication; at 10% of the rainfall). The results also show that the trees play a significant role in

Fig. 12 Simulated percolation in the thin (*left*) and thick (*right*) phytocaps in the presence of vegetation (15 years of data; 1992 to 2006)

reducing percolation (compare Figs. 11 and 12), and they achieve this via transpiration (up to 2.1 mm day⁻¹) and canopy rainfall interception (up to 53% of the rain).

4 Conclusion

Results from this study demonstrate that selection of the right species is very important for the sustainability of the phytocapping system. The tree species grew very well in the harsh landfill environment demonstrating good adaptability characteristics and performance with respect to growth, canopy interception and transpiration which grossly contributes to the prevention of rain water in to the buried waste.

HYDRUS 1D simulation estimated percolation rates of 16.7 to 23.8 mm year⁻¹ for thick and thin caps, respectively. The predicted percolation rate for the Rockhampton site is much lower than that expected from well-constructed and maintained clay-capped landfill (which is equivalent to 78 mm in Rockhampton; at 10% of the incident rain). This shows the better or equivalent ability of the phytocapping system to limit entry of water into the landfill (ca. 50% of clay cap). Comparing the two scenarios in modelling, it is clearly evident that tree species play a vital role in the phytocapping system and that optimising the right thickness for a region is equally important for tree growth and maximum moisture retention during heavy rainfall period.

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