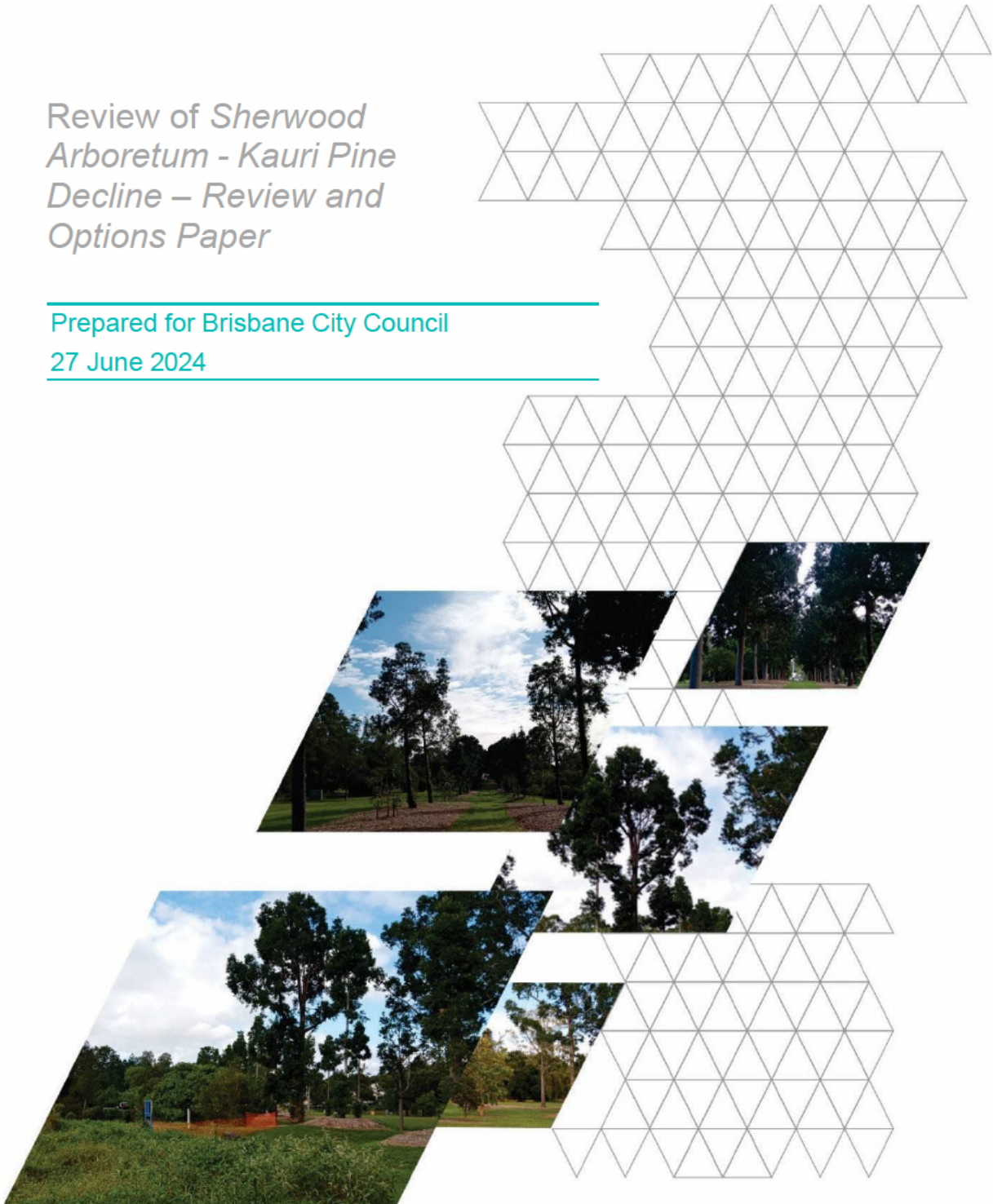


*Review of Sherwood
Arboretum - Kauri Pine
Decline – Review and
Options Paper*

Prepared for Brisbane City Council
27 June 2024



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Executive summary

- The decline of Kauri pines (*Agathis robusta*) at the Sherwood Arboretum is an ongoing concern for the last 100 years.
- Verterra Ecological Engineering reviewed the *Sherwood Arboretum - Kauri Pine Decline – Review and Options Paper* and associated technical reports and analytical results provided by Brisbane City Council.
- The assessment presented herein compared the northern end of the Kauri pine Avenue, which has healthy trees ("good site"), to the southern end of the Kauri pine Avenue which has stressed and dying trees ("poor site").
- Comparing the "good" and "poor" sites will highlight differences in soil conditions that could contribute to the differences in tree health and making the trees susceptible to pathogen attack.
- This report focused on the water table, salinity, sodicity and aluminium (Al) toxicity that may be present. Salinity refers to the presence of dissolved salts such as magnesium (Mg), sodium (Na), chloride (Cl), and sulphate (SO₄) in the soil, whereas sodicity refers to the presence of sodium (Na) ions on exchange sites, leading to an increase in the exchangeable sodium percentage (ESP) to above 5%. Al toxicity is caused by dissolution of Al containing minerals in soil, releasing Al³⁺ ions that are highly toxic to plant roots.
- Data collected by BCC indicate water saturated conditions (mottling) in soil at depths ranging from 0.2 m to 4 m below ground level. The water table fluctuated between 1.3 and 3.6 m. However, the water table was shallower at the "good" site, discounting the effect of water table as the leading cause of tree decline.
- The "poor" site had slightly saline soil conditions, ranging from 600-1000 µS/cm (in 1:5 Soil:Water extract) to 600-1400 µS/cm at the "good" site. Hence, soil salinity is not the main driver of tree decline.
- The sodicity (ESP) of the soil was similar at both sites, ranging from 11-30% at the poor site and 11-15% at the good site. The ESP affects mainly soil physical properties and is unlikely to be the cause of tree decline.
