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PLANT SELECTION FOR LANDFILL PHYTOCAPS: AUSTRALIAN CASE STUDIES

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ABSTRACT: Phytocaps are soil-plant systems that are installed on top of landfills after closure to achieve hydraulic containment of wastes and rehabilitation of the landform. They provide greater opportunity than other capping technologies to reinstate ecological value, as trees, grasses and shrubs are a core part of the design solution. Despite this, ecological approaches have not been emphasised in landfill rehabilitation. The soil profile of a phytocap is uncompacted and designed to support the vegetation community as well as the proliferation of roots throughout the landfill cap thickness. As phytocaps rely on plant transpiration and evaporation to remove stored water from the designed soil layer, plant selection is a critical factor impacting phytocap success. This paper showcases two Australian phytocap case studies, with a particular focus on plant selection. It outlines a transferable methodology that can be applied to any landfill site context to achieve better design outcomes for phytocaps. This method is based on four pillars. The first pillar is a good understanding and analysis of the constraints of the available soil. The second pillar is a good understanding of the indigenous ecosystems that surround and would have been present at the site prior to disturbance. The third pillar is understanding the current unique site context including differences in environmental conditions that may impact the success of the plant community and any specific compliance requirements that need to be taken into consideration during design. The fourth pillar is understanding the potential benefits that can be achieved beyond pollution abatement and compliance, including ecological, social and community benefits, and how these can be successfully incorporated to create a flourishing ecosystem.

Keywords: plant selection, site assessment, natural analogues, multi-benefit design, ecological services, phytocap, evapotranspiration landfill cover, landfill rehabilitation, landfill capping, Australian native plants

1. INTRODUCTION

Phytocaps offer many ecological and social benefits beyond engineering hydraulic containment. Intrinsic to a phytocap's engineering function is the fostering of a thriving plant community that also serves to enhance biodiversity by sustaining a wide variety of plant species that in turn provide habitat and food for mammals, birds, reptiles, amphibians, invertebrates, fungi and bacteria (Rawlinson et al., 2004; Summer and Reichelt-Brushett, 2018). With good planning, a phytocap can also be used to create high-value social and recreational space in the form of nature parks (Kim and Lee, 2005; Wang et al., 2020). This is of value in areas with high urban development and densification, where green space has not been adequately catered for.

Despite the importance of the plant community for phytocap performance, there has been a greater focus on the physical soil configuration compared with the plant selection and configuration (Chell et al., 2022; Forman, 2004; Forster et al., 2022; Kim et al., 2022). Commonly reported plant selection criteria in the phytocap literature include the selection of indigenous plant species for their adaptation to local site conditions (Bolen et al., 2001; Dwyer, 2001; Gill et al., 1999; Hauser and Gimon, 2004; Karr et al., 1999;

Kiel et al., 2002; McGuire et al., 2009), the inclusion of grasses, in particular, the selection of both C3 and C4 grasses to maximise plant cover and the window of active plant transpiration (Butler, 2004; Dwyer, 2001; Kiel et al, 2002; McGuire et al, 2009) and the selection of a diversity of plant species to ensure the resilience of the plant community (Gill et al, 1999; Karr et al, 1999; Smith and Waugh, 2004). Additionally, the landfill environment presents a unique context to plant communities establishing in capping soils, with the presence of decomposing waste having the potential to negatively influence soil-gas composition (i.e. through excessive CO_2 or exclusion of oxygen by CH_4) and increase temperatures from the native soil environment (Michael, 2023). The landfill gas and temperature impacts experienced within the cap will depend on the age of the landfill and the composition of underlying wastes.

The landfill cap context will usually have different slope and drainage patterns compared to the landscape before disturbance and this needs to be taken into consideration (Michael, 2010) alongside management of sediment and runoff discharges through appropriate surface water management (Michael et al., 2007; Michael et al., 2005; Michael et al., 2004). Other factors that influence the selection process include climate characteristics. The Australian continent compared to other continents of the world has: high climate variability (Croke and Jakeman, 2001), low soil fertility (Nix, 1981) and a high proportion of endemic plants, and structural types that do not occur elsewhere (Braithwaite, 1990; Flannery, 1994).

The aim of this paper is to showcase a methodology for selecting plants with two Australian case studies. The first site, the Wollert Landfill, is a municipal solid waste landfill in temperate Victoria. The second site, the New Chum Landfill, is a Construction and Demolition waste landfill in sub-tropical Queensland. Both landfills make use of voids created from extractive activities, basalt quarrying in the case of Wollert and coal mining in the case of New Chum. Both sites also have novel on-site spoils for use in phytocapping by virtue of their past extractive activities.

2. APPROACH

This paper presents an approach to plant selection based on four pillars: soil constraints; indigenous ecosystems; the landfill context and multiple benefits. An understanding of these four pillars creates a good foundation for a successful phytocap plant selection.

