Phytocapping of Landfills: An Australian Experience

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Abstract: Landfills have been the major repositories of urban wastes, and they will continue to be built, so long as the humans live in communities. The costs of construction, maintenance and remediation of landfills have escalated over the years and research is therefore required to identify alternative techniques that will not only minimise the costs but also demonstrate increased environmental performance and community benefits. An alternative landfill capping technique known as ‘Phytocapping’ (establishment of perennial plants on a layer of soil placed over the waste) was trialled in Rockhampton, Australia. In this technique, trees were used as ‘bio-pumps’ and ‘rainfall interceptors’ and soil cover as ‘storage’ of water. Tree performance was measured based on their canopy rainfall interception and water uptake potential. The percolation rate was estimated using HYDRUS 1D for two different scenarios (with and without vegetation) for the thick and thin covers respectively. Results from the simulations incorporating 15 years of meteorological data showed percolation rates of 16.7 mm yr\(^{-1}\) in thick cover and 23.8 mm yr\(^{-1}\) in thin cover, both of which are markedly lower than those expected from a clay cap.

Key words: phytocapping, transpiration, landfills, tree species, bio-pumps, canopy interception, methane, site water balance, HYDRUS 1D

1. Introduction

Landfills are the most economical and easiest means of disposing waste globally and in Australia (Scott et al. 2005) where up to 95% of the waste is placed in landfills (CSIRO 2001). This places Australia among the highest 10 solid waste generators within the Organisation for Economic Cooperation and Development (OECD) (Scott et al. 2005). About 70% of the Australian population live in coastal areas (Environmental Protection Agency, EPA 2006), and hence many of the landfills have been constructed in wrong places such as low lying areas of mangroves and marsh lands. In Queensland alone, around 1.7 million tonnes of domestic waste was deposited in landfills in 2006; of which only 14% was recycled (EPA 2006). Deposition of wastes in these places result in adverse environmental impacts such as leachate generation and methane emission (Scott...
et al. 2005, El-Fadel et al. 1997). Hence, to reduce the impact of landfills on the environment various technologies such as leachate collection systems (Rittman et al. 1998), compacted lay liners (Alston et al. 1997), composite liners (Halse et al. 1990), GCL's (Benson 2000), compacted clay covers (Khire et al. 1997), composite covers (High Density Polyethylene, HDPE) (Khire et al. 1997, Levin and Hammond 1990) have been introduced.

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 water into the waste (Scott et al. 2005). In recent years, conventional capping systems made of compacted clay (Othman et al. 1994); Geosynthetic Clay Liners (GCL) (Benson, 2000), Polyvinyl chloride (PVC) (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 clay capping (Fig 1) to minimise percolation of water into the waste (EPA 2005).

![Fig. 1 Schematic diagram of a typical clay cap used in Queensland (EPA 2005)](image)

In Australia, the caps constructed on landfills should be sustainable at least for 30 years. Recent studies however show that clay caps have shorter life span (Vasudevan et al. 2003) and fail to prevent percolation of water due to cracking (Khire et al. 1997, Benson and Othman 1993, Othman et al. 1994, Albright et al. 2004, Melchior 1997, Albright and Benson 2001). Furthermore, clay caps do not allow optimal interaction of methane with oxygen, which is a must for methane oxidation (Abichou et al. 2004).
A new technology called ‘Phytocapping’ was introduced in 1991 by Idaho National Engineering and Environmental Laboratory (INEEL) for the US Department of Energy 1991. In brief, phytocaps have two major components, viz the trees that act as ‘bio-pumps’ and ‘rain interceptors’ and the soil that acts as ‘storage’ (Fig 2). The soil and trees together minimise percolation of water into the waste. This concept system has been well received by the US EPA but is yet to be implemented in other countries. Thus the trial conducted at Lakes Creek Landfill; in Rockhampton, Australia is the first its kind in Australia.

In addition to minimising percolation effectively, phytocaps offer other advantages over conventional capping systems, including methane oxidation, providing park environment and biodiversity conservation. These benefits are not adequately tested although some studies have shown the advantages of phytocaps over conventional capping systems using lysimeters (Albright et al. 2004). Hence, a large scale field trial was therefore undertaken in Rockhampton, Australia, with the view to testing the effectiveness of phytocapping in minimising percolation and select suitable plant species and optimising agronomic conditions. The study also tests the role of phytocaps in methane oxidation.
2. Materials and Methods

Details of establishing the phytocapping trial is provided in Venkatraman and Ashwath (2007). In summary, a 5000 m² trial plot was established at Lakes Creek landfill in Rockhampton (22 year old), which constituted two soil treatments viz. a thin cap (700 mm) and a thick cap (1400 mm) (Fig 3). The thin and thick cap was replicated twice (total of 4 plots). On each of the plots, 21 tree species were established, with 18 plants/plot/species which were thinned to 9 plants/plot/species after two years of planting. The experimental site was mulched with shredded green waste (100 mm deep), and the plants were drip irrigated. The plant species were chosen based on a number of criteria, including salt tolerance (Ashwath et al. 1987), drought tolerance, leachate tolerance (Ashwath and Hood 2001), adaptability to local conditions, commercial valuel, aesthetic value and their ability to support wildlife (e.g. koalas, birds). Various plant and soil parameters were monitored over three years (Venkatraman and Ashwath 2007, Ashwath and Venkatraman 2007, Venkatraman and Ashwath 2006) and the site water balance was predicted using HYDRUS 1D (Venkatraman et al. 2008).