- The soil pH at the poor site was around pH 5.0-5.5 in the top 1 m, resulting in dissolution of Al minerals in soil and leading to the formation of Al-toxic conditions. At the poor site, the exchangeable Al percentage was around 20-30%, but 0% at the good site. Considering that Al is highly toxic to plant roots, it is possible that the Al saturation is the cause of poor root growth and tree decline.
- Further work is required to establish the extent of soil acidification before attempts can be undertaken to increase soil pH with limestone.
- Should soil amelioration not be feasible, the use of alternative tree species such as Hoop pine (*Araucaria cunninghamii*) could be considered as replacement for dying Kauri pines.

Review of the *Sherwood Arboretum Kauri Pine Decline – Review and Options Paper*

1. Introduction

The Sherwood Arboretum is a notable feature of the riverside suburb of Sherwood in Brisbane. Established around 100 years ago, the Arboretum features an avenue of Kauri pines (*Agathis robusta*) planted in 1924. These pines had failed to establish and grow well ever since, with the southern end of the avenue more severely affected than the northern end of the avenue. Brisbane City Council has investigated the poor growth of the Kauri pines at the Sherwood Arboretum for many years. While land elevation seems to play a role in the health of Kauri pine, other factors such as groundwater level, flood events, soil constraints, and diseases have been considered.

2. Scope

The outline for this work is as follows:

- Understand heritage considerations.
- Understand the site context and condition.
- Undertake a review of existing documentation and reports and compile them into a brief summary noting the work, its outcomes, and impacts.
- Prepare a high-level summary of actions undertaken by the Council to date to manage the Avenue.
- Provide management options that consider the future of Kauri Pines at the site including:
 - Reinstatement of the dying Kauri Pine with young Kauri Pine
 - Remediation to improve the soil and drainage and support the existing stands of Kauri Pines (includes drainage channels, soil replacement and mounding)
 - Replacing the Kauri Pines with a different species of tree.