2.1 Soil constraints – The First Pillar

An understanding of soil properties is the foundation for good phytocap design. The soil materials store water and support the phytocap plant community that plays an essential role in the function, performance and structural integrity of the phytocap. Transpiration by plants, together with evaporation, ensures the hydraulic objective of minimal drainage is achieved by the phytocap through a well-designed water balance scenario. Through comprehensive assessment and analysis of soils, a phytocap system can be designed to optimise plant growth and thereby achieve the engineering objectives.

Soil selection is in most cases constrained by distance from the site, with those materials accessible within practical haulage distances (e.g. 20 km) most economically beneficial. The nature and distribution of native field soils are influenced by geological and geomorphological characteristics. In certain instances, the whole profile of a source location may be appropriate, while in others, only a single soil layer may possess the necessary properties. Additionally, soils for phytocapping may be anthropogenic, originating from mining and quarrying activities such as the materials highlighted in these case studies.

Essential physical properties to be tested include:

- Maximum dry density.
- Particle size distribution including clay and silt content.
- Soil moisture characteristics including hydraulic conductivity.
- Atterberg limits including liquid limits, plastic limits, plasticity index and linear shrinkage.
- Dispersion (Emerson class).

Chemical properties include:

- pH and electrical conductivity.
- Nutrients including a range of macronutrients and micronutrients, importantly organic carbon, total nitrogen, total phosphorus, total sulphur and exchangeable cations.
- Heavy metals and other pollutants.

The determination of the maximum dry density of the substrate is essential to establish optimal compaction levels that influence the water storage capacity of the soil and the ability of the substrate to sustain plant growth. Substrate compaction plays a significant role in altering moisture retention and hydraulic conductivity. Previous research has identified that the optimal compaction level for phytocaps is between 70-83%, with a target optimum around 77% of the standard maximum dry density, yielding the best results in terms of plant water use, subsequent drainage reduction, and enhanced plant growth (Kim et al, 2022; Michael et al., 2019).

The soil moisture characteristic curve delineates the variation in soil moisture content in response to increasing soil suction, providing insights into the soil's capacity to retain water throughout various phases of the drying process. Typically, this test is conducted in a laboratory setting, where the moisture content of prepared samples is monitored in correlation with the suctions applied. Two specific pressure points are especially pertinent to the phytocap plant community: the field capacity (FC) and the wilting point (WP). Field capacity refers to the moisture content at which the soil has maximized its water-holding capacity, traditionally identified as occurring at a suction range of 10-30kPa (Ashman and Puri, 2002).

The volume of water retained at field capacity is predominantly influenced by the soil structure and the presence of large, continuous pores (Robinson, 2003). Conversely, the permanent wilting point is the moisture content at which plants are no longer able to extract water, resulting in loss of turgor and wilting, and is ascertained at 1500kPa (White, 1997).

Regarding the chemical properties: pH and electrical conductivity are important constraints for plant growth. The pH of the phytocap substrate influences seed germination, plant growth, nutrient availability, uptake and mobility (Neina, 2019). The electrical conductivity or salinity also can impact plant growth, when at excessive levels (Bernstein, 1975). In humid regions, rainfall aids in the gradual reduction of salt content through leaching. However, in arid and semi-arid regions, the process of salinity reduction can be problematic due to the extended duration it takes.

Australian soils are skeletal and many are extremely badly leached leading to a deficiency in nitrogen and phosophorus, and therefore Australian plants are well-adapted to these conditions. For example, the small hard leaves of eucalpys and many acacias, melaleucas, and members of the proteceae family are thought to be an adaption to nutrient poor soils, and eucalypts are are able to extract most of the nutrients from dying leaves before they fall off as an additional method to conserve nutrients (Costermans, 1986). Therefore soil results in the Australian context need to be evaluated with Australian vegetation in mind. An over-supply of nutrients can mean an influx of weeds, and a competitive disadvantage for native plants, that may thrive and have a competitive advantage in poorer nutrient scenarios. Similarly, a high nutrient scenario may lead to a predominance of plants that were not intended in the original design (Michael et al, 2005). Native grasses are particularly susceptible to arranging their composition and structure along nutrient gradients.

With this in mind, if the chosen phytocap substrate possesses sufficient nutrients essential for plant growth, and there is no significant nutrient leaching due to water percolating through the substrate profile, then it is probable that the substrate will facilitate plant growth with little maintenance required (Hauser, 2009). However, if this condition is not met, it may be necessary to consider the use of fertilizers or other soil enhancers, but these need to be considered carefully.

The designer needs to review the soil results with the aim to provide conditions that will sustain a flourishing phytocap plant community in the long-term. This is not an agricultural objective, but one that needs to be grounded in a good understanding of the needs of the soil-plant communities present within the indigenous ecosystem.