Initially, the established plants were observed for their survival and growth. Of the 21 established species, Populus sp. and Salix sp. did not survive well. Height and stem girth was measured every six months during the study using an 8 m calibrated collapsible rod and a digital vernier calipers respectively.

Transpiration rates in different tree species was estimated using Thermal Dissipation Probes (TDP) developed by Granier’s (1985) and Heat balance method developed (Dyngauge) by Vieweg and Ziegler (1960) and advanced lastly by Weibel and Vos.
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(1994). The TDP sensors were preferred due to its simplicity, low energy demand, accuracy and low cost (Andräde et al. 1998, Braun and Schmid 1999). Installation of TDP sensors require trees with a minimum diameter of 50 mm and hence only 14 out of 21 tree species were studied using TDP sensors. A dynagauge was used to measure the sapflow in bamboo due to its hollow nature. Sapflow rates of the fourteen tree species are therefore only presented in this paper. Estimation of sap area is essential to calculate the sap flow in individual species. Sap area was calculated as follows as described in Venkatraman et al. (2006).

Throughfall and stem flow was measured in individual tree species over a 2 year period with the rainfall ranging from 0.60 mm to 80 mm. Detailed description of the method is explained by Venkatraman and Ashwath (2006). The canopy rainfall interception and stemflow were calculated as follows:

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\text{Canopy rainfall interception} \, (\%) = \frac{\text{Total rainfall received at the site (mm)} - \text{Throughfall (mm)} - \text{Stem flow (mm/m² of the canopy spread)})}{\text{Total rainfall (mm)}} \times 100
\]

\[
\text{Stem flow (mm)} = \frac{\text{Volume of rain water collected (litre) in a rainfall event}}{\text{Crown spread of that tree (m²)}}
\]

Methane emission was measured within each of the 19 tree species in both thick and thin capping treatments, using a portable methane gas meter (Gastech, Australia 2004). Methane emissions were also monitored in the adjacent areas of the experimental site that were kept devoid of vegetation (bare site that contained 50 cm to 100 cm interim uncompacted soil cover over the refuse). Methane concentrations were measured at two depths, one on the surface and the other in the root zone (30 cm below the surface).

Diurnal variations in methane emissions were determined by monitoring methane continuously over 24 hours at 17 months (19 February 2005), 18 months (15 March 2005) and 19 months (22 April 2005) respectively, after planting, using PVC tubes that were inserted around plants down to a depth of 30 cm (root zone). Methane readings were consistently highest between 9 am and 12 noon and as such all further methane readings were recorded during this period. Detailed information on the diurnal variation is given in Venkatraman and Ashwath (2006).

HYDRUS 1D was used in this study to predict site water balance. HYDRUS 1D uses soil hydraulic parameters, tree parameters such as transpiration rate and root depth and climate data (rainfall and evaporation). Root depth was measured during biomass estimation by excavation method. Soil hydraulic parameters were taken from the studies conducted by Dr Ian Phillips (Griffith University, 2004) and mulch hydraulic parameters were obtained from Findeling et al. (2007). Precipitation and evaporation data were
obtained from the Bureau of Meteorology (BOM) and the weather station located at the landfill site. Final simulations were completed using the average values obtained for the selected 10 tree species (Fig 4) grown in the phytocapping system.

Two scenarios namely; 1) without vegetation and 2) with vegetation were considered while simulating the site water balance. Before running the model for scenario two, canopy interception (32%) was deducted from the actual total rainfall data for the experimental site. Irrigation values were added to the rainfall data, and the rate of soil evaporation was taken as 50% of that of the un-vegetated site (worst case scenario), as the soil evaporation under agroforestry (Albright et al. 2002) systems will be much less than that under a tree canopy (reduced by 23% to 40%; Wallace et al. 2000, Jackson and Wallace 2000). Merta et al. (2006) found that the soil evaporation under agricultural crops was considerably low under high Leaf Area Index (LAI). For example, the soil evaporation was 50% at a LAI of 1.5. Based on these data, soil evaporation was taken as 50% of that reported by the BOM.

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. The patterns of height response differ markedly
between species, and this was expected, as this is related to genetic differences between
the species. On an average the species grew 4.7 m tall with an average stem girth of 84
mm. However, the growth difference between thick and thin cap was very marginal.
These differences in plant performance between the two types of cap imply that the thick
cap’s greater soil water storage capacity allows the plants to grow faster and, thus, to
transpire at a higher rate.

