USE OF PHYTOCAPS IN REMEDIATION OF CLOSED LANDFILLS

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Abstract
The suitability of a phytocap as an alternate capping system in the management of closed landfills was investigated. A field trial involving a range of native trees, shrubs and grasses, irrigated with landfill leachate of varying strength was undertaken at the former Nudgee Landfill. Laboratory and field-testing evaluated the effect of leachate on soil physical and chemical properties, and on plant performance. Changes in key soil physical properties (aggregate stability, hydraulic conductivity and infiltration) resulted from the application of leachate. Leachate significantly affected the survival and growth rates of many of the plant species. This trial has provided important information on design of phytocaps, and the incorporation of leachate-tolerant plant species in landfill management.

Additional Keywords: nitrogen, carbon, hydraulic properties, aggregation, landfill leachate, capping systems

Introduction
Leachate management continues to be one of the major issues facing regulatory authorities responsible for remediation of closed landfills. Various strategies for minimising leachate release into the environment can be engineered into landfill design such as drainage collection systems, cut-off walls, reactive permeable barriers, collection and recirculation systems, and the construction of low-permeability (engineered) surface caps. Engineered caps have been widely used as an effective method to minimise water entry into landfills, and consequently, the potential for leachate generation. Recently, less-costly capping designs that incorporate leachate-tolerant plants have been investigated as an alternate capping system to engineered caps. These alternative designs involve planting trees and shrubs directly into the landfill cover material, or into a thin layer of topsoil (approx. 30 cm) above the landfill cover, and have been termed "*phytoremediation caps* (or *phytocaps*)". The phytocap principally involves the use of plants that are tolerant to highly saline, ammonium-rich leachate, and is closely related to the established remediation technology referred to as "*phytoremediation*".

In 2002, Brisbane City Council (BCC) commenced a major innovative project to investigate the applicability of phytocaps as a method of managing leachate at the former Nudgee Landfill. This represents one of the first phytoremediation trials to be undertaken at a Queensland landfill, and possibly the first of its kind in Australia. The principle aims of the trial were to assess whether the concept of phytoremediation can be incorporated into landfill capping design, identify a range of native plants that have the potential to treat leachate on-site, and to evaluate the suitability of the phytocap as an alternative capping system to the more costly engineered cap.

Materials and Methods
The phytoremediation trial was constructed on the western batter of the former Nudgee Landfill, and commenced in April 2002. The trial comprised of 12 plots (22.5 m long by 12 m wide), and included 2 capping designs (engineered and phytocap), 3 leachate qualities (0, 40 and 100%) and 2 replicates of each plot (replicate 1 and 2). Each cap was constructed on top of the existing landfill surface. The engineered cap comprised of 0.5 m of compacted clay, overlain by 0.3 m of gravel, overlain by geotextile cloth, overlain by 0.3 m of topsoil. The phytocap consisted of 0.3 m of topsoil only. The general composition of the leachate (100% strength) was: pH = 7.1; Electrical Conductivity (EC) = 15000 μS/cm; Total Organic Carbon (TOC) = 230 mg C/L; BOD_5 = 21 mg/L; Total Kjeldahl N = 510 mg N/L; NH_4 = 330 mg N/L; NO_3 = 4.9 mg N/L; Total Alkalinity ($CaCO_3$ equivalent) = 1700 mg/L; Chloride (Cl) = 5000 mg/L; Calcium (Ca) = 130 mg/L; Magnesium (Mg) = 180 mg/L; Sodium (Na) = 2900 mg/L; and Sulfate (SO_4) = 240 mg/L.

Preliminary studies (Ashwath and Hood, 2001) identified eighteen plant species that were suitable for the trial, which included a number of trees (acacias, eucalypts and grevilleas) and grasses (vetiva and juncus). Species were planted in a randomized block design, and drip irrigated at a daily rate of 3.7 mm. Plant characteristics such as height and girth were monitored throughout the trial, and leaf samples of each plant were collected for Total N and Total C analysis using mass spectrommetry. Soil from across each plot was analysed for gravimetric water content pH, EC and 2M KCl NH_4 and NO_3 using standard techniques.

Laboratory and field testing was undertaken to investigate the effect of leachate (0, 40 and 100%) on soil physical and chemical properties. The saturated hydraulic conductivity (k_{sat}), stability of soil aggregates, inorganic and organic N adsorption isotherms, and soil N transformations, were determined using soil from the topsoil and underlying clay layers by standard analytical techniques.

Results and Discussion

Soil Physical Properties

Slaking was observed for all soil aggregates following immersion in the 0, 40 and 100% leachate solutions. Air was observed to diffuse out of the aggregate into the solution, followed by disintegration of the aggregate. The topsoil used in the trial was classified as a sandy clay loam, and contained little binding materials such as organic matter and/or sesquioxides. The slaking character of this soil was observed to cause a significant (10-fold) reduction in the saturated hydraulic conductivity (k_{sat}). During the k_{sat} experiments (Fig. 1), it was observed that the surface few millimetres of the soil columns contained a high proportion of very fine soil material (probably generated through slaking), and this material probably formed a low permeability layer that inhibited infiltration of applied solutions. Subsequent application of a 0.1 M $CaCl_2$ could not re-flocculate this material, suggesting that formation of the low permeability layer was an irreversible process. Blockage of conducting pores by this layer of colloidal material may largely be responsible for the large, permanent decrease in k_{sat} observed in these soils. Minhas and Sharma (1986) reported similar findings for a clay loam soil.