2.2 Indigenous ecosystems – The Second Pillar

An understanding of the original indigenous ecosystems that would have once been present at the landfill site or in the surrounding region is necessary for understanding the rehabilitation objective. It also gives insight into the plant community structure that is likely to be sustained in the given climate context. Furthermore, plant water use within many ecosystems throughout the world was largely in balance with rainfall (Eberbach, 2003). Understanding the dominant drivers on the native ecosystem hydrologically is therefore valuable given the objective of a phytocap. Evaluation of the chemical characteristics of the indigenous soils helps to determine the suitability of the selected soil for reaching the phytocap objectives.

Ground-truthed plant surveys and soil testing reports of the native soil are extremely valuable and should be searched for in the first instance. In their absence, a designer will need to rely on mapping tools that describe the regional ecosystems and their species more broadly, however, these lists are not always perfectly delineated and need to be supplemented with on-the-ground experience. Sometimes it is worthwhile, particularly if looking to enhance connectivity with surrounding ecosystems, to survey the remnant ecosystems on the landfill boundaries with an experienced person/people in plant identification as many insights can be gained to assist your design. Local nurseries, bush care groups, and volunteer *'friends of'* natural areas groups can be useful in gaining valuable insight into plant drivers and likely success based on experience. Relationships and discussions with traditional owners can be extremely valuable. Where knowledge is gained by relationship, it is essential that designers provide a genuine commitment to two-way knowledge sharing and continuation of the relationship through to completion of the project based on the level of interest of the parties.

This process is part systematic, part exploratory and part emergent. Sometimes the information collected from a range of sources may be conflicting and it is the job of the designer to triage and filter the different inputs into a cohesive concept:

- Regional ecosystem maps
- Existing local plant surveys and soil results
- Surveys of plants and soils at reference sites as part of the project
- Discussions with nurseries, bush-care groups and volunteer '*friends of*' natural areas
- Genuine and enduring relationships with traditional owners

2.3 Landfill context – The Third Pillar

A landfill is a disturbed site that is different from a natural land rehabilitation context. Depending on licensing requirements, a site owner may have permission to change the topography and finished level of the landform relative to natural ground level. Furthermore, the decomposition of waste materials presents unique challenges for the establishing plant community if not controlled. These include the production of landfill gas: whereby methane in the soil profile acts to exclude oxygen needed for root respiration (in a similar way to flooding); and carbon dioxide which is detrimental to plants above 5-10% and lethal above 25%. Ideally, phytocaps are built on sites that either have a landfill gas capture system in place, or on sites where landfill gas levels have been reduced to sustainable levels for plant growth.

In either case, the selection of plant species that may be able to tolerate a landfill gas 'flooding' event is worthwhile and reduces the risk of plant failure. In some Australian states, a substrate depth of 1.5 m is mandated. This reduces the risk of wind-throw to a similar level as most forest soils and provides a buffer from methane and carbon dioxide compared with thinner covers (Moffat and Houston, 1991).

The newly graded surface of a landfill cap is vulnerable to erosion and sediment run-off when first established, which is of particular concern when placing less-compacted soils. Therefore irrespective of whether grasses predominate in the indigenous ecosystem, grasses are an essential component of any phytocap project, as their fibrous roots stabilize the surface and limit erosion (Breshears et al., 2005).

Biodiversity is inherent in natural ecosystems, and particularly important in a landfill phytocap context as it reduces the risk of failure, increases resilience and through diverse niche occupation allows year-round water extraction from different regions of the cap.

2.4 Multiple benefits – The Fourth Pillar

The number of plant species that can be incorporated into a project is oftentimes constrained, usually ranging from 20 to 30 species, unless the site owner is committed to achieving ecological goals. Employing a multi-benefit perspective is advantageous for refining plant lists, ensuring not only that the chosen species align with the engineering goals but also contribute additional, synergistic advantages as part of the design (Abuseif et al., 2022):

- **Ecological Values:** The selected plant serves as a habitat, a food source, or is crucial for the life cycle of native fauna, including animals, insects, and birds.
- **Traditional Uses:** The plant has edible parts (e.g., bush food), medicinal properties, or other traditional cultural applications, such as tool, weapon, or ceremonial item production, which enhance engagement with the landscape.
- **Recreational Values:** The plant contributes to the overall recreational theme by offering shade, aesthetic appeal, and interest.

Moreover, it is essential to consider the long-term impact of the selected plants on the local ecosystem. The chosen species should ideally be indigenous to the area or, at the very least, non-invasive and compatible with the local flora and fauna. This preserves the natural biodiversity of the region, minimizes the need for maintenance and reduces the risk of unintended negative ecological consequences. Ultimately, a well-thought-out plant selection that considers multiple benefits can contribute significantly to the success and sustainability of a project while enhancing the local ecosystem and providing valuable resources and recreational spaces for the community.