3. Review of work conducted by Brisbane City Council

Information supplied by Brisbane City Council (BCC) to Verterra (*Sherwood Arboretum – Kauri Pine Decline-Review and Options Paper, 2024*) succinctly summarises the extensive body of research conducted by BCC into the decline of Kauri pines at the Arboretum. The report includes a map showing elevations and tree health (Figure 1), with trees at the northern side of the avenue generally being healthy, but trees at the southern side being of poor health or dead. Figure 2 and Figure 3 were taken 11 May 2024 by Verterra staff and confirm the differences in health and elevation.

Figure 1: Aerial composite image of Sherwood Arboretum, showing the elevation of the land surface superimposed on a map of tree health (Image from *Sherwood Arboretum Kauri Pine Decline – Review and Options Paper*, 2024)



Figure 2: View from the southern end of the avenue toward the northern end showing the difference in elevation. Trees in the foreground (southern side of the avenue) are younger (more recently replanted) than the trees in the background on the northern side of the avenue. (Image B. Wehr)



Figure 3: Recently replanted Kauri pine the southern end of the avenue, showing signs of severe stress (Image B. Wehr).



COMMERCIAL – IN – CONFIDENCE

3.1 Elevation and depth to groundwater

Figure 1 and Figure 2 suggest that elevation is a determinant of Kauri pine survival, but this does not explain the underlying causes. BCC commissioned research into depth to groundwater and found that groundwater is fluctuating with rainfall. Groundwater fluctuations are also likely with tides, but this is not clear from the hydrographs supplied in the *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*. While it is expected that depth to groundwater would be greater for trees on the northern end of the avenue, this was not necessarily true (*Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, 2024). Indeed, the better performing area has groundwater at 4.2 m below ground surface, whereas the poor site has groundwater at 6.2 m below the surface. In any case, depth to groundwater is not constant and soil wetness normally fluctuates with rain events. Bore hole logs give some indication of soil conditions in the subsurface. Mottling of soil is a sign of fluctuating water table, and gley colours (i.e., pale grey, bluish, or greenish colours) are indicative of water saturated soil conditions. These colours take years to decades to develop, hence these colours integrate the soil water conditions over long periods, whereas measurements of the water table only indicate current conditions but give no information about past conditions. Mottling was described at depths ranging from 0.5 m (BH06/16) to 4.0 m (BH03/16) (*Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*), indicating that the water table is between 0.5 and 4 m below the surface.

3.2 The swamp/wetland

In 1936, aerial images do not show a wetland on the eastern side of the Kauri Avenue (Figure 4). It was likely a local drainage depression (i.e., a naturally low part of the landscape that collected runoff and would be wet for varying periods of time, depending on rainfall) and was likely drained at an early stage for agricultural development (Figure 4 shows a drainage/creek feature extending from the drainage depression to the river). From 1976 onwards it was established as a wetland. Considering that tree deaths occurred long before the wetland was established, excludes the establishment of the wetland as a determinative factor in tree health. The proximity of the Kauri pines to the wetland is noticeable (Figure 5) and indicates that soils have low permeability otherwise the wetland would not retain water. The water table was recorded between 1.5 m below surface (BH06/16) and 5.5 m below the surface (BH04/16 and BH05/16), suggesting that the wetland is caused by a perched water table (i.e. a layer of soil that is poorly permeable to water causes ponding of water, with drier soil layers below it).

Figure 4: Aerial image dated 20 April 1936 of the Sherwood Arboretum showing the avenue of Kauri pines; the swamp on the eastern side of the Avenue appears to be ephemeral. (Qimagery.information.qld.gov.au).



Figure 5: Proximity of Kauri pines to the wetlands (Image B. Wehr)



3.3 Pests and Diseases

Investigations by The Tree Doctors (2022) and Asset Horticultural Consultants (2015), on behalf of Brisbane City Council revealed the presence of fungal pathogens, notably *Phytophthora*. This fungus spreads by zoospores during periods of very wet soil. During periods of high rainfall and soil saturation with water, the tree roots will be stressed, increasing the susceptibility of roots to fungal attack. This results in increased tree mortality after periods of wetness. The pathogen is attacking vascular elements in roots and stems, and this takes time to manifest in the plant. Hence, signs of *Phytophthora* only becoming visible some months after a flooding event. It was mentioned by The Tree Doctors that injection of phosphite fungicides into trunk can be trialed. This technique has been used for tree crops affected by *Phytophthora* (e.g., Avocadoes) and may be feasible for high-value plants like those in the Kauri pine Avenue. Indeed, the small number of trees requiring treatment would make the approach feasible, but it is not clear if it can be a long-term sustainable approach since the treatments will likely not cure the infection but only slow or arrest the tree decline. Horticulturists with knowledge of the technique are better placed to advise on the process's technicalities.