Soil Chemical Properties

Inorganic nitrogen (NH_4) was either adsorbed by the cation exchange complex, or transformed to nitrate through microbial activity following addition to the topsoil. After the added NH_4 attained exchange equilibrium (<1 day), it was found to decrease exponentially with time, and demonstrated a half-life of about 8 days. The decrease in NH_4 was generally accompanied by a concomitant increase in NO_3. The NH_4 sorption isotherm was well described by the Freundlich equation: $S = k_f c^n$ where S is the increase in sorbed NH_4 (mg/kg), c is the final NH_4 solution concentration (mg/L), k_f and n are empirical fitting constants ($r^2 = 0.99$; Fig. 2a). These results show the topsoil has a good ability to remove NH_4 from applied leachate once it infiltrates the soil. Furthermore, removal from solution should reduce the quantity leached with the drainage water, and act as a storage reservoir of NH_4, and as a source of plant-available NO_3.

The data also showed that the topsoil removed significant amounts of organic N, and that the maximum increase in adsorbed concentration was about 100 mg/kg (Figure 2b). Sorption of amino acids (a common source of organic N) by a sandy loam soil was reported by Jones and Hodge (1999), and the shape of these isotherms was similar to those in Fig. 2b. Organic compounds which contain N (e.g. amino acids, polypeptides, and proteins) can be sorbed by various processes such as hydrophobic sorption, hydrogen bonding, ligand exchange, cation exchange and anion exchange. The short duration of the equilibration study, coupled with no obvious increases in inorganic N, suggests that the loss of organic N did not result from microbial activity. It is possible that this loss was due to reactions with the soil charged components (i.e. clay minerals, organic matter, and/or Fe oxides) since decreases in soluble organic carbon were also observed (data not presented). Kaiser and Zech (2000) and Kaiser (2001) studied the sorption of dissolved organic carbon, nitrogen, phosphorus and sulfur by a range of soil materials, and found that dissolved organic N sorbed to amorphous Fe and Al hydrous oxides almost completely, and that no sorption maxima was reached. Sorption by clay minerals such as kaolinite and illite, however, was found to be non-linear and a maximum sorption value was observed. This type of isotherm was also observed for the topsoil. This trend was not observed for dissolved organic carbon, and was consistent with other workers (Kaiser and Zech, 2000) who found sorptive retention of organic N to be less than that of organic C. This has been attributed to much of the N-containing compounds being present in the weakly sorbed hydrophilic fraction of dissolved organic matter (Kaiser and Zech, 2000). Although these findings suggest organic N was more susceptible to leaching than is organic C, the studies by Kaiser and Zech (2000) and Kaiser (2000) were performed under acidic (pH 4) conditions. It is uncertain if similar findings would be found for alkaline conditions and less-labile forms of organic matter such as expected with landfill leachate.

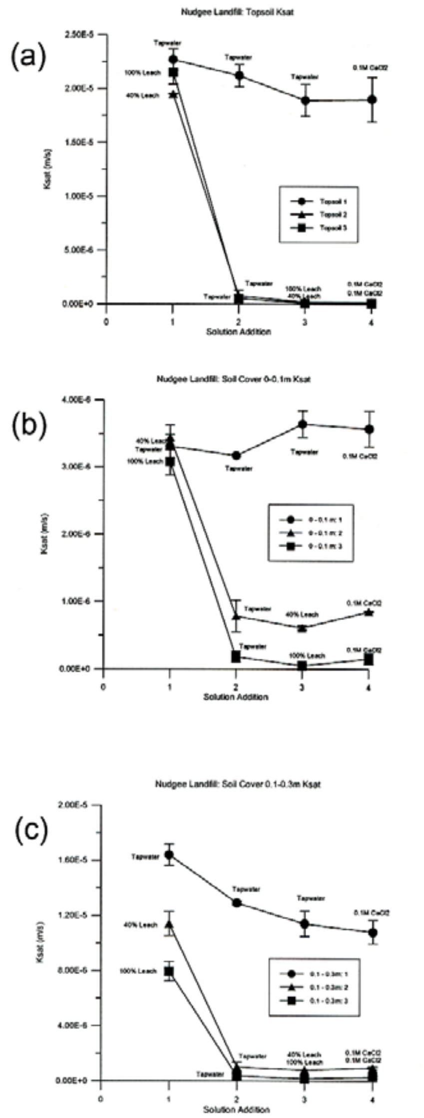

Figure 1. Effects of leaching solution on k_{sat} for (a) topsoil; (b) cover 0-0.1 m; and (c) cover 0.1-0.3 m