2.5 Development of selection criteria

In developing selection criteria, we need to take the four pillars of plant selection into consideration. With the knowledge we have about *Pillar 1 – soil constraints* we can identify where we may need to select species with specific tolerances to those constraints. Our highest preference is to choose plants from the indigenous ecosystem, however, in some cases we need to look outside our plant list for specific tolerances particularly if our soil is not a native soil (Michael, 2010). There is also the option to ameliorate the soil to make it more conducive to plant growth, but where possible it is good to select a soil that does not pose significant constraints to plant growth in the first instance, understanding that many Australian native plants are highly tolerant to low organic matter and low soil nutrients and have capacity to improve the soil over time as the canopy and leaf little develops and breaks down. *Pillar 2 – indigenous ecosystems* helps us to better understand which specific plant communities may be suitable from the broader indigenous plant list, and to better understand the unique drivers to phytocap success based on the endemic ecohydrological context. *Pillar 3 – landfill context* is where we look squarely at the landfill site and proposed capping solution and do a side-by-side comparison between the indigenous ecosystem conditions and the altered designed site conditions to identify areas of risk or significance that need to be considered as part of the plant selection. The following are areas useful to compare:

- Finished site levels, slopes and drainage contours
- Soil depth and soil density
- Soil physical and chemical properties
- Exposure to sun and wind
- Climate change adaptations

Pillar 4 – Multi-benefits is where we deepen our understanding of the beneficial relationships between the plants chosen and attempt to select those that have the highest benefit ecologically, socially and culturally. If whittling down or filtering a plant list we might choose those that are food plants, host plants or have traditional uses as medicine or bush foods.

2.6 Plant availability

Plant selection for a project may be further constrained by plant availability. It's important to recognize that plants have their own rhythm and timing of seed production, plant establishment and growth related to the seasons, and plant nurseries usually work in with these natural cycles for seed collection, plant propagation and cultivation. It is essential to plan your project to work in with these cycles and to communicate with suppliers or with your vegetation contractor who is connected to the suppliers as early as possible. Nurseries will only have a limited range of available plants based on community demand. However, nurseries may also be open to partnering with the project to collect seeds and propagate plants that are not part of their usual offering if there is a guaranteed purchase. To create high-quality rehabilitation outcomes that incorporate rare or endangered plants, this is likely to be needed, and enhances the site owners social capital alongside the ecological benefits.

3. RESULTS

3.1 Case study 1: Wollert Landfill, Wollert, Victoria

The Wollert Landfill is a municipal solid waste landfill licensed to accept putrescible and inert wastes, low-level contaminated soils and asbestos. The site is situated on the Basalt Plains, Victoria, Australia, approximately 50km Northeast of Melbourne's CBD and makes use of spaces created from the excavation of basalt as part of adjacent bluestone quarry operations (Michael, 2010).

3.1.1 Soil constraints (Pillar 1)

A large quantity of waste rock or "quarry scalpings" is created at Wollert as a by-product of basalt quarrying. This material is comprised of crushed basalt and subsoil and is produced at a rate of 270,000 tonnes per annum, stockpiled at the site in a range of size classes depending on operational decisions for extracting basalt from the quarry feed. Special care needed to be taken to sample and characterize the quarry scalpings due to the particle size segregation that occurs in stockpiles.

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) giving it high susceptibility to compaction. The water storage capacity of the substrate was 172-234mm/m, with extremely low plant available water (30mm/m).

The pH range of the quarry scalpings was 8.1-8.6, which is high enough to limit the availability of some essential elements for plant function, with confirmed presence of $CaCO_3$. It could be considered non-saline (0.33-0.42 mS/cm). Due to its origins as unweathered subsoil and rock, the substrate also had extremely low organic matter and a paucity of phosphorus and nitrogen. The effective cation exchange capacity (CEC_e) was high (16 meq/100g) with a predominance of magnesium over calcium leading to surface skinning, and an exchangeable sodium percentage (ESP) of 11% indicating sodicity.

3.1.2 Indigenous ecosystems (Pillar 2)

The landfill is situated on the far eastern edge of an extensive basalt plain, a bioregion with unique landscape features, soils and vegetation communities. Due to the fingering of basalt, the endemic soils consisted of undulating plains and stony rises of alternating soil types. The plains soils were typically low permeability and susceptible to compaction and waterlogging: stony dark brown clay soils of uniform texture to a depth of 0.5m; heavy black clay soils of uniform texture to a depth of 0.8m; and, yellow-brown calcareous sodic duplex soils with coarse underlying structure and hard setting low permeability clay-loam surface soils to a depth of 1.5m. In contrast, the stony rise soils were typically high-permeability consisting of stony red gradational soils with a loam to clay-loam texture to a depth of only 0.3m. The endemic soils have pH ranging from 5.2-7.6 with moderately acidic surface soils; organic carbon 1.1-14% w/w with moderate phosphorus (6-23mg/kg) at the surface (<300mm) and low phosphorus at depths >

500mm (3-5mg/kg).