3.4 Soil chemical constraints

Soil and groundwater surveys were conducted between 2016 and 2023. The spatial distribution of boreholes and test pits is shown in Figure 6. Earlier testing in 2016 had incomplete soil analyses (soil water extracts), hence these data could not be interpreted. Samples taken in 2023 included comprehensive soil analyses from one site at the northern side of the Avenue (healthy stand) (BH02/23) and southern side of the Avenue (poor stand (BH01/23)). The discussion in this report focusses on the 2023 data sets.

Figure 6: Location of some of the test pits and boreholes in 2016 and 2023.



These tests revealed some soil constraints, such as salinity and sodicity in the root zone (Appendix B of *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, 2024). The southern end of the avenue (poor stand) had no salinity but had high ESP in the top 1m of the soil, mottling at 0.2 m, and water at 3.5 m (Table 1). By contrast, the Northern end of the avenue (Good stand) was saline and had moderate ESP, mottling at 1.7 m and water at 1.8 m (Table 1). Hence, salinity and ESP is not determinative. However, it should be noted that these constraints, while not causing tree death directly, may make the trees more susceptible to pathogen attack. The most severe soil constraint would be the high exchangeable aluminium observed in the poor stand. BH01/23 had low pH in the top 1m of the soil, signs of Jarosite at depth (6.2 m) and a high concentration of exchangeable aluminium (Al). The low pH (below pH 5) may indicate a disturbance of acid sulfate minerals in the soil, leading to jarosite and sulfuric acid formation. The sulfuric acid lowers the pH and this results in the dissolution of clay particles which release Al^{3+} ions that are highly toxic to roots. Al minerals become more soluble the lower the pH, and solubility increases 10-fold with every 1 unit decrease in pH. At $pH \leq 5$, risk of Al toxicity in soil increases. Plants affected by Al toxicity generally have a sparse root system and this may be the reason why an earlier investigation into the root system with ground-penetrating radar did not find evidence of a well-developed root system (Report in *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, 2024). Site BH01 had up to 20% Al saturation, and this will result in acid soil infertility in which Al ions displace Ca, Mg, K and Na from colloidal exchange sites, results in induced nutrient deficiency and precipitation of phosphate as highly insoluble Al-phosphate. The result is poor plant growth without causing clear foliar symptoms. The presence of low concentrations of acid sulfate minerals was also confirmed in 2017 when deep soil samples were taken (BH01/16 and BH02/16) (*Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, 2024). Such soils must not be drained or exposed to oxygen since this will trigger oxidation of the sulfidic minerals and acid release from these soils. It is possible that earlier attempts to drain or disturb the soil have exposed sediments to air, resulting in the low pH.

Soil acidity can be treated with the application of finely powdered limestone. However, movement of limestone in the soil is very slow, hence it needs to be mixed with the soil volume to be treated. Surface application of limestone will not be effective to ameliorate the top 1 m of soil (which is

acidic), the limestone needs to be incorporated to a depth of 1 m, which causes practical issues. Before liming is considered, a more detailed soil analysis is required to determine the areal extent of the acid soil problem and calculate the required limestone quantities.

Table 1: Summary of soil chemical conditions are the good and poor sites at the Sherwood Arboretum Kauri Pine Avenue. The comprehensive soil analysis in 2023 only sampled two sites (BH02/23 and BH01/23), hence nearby soil samples from 2016 were also included (BH03/16, BH11/16, BH05/16). Other samples from 2016 were not included since they further away from the 2023 sampling sites.