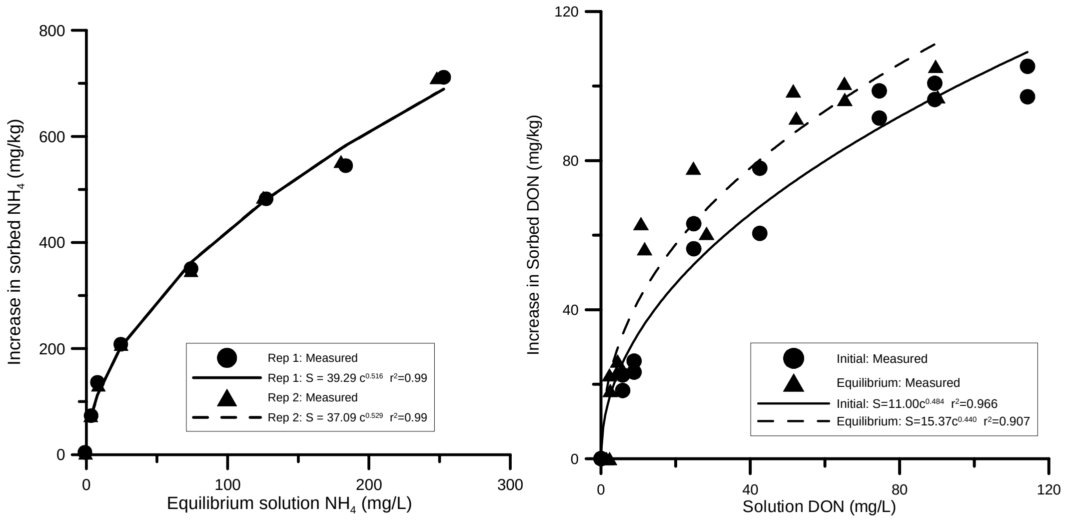

Figure 2. (a) Ammonium adsorption isotherm and (b) dissolved organic N adsorption isotherm. [Initial refers to a plot of Initial DOC added vs Sorbed DOC, and Equilibrium refers to Equilibrium solution DOC vs Sorbed DOC]

Plant Total N and Total C
There was no major difference in the Total N and C levels found in the leaves of plants between the two capping systems. Average Total N and Total C values for the Engineered cap and Phytocap were: 14.4 and 13.6 g/kg, and 46.0 and 46.2 %, respectively. Thus, on the basis of these data, the plants growing on the phytocap appear to have taken up similar amounts of N and C from the soil as plants on the engineered cap.

The average Relative Growth Rate (RGR) for all species as a function of treatment was found to be about 6, 4 and 3×10^{-4} cm/cm/day, and the application of leachate caused a significant decrease in the growth rate of plants relative to the control (BCC, *personal communication*). Average species survival rates were calculated for the 0, 40 and 100% leachate treatments to be 78, 80 and 58% respectively (BCC, *personal communication*). The species *Lomandra longifolia*, *Ficus macrocarpa hilli*, *Juncus usitatis*, *Araucaria cunninghammi* (100% leachate treatment only), *Acacia hypophylla*, *Acacia mangium* (100% leachate treatment only), *Callistemon viminalis* (100% leachate treatment only), *Grevillea robusta* (100% leachate treatment only), and *Pinus caribea ellotti* (100% leachate treatment only) demonstrated a relatively low survival rate (<60%), while *Melaleuca leucadendron*, *Cupaniopsis anacardioides*, *Casuarina equisetifolia*, *Eucalyptus mollucana*, and *Eucalyptus robusta* demonstrated high survival rates (>80%) irrespective of leachate treatment. Although the survival of certain species was affected by external influences such as rabbits, the results to date indicate that only a few of the trialed plant species appear suitable for phytoremdiation using 100% strength landfill leachate.

Plants receiving leachate contained significantly ($p \leq 0.05$) higher Total N concentrations, and tended to contain more Total C than plants grown in the absence of leachate. For example, average Total N concentrations for the 0, 40 and 100% leachate treatments were 11.7, 13.1 and 17.2 g/kg respectively, and the average Total C concentrations were 45.6, 45.9 and 46.8 % respectively. Thus, a proportion of the applied N in the leachate appears to have been taken up by the surviving plants. The overall amount of N and C removed via uptake however cannot be quantified since the N content in the remaining plant biomass (stems, roots and branches) has not been determined.

Conclusions
The phytoremediation trial at the former Nudgee Landfill has provided considerable baseline data on the suitability of alternate capping designs and to identify leachate-tolerant Australian native plant species. These species have the potential to be planted at leachate-seepage points, and to act as a hydraulic barrier to reduce off-site migration of leachate-contaminated groundwater. This trial has however demonstrated that care must be taken in selection of soil types, rate of irrigation and mode of irrigation delivery. Experience from this trial will form the basis of future phytoremediation trials.

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