The original vegetation of the site was a mosaic community of *River Red Gum Grassy Woodland* and *Stony Knoll Grassland and Cliff/Escarpment Vegetation*. The River Red Gum Grassy Woodland has an open structure with approximately 10% tree cover of *Eucalyptus camaldulensis* (River Red Gum), the density of which influences the nature of the sparse mid-storey of Acacias, and the spacing and cover of tussock grasses which in turn influences the establishment and diversity of herbs and wildflowers in the inter-tussock spaces (DSE, 2004) (Specht, 2000). Acacias in the mid and ground layers, despite their sparse covering, contribute significantly to the soil nutrient dynamics, through their ability to fix atmospheric nitrogen and make it biologically available.

The endemic plant communities were generally comprised of species that had the capability to actively grow and transpire during summer, exhausting the soil moisture store prior to the winter rains thus minimising deep drainage (Johnston et al., 1999).

3.1.3 Landfill context (Pillar 3)

As part of the basalt plains, the surrounding area is relatively flat with undulating small rocky rises. In formation of the landfill and subsequent capping, the designed drainage lines are substantially different from the native ecosystem and rise above the surrounding rural pastureland graded to a 1:12.5 (8%) continuous slope. These differences need to be taken into consideration during plant selection. Leachate recirculation is practiced meaning the waste mass is wet and capable of producing significant landfill gas. Landfill gas capture is operational but was not installed 8 months after phytocap planting and therefore plants were exposed to landfill gas during early establishment. Similarly, the presence of landfill factors needs to be taken into consideration during plant selection. Due to basalt intersecting the surface, the endemic soil profiles were shallow, and the selected phytocap thickness of 1.5 m provides the maximum amount of rooting depth provided in the surrounding ecosystem and was therefore not considered to be of significance.

3.1.4 Multi-benefits (Pillar 4)

The *Grassy Eucalypt Woodland* of the Victorian Volcanic Plain Bioregion is critically endangered and therefore there were ecological benefits to be derived from reinstatement of plants from this bioregion. Cineole-rich oil producing Eucalyptus species were also considered as they are well suited to commercial harvesting due to their coppicing nature. Allocasuarina spp. were reviewed as an important food source for a variety of parrots including cockatoos (Schodde, 1993). Plant species were also reviewed for their overall ecological benefit.

3.1.5 Development of selection criteria

The selected 1.5m phytocap profile of the phytocap is expected to provide sufficient rooting depth for the endemic plant species which naturally occur on shallower soils (Table 1). However, perennial species will ensure the depth of the profile is fully exploited by roots. The landform and drainage lines of the study area have been significantly altered. The gravelly texture of the quarry scalpings differs strongly from the soil textures on the plains but is more similar to the stony rises in the pre-clearance landscape. While these communities are well adapted to high drainage and low total available water (TAW), the potential for landfill gas intrusion, favours those species that naturally occur on the plains and are adapted to periodic waterlogging. The endemic soils have higher fertility, organic matter and are more acidic that the nutrient poor, moderately to highly alkaline quarry scalpings. As high pH may limit the availability of elements for healthy plant function, therefore it’s important to choose plants broadly tolerant of alkaline conditions.

Table 1. Comparison between the original ecosystem and phytocap ecosystem context

Characteristic	Original ecosystem	Phytocap ecosystem	Significance of difference	Criteria
Rooting depth	0.3-1.5m	1.5m	Nil	Perennial grass species and trees that will develop roots over many years
Landform and drainage lines	Mostly flat, with undulating stony rises	Graded bare exposed slope	Large	Grasses for erosion control, pioneer species, drought tolerant species, wind-break species
Landfill gas	None	Potential intrusion of landfill gas during early establishment	Large	Plants species tolerant of periodic flooding
Phosphorus, Nitrogen, Organic Carbon	Varied from low-moderate to moderate-high	Very low nitrogen and phosphorus, extremely low organic matter	Moderate	Plant species tolerant of low nutrient conditions, that will produce leaf litter and add to the soil carbon
pH and salinity	Strongly acidic-moderately acidic surface soils, moderately alkaline at depth	Moderately to highly alkaline	High	Plant species that are alkaline tolerant, tolerant of wide range of pH's
Texture and total available water (TAW)	Likely to be high soil water storage based on clay textures and organic carbon content	Moderate water storage capacity and low plant total available water due to high gravel content	Moderate-high	Drought tolerant plant species, tolerant of free draining soils

In summary, the following plant selection criteria were used to guide plant selection:

- Tolerant of medium-strongly alkaline soils
- Tolerant of low soil fertility.
- Tolerant of free-draining soils.
- Tolerant of flooding
- Incorporating perennial grasses
- Incorporating biodiversity