Sap flow measurements were recorded in *Acacia mangium, Acacia harpophylla, Casuarina cunninghamiana, Eucalyptus grandis, Eucalyptus raveretiana, Eucalyptus tereticornis, Ficus microcarpa, Ficus racemosa, Glochidion lobocarpum, Hibiscus tiliaceus, Melaleuca leucadendra, Pongamia pinnata, Cupiniopsis anacardioides and Syzygium australis* on different occasions. Results from 48 observations show that sap flow varied significantly among species. On an average the species were able to take up 1.4 mm day\(^{-1}\). The species could also withstand water stress conditions and take up water as low as 300 ml day\(^{-1}\). This shows the potential of the selected species to adapt to the seasonal variation, and at the same time take up maximum during rain events.

Three year old trees grown on the phytocaps were able to intercept up to 50% rainfall on per storm basis, with an average of 30% of the total rainfall received at Rockhampton. This is quite a significant contribution towards the hydrological balance of the phytocapping system. Average rainfall received at Rockhampton is around 780 mm (average of 47 years rainfall data) and with the current performance of the trees, only 546 mm of the total rainfall actually reaches the ground surface. This not only reduces the load off the soil layer but also reduces the cost of soil to be placed on the landfill to hold excess water. *Acacia mangium, Casuarina cunninghamiana, Hibiscus tiliaceus, Glochidion lobocarpum, Ficus microcarpa, Dendrocalamus maroochy, and Syzygium australis* intercepted more than 30% of the rainfall (Fig 5).
I.

\[ I_s = 3.537 \]

\[ 30 \]

\[ 1 \]

\[ H \]

\[ 0.2 \]

\[ 15 \]

\[ 0 \]

Fig. 5 Canopy Rainfall Interception by 19 tree species grown on phytocaps in Rockhampton. Data are means of 50 events x 2 measurements over a 2 year period.

Results from this study show a significant difference \( (P<0.001) \) in rainfall interception due to the variation in the morphology and characteristics (Crockford and Richardson 2000). Among the 19 tree species studied, few had needle shaped leaves (e.g. Casuarinas) and few broad leaved (e.g. Eucalypts).

Methane concentration in the root zone and surface were consistently low in thick cap than in thin cap for all the tested species. The surface methane emission was also low in thick cap for the majority of the tested species. The methane concentrations were significantly \( (P<0.001) \) lower on the surface than in the root zone for majority of the tested species. This could have been contributed by the root system, soil and mulch (Bogner et al. 1997, Christopherson et al. 2000). Overall, the thick cap was 45% more efficient in reducing methane emission compared to the thin cap. The significantly \( (P<0.001) \) lower levels of methane emissions in the thick cap than in thin cap could be due to greater exposure of methane to larger volume (depth) of the soil, or an increased rate of oxidation by the soil bacteria (Bogner et al. 1997, Khalil et al. 1998, Kallistova et al. 2005). The differences between thick and thin caps were much larger for the root zone methane than for surface methane (with the thick cap having less methane than thin cap). The unvegetated site adjacent to the experimental site had similar depth of interim soil over the refuse as in thin cap, but it had no mulch placed over it. Thus the surface methane concentrations were significantly \( (P<0.001) \) lower in the phytocap (thick or thin) than in the adjacent unvegetated site (Fig 6). Phytocaps can therefore reduce methane emission 4 to 5 times compared to a bare (un-vegetated) site.
Site water balance was simulated for two scenarios as mentioned above.

**Scenario 1:** Percolation simulated for the thick cover (1400 mm) and the thin cover (700 mm) without vegetation was 133.3 mm yr$^{-1}$ and 153 mm yr$^{-1}$ respectively (Fig 7). This difference between the two covers was expected, as the soil depth plays a vital role in retaining maximum amount of water (Warren *et al.* 1996). Detailed description of the simulate runoff and storage capacity is given in Venkatraman *et al.* (2008).

**Fig. 7** Simulated percolation of water in thin (left) and thick (right) covers respectively in the absence of vegetation (cumulative of 15 years data; 1992 to 2006)
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 top 10 selected tree species grown on the experimental site. The average rain intercepted by the top 10 tree species was 32%. Therefore, the incident rain was reduced by 32% and this corrected rainfall was used in the simulation.

The HYDRUS 1D simulation for the vegetated site showed a percolation of 16.7 mm yr$^{-1}$ for the thick cover and 23.8 mm yr$^{-1}$ for the thin cover (Fig 8). The percolation for vegetated covers was 8 to 10 times less than that simulated for non-vegetated sites. This clearly demonstrates the role played by the vegetation in phytocapping.

Results from the above simulation suggest that phytocaps are very effective in reducing percolation of water into the waste. In this simulation, establishment of 10 selected tree species using 1400 mm layer of unconsolidated soil will allow a percolation of 251 mm in 15 years. This is equivalent to 16.7 mm yr$^{-1}$. This value is significantly lower than the percolation rate expected for a clay cover (c. 10%; Geoff Thompson; pers. Comm.). The results also show that the reduced percolation was due to the presence of deep rooted tree species (compare Fig 7 and 8).