	GOOD SITES			POOR SITES	
SITE	BH03/16	BH11/16	BH02/23	BH05/16	BH01/23
Mottling	4.0 m	2.0 m	1.7 m	3.5 m	0.2 m
Groundwater	2-3.6 m 4.0 m	No GWL	1.8 m	1.3-3.1 m	3.5
pH1:5 w (to 1 m)		7.0	5.8- 7.3	5.0	5.4-5.5
pH water	7.1			7.1	
ESP (to 1 m)			11%		11-18%
Acid sulfate			ND		6.2 m
Al sat (to 1 m)			0%		20-32%

3.5 Salinity

3.5.1 Soil salinity and rainfall

Since Brisbane River is tidal at Sherwood, the salinity in the soil profile is likely caused by the river. High rainfall and flooding events will not increase soil salinity but rather dilute salt and “push” the salt in the soil deeper down the soil profile and below the root zone. Hence flooding will not cause tree death due to salinity. But during periods of low rainfall, salt will accumulate in the root zone since roots take up water but not dissolved salts. Once the soil wets up again during rainfall, the accumulated salt may be mobilised and cause severe plant stress. Extended dry periods, with high salt accumulation, are often broken by flooding events. It may be the salt accumulation during the dry periods, rather than flooding, is the cause of tree decline.

3.5.2 Salinity and sodicity

Salinity in the soil and groundwater would be expected due to the proximity to the tidal Brisbane River. Soil salinity will eventually cause soil sodicity, which is a condition that causes poor soil structure due to presence of sodium ions on the soil exchange sites; this condition is expressed in terms of exchangeable sodium percentage (ESP), with values greater than 5% indicative of poor soil structure. The presence of high concentrations of sodium (Na), magnesium (Mg) and sulfate in groundwater indicate the presence and influence of seawater on the ionic composition of the groundwater. Sodic soils will become dense over time and impair oxygen diffusion through the soil, which will result in poor root growth. Sodicity can be alleviated with calcium ions, but the presence of sodium in the groundwater will make this approach unsustainable in the long term.

However, salinity and sodicity is present at both good and poor sites, hence it is not the determining factor of tree health but may place the tree roots under stress.

3.6 Soil compaction

While it has been claimed that soil compaction may contribute to the poor survival of the trees, it has not been identified what causes the compaction. It may be an inaccurate terminology in the *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper* (2024) and the authors may have referred to dense soil instead. Dense soils are a result of particle size and packing, and are a natural consequence of soil formation processes, whereas compaction is caused by external influence (i.e., wheel tracks, pressure applied to the surface). Increased soil density leads to increased penetration resistance of roots and impairs root growth but is not likely to cause tree death per se. Dense soils have smaller pores and this will increase wicking of water into the rootzone rather than prevent water movement into the root zone. However, under periods of high-water extraction by roots, the soil will dry in the rootzone and replenishment of water from the groundwater table will be slow. During periods of low evapotranspiration (e.g., during nighttime), the wicking action will replenish the water in the root zone again. Like soil compaction, high clay content of soils makes water extraction by plant roots more difficult (i.e., plants need to expend more energy to take up water from soil) (Sustainable Minerals Institute Hydrological Characterisation report 2017, as reported in *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*).

3.7 Drainage

To minimise tree stress and improve growth and survival, recommendations made by The Tree Doctors (reproduced in the *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*) are sound, apart from the recommendations on drainage. Increasing drainage and trying to lower the water table under the trees is unlikely to improve tree health.

Firstly, the wetlands will likely be affected by the drainage because of the proximity between trees and wetlands (Figure 5). The clayey soils under the kauri pines have low hydraulic conductivity, i.e., have poor internal drainage. This requires a narrow spacing of drainage channels to lower the water table under the trees.

Secondly, the engineering required is substantial, requiring major earthworks.

Thirdly, the risk of exposing acid sulfate sediments is great. A map showing possible acid sulfate soils was included in Figure 15 of the *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, and jarosite (a mineral formed in acid sulfate soils) was determined in site BH01/23. Hence, drainage should not be considered.