3.1.6 Characteristics of selected plant community

A total of ten tree species and six grass species were selected. These represented a high diversity of tree species, but a greatly simplified grassland understorey that would need to be successively expanded to enhance biodiversity. Of the ten tree species selected, half were indigenous trees, and half were non-indigenous native trees selected for their tolerances. Indigenous plant species including the dominant Eucalyptus species: 20-45m *Eucalyptus camaldulensis* (River Red Gum), 12-30m *Eucalyptus melliodora* (Yellow Box) and nitrogen fixing mid-storey species such as 5-15m *Acacia mearnsii* (Black Wattle), *Acacia pycnantha* (Golden Wattle) and 4-10m *Allocasuarina verticillata* (Drooping she-oak). Native tree species were selected to address soil constraints where the differences between the endemic soils and quarry scalpings and/or the original site conditions and the phytocap context varied considerably. These included small (3-9m) tree species from an inland area known as the 'mallee' in Victoria where the rainfall is considerably lower (drought and flood tolerant) and the soils are strongly alkaline (>9.0). The grass species were a mixture of C3 and C4 perennial grasses emulating the indigenous ecosystem, capable of extending their roots over multiple seasons and years and contributing to the addition of organic matter supplied by the turnover of roots and other plant tissues. These included *Themeda triandra* (Kangaroo grass), *Bothriochloa macra* (Red grass), *Microlaena stipoides* (Weeping Grass) and Austrodanthonia spp. (Wallaby grasses).

3.2 Case Study 2: New Chum Landfill, Ipswich, Queensland

The New Chum Landfill was formerly an open-cut coal mine and in 1998 was converted to a landfill for general waste, inert construction waste, soil and dry commercial waste. The site is situated in Ipswich, Queensland, 26km West of Brisbane's CBD (Kim, 2023).

3.2.1 Soil constraints (Pillar 1)

By virtue of past coal mining, a large quantity (approximately 75,000m^3) of coal overburden was stockpiled at the landfill site, sparsely covered with colonising casuarinas, acacias, eucalypts and swamp foxtail grasses. The stockpile had extensive variability that could be recognised by distinct colour changes tinges of white, yellow, pale brown, grey and dark grey, but was likely a mixture of subsoils and fragments of Ipswich Coal measures (shale, conglomerate, sandstone, coal, siltstone, basalt and tuff).

From a particle size distribution perspective, the coal overburden was a gravel-sand-clay mixture containing some coal fragments. This corresponded to the classification, GC, according to the Unified Soil Classification Scheme comprising: 47% gravel (2 - 20 mm), 34% sand (75–2360 μm), and 18% fines (<75μm). The water storage capacity of the coal overburden ranged 26.8 – 52.3%, with an average plant available water of 24.6%. The pH values varied from 5.3-8.1, which were within the tolerable range reported. The EC was in the low range of 0.43 to 0.69 dS/m classified as slightly saline to moderately saline (Hazelton and Murphy, 2016).

Due to its subsoil and coal origins, the substrate also had extremely low organic matter and a paucity of phosphorus and nitrogen (Bennett et al., 2021). The effective cation exchange capacity (CEC_e) was high (13 -34.6 cmol/kg) with a predominance of magnesium over calcium leading to surface skinning, and an exchangeable sodium percentage (ESP) of 21% indicating sodicity. Also sulphur possibly originating from coal fragments was high in the soil ranging from 184 – 358 mg/kg, which is known to cause high mortality in plants (Dowarah et al., 2009).

3.2.2 Indigenous ecosystems (Pillar 2)

The endemic soils were poorly drained hydrosols consisting of a mixture of clay and sand, and dermosols, clay-rich soils with well-structured subsoils (Ipswich City Council, 2014). Hydrosols in the region were waterlogged for prolonged periods and have uniform clay texture with a grey colour with signs of mottling. They occur in the lower part of the landscape and may result in the accumulation of salts. Dermosols have clay to clay loam texture with a dark brown colour throughout with moderate and well-structured topsoil and subsoils.

The indigenous phytocap plant species list was extracted from the broad vegetation group survey on pre-clearing vegetation and remnant vegetation from the GIS database (Department of Resources, 2019) supplemented with the Ipswich vegetation maps published in 1991 (Elsol, 1991).

Based on these sources, the endemic vegetation was a combination of dry woodlands to open woodlands dominated by *Eucalyptus crebra* (narrow-leaved ironbark) and *Eucalyptus tereticornis* (Queensland blue gum) and moist open forests to woodlands dominated by *Corymbia citriodora* (spotted gum). The open woodlands had 30~70% canopy cover by from 2 to 9 tree species including *E. crebra, E. moluccana* and *E. tereticornis.* Nitrogen-fixing acacias and allocasuarinas were found in the woodlands. Grass species were also present in the endemic ecosystems including: *Cymbopogon refractus, Themeda triandra, Microlaena stipoides, Imperata cylindrica* and *Alloteropsis semialata* (Elsol, 1991). Most of the grass species were C_4 photosysthesis pathway warm season grasses except for *Microlaena stipoides* which is C_3. Due to high summer rainfall in Southeast Queensland, summer active grasses are critical component for inclusion in the phytocap.

3.2.3 Landfill Context (Pillar 3)

The climate of the site is humid and subtropical with dry winters, a mean annual precipitation of 834mm and an annual average pan evaporation between 1600 and 1800mm (Bureau of Meteorology, 2022). The landfill cap is a north-exposed 1:5 slope with the surrounding land being a sequence of undulating valleys and hills. Landfill gas capture was operational at the site from the commencement of the study. As the waste was construction and demolition waste, with a low proportion of organic matter, landfill gas levels were not expected to be high, However, the presence of the landfill gas posed a risk and was taken into consideration during plant selection. Surrounding areas are highly developed industrial, commercial and residential areas with small patches of remnant vegetation. There had been natural recruitment of some species onto the coal overburden stockpile at New Chum landfill including by the grass *Pennisetum alopecuroides* (Swamp Foxtail)*,* and acacia and allocasuarina tree species indicating these species were likely to be successful colonisers.

3.2.4 Multi-benefits (Pillar 4)

The project aimed to achieve a well-established canopy to enhance the phytocap performance but also for its habitat value. Food trees were selected for pollinators, birds, and koalas. The landfill was located within 500m of a Core Koala Habitat zone (Department of Resources, 2019). The inclusion of Koala food trees in the rehabilitated landfill area contributes towards improving the Koala population by providing additional habitat. Allocasuarina trees were selected to provide food for the Glossy Black Cockatoo which is classified as a vulnerable bird species in the area and solely feeds on allocasuarina seeds (Eyre et al., 2016). Flowering trees such as acacia, callistemon and melaleuca provide pollen and nectar to birds and pollinating insects such as native honey bees (Stone et al., 2003).

3.2.5 Selection criteria

The 1.5m phytocap profile of the phytocap is expected to provide sufficient rooting depth (Table 2). Although there was no information on the endemic context, the streetscape guidelines for the region outlined successful establishment of the tallest tree *E. tereticornis* (Blue Gum) in 1m of soil (Ipswich City Council, 2015). Compared with the quarry scalpings, the characteristics of the coal overburden varied widely in terms of pH and nutrients which needed to be considered. A similar gravelly texture with potential for landfill gas extrusion meant that drought and flood tolerance remained key selection criteria.

Table 2. Comparison between the original ecosystem and phytocap ecosystem context for New Chum landfill

Characteristic	Original ecosystem	Phytocap ecosystem	Significance of difference	Criteria
Rooting depth (soil depth)	1m minimum is provided in the streetscape guidelines	1.5m	Nil	Perennial grass species and trees that will develop roots over many years
Landform	Undulating valleys and hills	Graded bare exposed slope	Moderate	Grasses for erosion control, pioneer species, drought tolerant species
Landfill gas	None	Potential ingress of landfill gas in the event of a gas collection system malfunction	Moderate	Plants species tolerant of periodic flooding
Phosphorus, Nitrogen, Organic Carbon	Varied from low-moderate to moderate.	Very low nitrogen and phosphorus, extremely low organic matter	Moderate	Plant species tolerant of low nutrient conditions, that will produce leaf litter and add to the soil carbon
pH and salinity	Moderately alkaline	Variable from moderately acidic to moderately alkaline, moderately saline	Moderate	Plant species that are tolerant of wide range of pH’s, Salt tolerant species
Texture and total available water (TAW)	Likely to be high soil water storage based on clay textures	Moderate water storage capacity and low plant total available water due to high gravel	High	Drought tolerant plant species, tolerant of clay soils

In summary, the following plant selection criteria were used to guide plant selection:

- Tolerant of a wide range of soil types due to inherent variability in the coal overburden stockpile
- Tolerant of a wide range of pH's from mildly acidic 4.5 to moderately alkaline 9.0
- Tolerant of low organic carbon and low nutrient availability.
- Tolerant of drought and flood.
- Indigenous species, including late-successional and nitrogen-fixing pioneer species.
- Native grasses, which are perennial and C4.
- Food and habitat species for koalas, birds, and other local fauna.
- Fire retarding species to mitigate bush fire.

3.2.6 Characteristics of Selected Plant Community

Using the identified plant selection criteria, 21 native trees and 5 grasses were selected. This included 11 pioneer (primary succession) woody species, such as, *Acacia concurrens*, *Acacia leiocalyx, Acacia fimbriata and Allocasuarina littoralis,* and 10 climax (secondary succession) woody species including *E. crebra, E. moluccana* and *E. tereticornis*. The woody species included five Koala food tree species, ten species of flowering trees with nectar and pollen and six fire-retarding species. Four species were non-indigenous native trees selected for their tolerances and provision of food to pollinators and birds, such as *Melaleuca linariifolia, Callistemon viminalis, Callistemon salignus, and Casuarina glauca.*

Fire-retarding species such as *Angophora floribunda, Angophora leiocarpa, Eucalyptus carnea, Lophostemon confertus, Acacia concurrens, Acacia fimbriata,* and *Acacia melanoxylon* were also preferred due to the presence of coal minerals in the soil that could contribute to bushfires.