4. Summary and conclusion

In summary, at the southern side of the Avenue (BH01/23), acid soil is present in the top 1m of the soil, which will inhibit root growth and establishment of the newly planted trees since they have shallow roots while young. At site BH01, Al saturation increases to 20%, with the Na percentage ranging between 10% in the upper soil layer and increasing to 30% at 2.5 m depth. These conditions will affect root growth, cause dense and infertile soils, other nearby soil sampling sites also show low pH. While low pH is not very detrimental to roots, it often leads to high Al saturation, and this causes root growth inhibition and poor plant health. Hence, Al saturation may be the main driver of poor root growth, leading to increased plant stress and increased susceptibility to pathogens.

At the northern end of the Avenue (site BH02/23) no high Al saturation was measured, although the soil is still sodic and saline. Since these trees show good growth and survival, it is suggested that sodicity and salinity are not the main cause of tree decline.

The analogue site at the Secret Forest at the Oxley Commons is also affected by salinity and sodicity and shallow water table. This site supports healthy and mature trees of the related species *Araucaria cunninghamii* (Hoop pine). Hence, it is unlikely that salinity and sodicity affects Hoop pine as much as it does affect Kauri pine. However, it is not clear if Hoop pine is as susceptible to soil acidity as Kauri pine, but it was reported that BH04/23 in the Secret Forest also had low pH and the Hoop pines at that location appear healthy.

The use of alternative tree species has been proposed and this may indeed be long-term solution. However, there are societal expectations around replacement of trees with other species better suited to conditions such as Hoop pine, and these expectations are beyond the scope of this opinion paper. It is our opinion that further investigations are needed before considering replacing Kauri pines at the southern end of the Avenue. However, the analogue site at the Secret Forest has similar soil conditions to the Kauri pine Avenue and supports healthy hoop pines. Hence, this species may be a suitable alternative tree species.

Based on this review, the following option could be considered:

- Systematically collect soil samples under the poor stand (Southern side of the Avenue) to measure Aluminium (Al) saturation of the soil in the root zone of trees. This requires 1M KCl extraction of soil and quantification of titratable acidity and exchangeable aluminium (standard laboratory method 15G1 in Rayment and Lyons). Additionally, samples should be analysed to determine their cation exchange capacity (CEC) using 1 M ammonium chloride at pH 7.0, pre-treatment for soluble salts (standard lab method R&L15B2). This will allow us to establish the areal extent of soil acidity and if it is indeed the cause of tree decline at the poor stand. Sampling under the good stand will not be essential but may establish a baseline against which future soil samples can be compared.
- If the Al toxicity is widespread, consider amelioration of the acid soil with injection of micronised limestone to increase pH.
- Treat trees with stem injections of phosphite fungicide to avoid further deterioration.

If these approaches are not successful, or considered impractical, only then is it suggested to consider:

- Replace dying Kauri pines with Hoop pines.

In the *Sherwood Arboretum Kauri Pine Decline - Review and Options Paper*, the following approaches have been proposed by various consultants. It is considered that these approaches are unlikely to be successful for the reasons indicated:

- Install drainage to lower the water table.
 - This will likely affect the wetland, expose acid sulfate sediments, and make the issue more severe.
- Excavate the soil and replace with fresh soil.
 - This will risk exposing acid sulfate minerals and does not guarantee that the new soil does not contain pathogens.
- Mounding of pines above the natural soil surface.
 - Will not affect soil below mounds, hence the rootzone is still limited and will not improve growth.

Verterra's core ecological engineering principles give preference to working with nature, i.e., treating soil constraints with minimal intervention and selecting plant species suited to the edaphic and climatic conditions encountered at the site. Rebuilding soil profiles, major drainage earthworks, or ongoing interventions are likely not feasible. Hence, attempting to treat the acid soil and/or selecting more suitable tree species (e.g., Hoop pine) is considered a better approach.

For future monitoring of soil conditions, it is recommended that soil samples be analysed for pH and EC (1:5 water), exchangeable cations including Al, sulfur, phosphorus, and micronutrients ("soil fertility suite"). Measurement of soluble ions in soil water suspensions is not informative.

BCC2003 Review of Sherwood Arboretum-Kauri Pine Decline-Review and Options Paper

Final Audit Report

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