The native grasses were perennial C_4 species to withstand the dry micro-climate of the landfill. Drought-resistant indigenous grass species such as *Themeda triandra* (Kangaroo grass)*, Cymbopogon refractus* (Barbed wire grass)*, Pennisetum alopecuroides* (Swamp Foxtail) and *Imperata cylindrica* (Blady grass), all grass species with C_4 photosynthetic pathways (Witwicki et al., 2016). A non-indigenous native grass, Queensland blue grass (*Dichanthium sericeum*) was added to the list because of its wide ranges of habitat, productive growth, low nutrient requirement and clay soil tolerances (PlantNET, 2020).

4. DISCUSSION

This research has highlighted important understandings that form the pillars of good phytocap plant selection to achieve the best engineering and multi-benefit outcomes. The planting of indigenous plant species ensures the best chance of engineering success as they are best suited to the local climate, and simultaneously enable the restoration of local flora and a myriad of other benefits that come with the return of native ecosystems. This plant design process requires collaboration with the Civil Engineering team responsible for the final capping contour. Beyond plant selection, we also need to specify the specific configuration of the plants across the landfill cap including planting density and relationships between plants and drainage patterns e.g. plants may be specified differently for the upper and lower slopes. For now, it is standard practice to create long continuous slopes for landfill caps in a similar manner to clay and geosynthetic caps, though it is hoped in future there contouring and other techniques that provide a more natural landform will be applied. Natural landform modelling is a big part of mining rehabilitation where the objectives are to reinstate the original soil and plant ecosystems. In contrast, landfill rehabilitation still focuses on pollution mitigation with little consideration for ecological rehabilitation.

Two case studies were examined to demonstrate a four-pillared approach to plant selection for phytocaps. These case studies employed novel “soil” materials typical of extractive industries, bluestone quarrying in the case of Wollert landfill and coal mining in the case of New Chum landfill. They both demonstrated a successful way to select plants based on the unique constraints of these soil materials, taking into consideration the landfill context and using knowledge of the local indigenous ecosystem as a natural analogue for plant selection. These case studies also demonstrated ways in which phytocaps can use plant selection to provide additional benefits beyond engineering hydraulic containment, by incorporating plant species of high ecological value (returning endangered ecosystems and koala habitat food trees). These are only some of the multi-benefits that could be incorporated. As we get to know the individual plant species and their role in the ecosystem, and their traditional and cultural uses, further value can be incorporated into phytocap projects. Once confidence has been gained in an initial selection of plants, further benefits can be overlayed as part of an adaptive design process in alignment with the capping program and best practice progressive landfill rehabilitation. Additionally, greater ecological value can be incorporated into the foundational phytocap. The development of canopy and accumulation of leaf litter and woody debris provides an avenue for inter-row planting of later successional plants. Ideally, natural recruitment processes, whereby seeds are brought in by birds and other animal species, would also begin to occur as the phytocap ecosystem develops, further enhancing the biodiversity, ecosystem restoration, and carbon sequestration potential of phytocaps.

Phytocaps provide the highest possible ecological outcome for a landfill cap due to the incorporation of deeper uncompacted soil layers. These soil layers can sustain multiple canopy layers including tall trees, medium-sized trees and shrubs, and opportunity that is lost with other landfill cap types such as clay and geosynthetic caps where shallow soil layers cannot adequately support trees and there is a perceived concern about tree roots impacting the “barrier”. However, even with shallow soils, plants can be selected using the process outlined in this paper to enhance the ecological value of these caps. The shallow soil layers (typically 300mm) would be a constraint that would be addressed under *Pillar 3 - Landfill context* and would restrict mid and upper-canopy plant species from being selected. Considering *Pillar 4 – Multi-benefits*, indigenous grassland species could still be selected that would enhance the ecological and social value of the landfill cap scenario. Native grasslands are one of the most floristically diverse and threatened ecosystems in Australia, and restoration of these habitats on top of landfills would provide enormous benefits for pollinators, insects, reptiles and birds, especially those that build their nests in grasslands if they were able to be naturally managed. Once established, they would also present a low-maintenance alternative to exotic grasses and turf that require mowing and irrigation. Furthermore, if high-value planted areas can be established and flourish, they can become important providers of seed that can be harvested and used for rehabilitation efforts in surrounding areas. Given the amount of area that landfills occupy and their unsuitability for development, prioritization of ecological rehabilitation of landfills is warranted whatever the style of cap selected.

CONCLUSIONS

Plant selection is a foundational and intrinsic part of phytocap design that needs to be considered systematically to achieve the best engineering outcomes. This paper has proposed four pillars of understanding that will assist with making good plant selection choices that will serve to provide better phytocap outcomes. Development of plant selection criteria needs to be undertaken by an experienced ecological engineer who understands the engineering and plant performance objectives. With proper consultation and planning with site owners and community, ecological, social and cultural benefits can also be derived from landfill capping projects.

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