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Phytoremediation in New Zealand and Australia

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Summary

Phytoremediation in New Zealand and Australia stemmed from pioneering work by Professor R. R. Brooks on plants that hyperaccumulate heavy metals. Although original work focused on the extraction of heavy metals from contaminated sites, successful phytoremediation now employs plants as biopumps to reduce contaminant mobility and enhance the *in situ* degredation of some pesticides. In the first years of the 21st century, phytoremediation became established in the commercial environment with the appearance of dedicated phytoremediation companies. Phytoremediation offers a low-cost means of maintaining Australasia's "clean-green" image abroad. Use of this technology will increase because of increased pressure from regulators and future scientific achievements. In New Zealand, phytoremediation is used to improve degraded lands resulting from agricultural and silvicultural production, whereas in Australia its greatest potential is the remediation of mining-affected lands. Phytoremediation is most effective on lands where the clean-up cost of alternative technologies is greater than the land value. This reduces the importance of the longer time needed for phytoremediation. This chapter discusses, using case studies, the development of phytoremediation in Australia applied to a range of contaminated lands under various climatic conditions.

Key Words: Biopumps; biosolids; hydraulic control; mining; sheep dip; timber production.

1. Introduction

Phytoremediation is the use of plants to improve degraded environments *(1)*. Pioneering work by the late Professor Robert Brooks at Massey University, Palmerston North, New Zealand, popularized the study of plants that accumulate inordinate amounts of heavy metals. Phytoremediation research in Australasia has stemmed from the investigation of these so-called "hyperaccumulator" plants. Professor Brooks was responsible for setting up a New Zealand phytoremediation program in the mid-1990s. Since these early studies

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on the plant extraction of heavy metals, phytoremediation has been developed for the treatment of a whole suite of contaminated sites. In Australasia, this technology has been successfully transferred to the commercial environment.

In New Zealand, HortResearch (www.hortresearch.co.nz) and the Soil and Earth Sciences Group of the Institute of Natural Resources at Massey University (soils-earth.massey.ac.nz) have active phytoremediation programs. Tiaki Resources Ltd. (projects@tiaki.co.nz) provides commercial phytoremediation. In Australia, the Botany Department at the University of Melbourne (www.botany.unimelb.edu.au), the Centre for Mined Land Rehabilitation (www.cmlr.uq.edu.au), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (www.csiro.au), and several other universities have phytoremediation programs. Phytolink Australia Pty (www.phytolink.com.au) is a dedicated phytoremediation company. As elsewhere, the commercial use of phytoremediation in Australasia is driven by pressure from regulators.

Phytoremediation in Australasia has focused on the use of plants as biopumps *(1)*. Here, plants use the sun's energy to dewater contaminated sites and control leaching, as well as enhance the organic matter and microbial activity in the rhizosphere. These root-zone processes thereby augment contaminant degradation and reduce the mobility of heavy metals. We therefore use the term phytoremediation to cover a wide-range of plant-based environmental applications, ranging from mine-site revegetation through to riparian management and phytoextraction. In Australasia, the most important role of phytoremediation is to reduce contaminant mobility and to degrade organic pollutants, rather than the phytoextraction of heavy metals. In this chapter, we discuss the most important environmental issues in New Zealand and Australia and demonstrate, using case studies, how phytoremediation can be used to address land degradation.

2. The Relevance of Phytoremediation in the Australasian Context

The New Zealand economy is underpinned by an internationally perceived "clean-green" image. Contaminant-free agricultural exports and tourism contribute 16 and 9%, respectively to New Zealand's gross domestic product *(2)*. Environmental degradation thus poses a significant risk to economic growth, and the government has consequently implemented strict environmental controls via the Resource Management Act, 1992. Australia's economy is similar to New Zealand's, although mining is now Australia's single biggest export earner. Unlike New Zealand, however, Australia has no overarching environmental legislation. Rather, disparate bills have been passed that address specific environmental issues. These may vary between states.

Most contaminated sites in New Zealand are associated with agricultural and silvicultural production: there are an estimated 50,000 disused sheep-dipping sites that may contain elevated levels of persistent pesticides such as dieldrin and sodium arsenate. Similarly, there are numerous sites contaminated with timber treatment compounds such as copper-chromium-arsenate, pentachlorophenol, and boron. In addition to agricultural- and silvicultural-contaminated sites, Australia has over 2 million ha of open-cast mining and many contaminated sites associated with smelting and processing *(3)*. Both countries face environmental issues associated with urban development, especially the disposal and treatment of sewage sludge and burgeoning landfills.

New Zealand has a temperate oceanic climate with high rainfall. Meteorological conditions seldom prohibit plant growth making phytoremediation a viable option for many contaminated sites. However, the high rainfall:evapotranspiration ratio can limit the effectiveness of phytoremediation to provide hydraulic control on contaminated sites. Australia, on the other hand, often suffers from drought and associated soil salinity, both of which can negatively affect plant growth, but render phytoremediation effective for the mitigation of leaching.

Phytoremediation is best suited to the long-term cleanup of low-value land where other remediation options are prohibitively expensive *(4)*. This technology is therefore well suited for use on contaminated sites in the extensive production systems of Australasia. The low population densities of both New Zealand (14.8 people/km^2) and Australia (2.4 people/km^2) keep land values relatively low and reduce the pressure for the rapid remediation of contaminated sites.

3. Phytoremediation Case Studies

3.1. Phytoremediation of a Timber-Industry Waste Site

New Zealand has 1.6 million ha of *Pinus radiata* plantations for pulp and timber production. Most timber products are treated with biocides to prevent decay. In the past, pentachlorophenol and boron have been used to treat timber. Currently, copper-chromium-arsenic is the treatment of choice. Treatment sites and wood-waste disposal sites have become contaminated with the aforementioned biocides and pose a risk to ground and surface waters through contaminant leaching. Here, we outline the use of phytoremediation to mitigate the environmental risk associated with a timber-industry waste site.

The Kopu timber-waste pile is located at the base of the Coromandel peninsula, North Island, New Zealand (37.2°S, 175.6°E). The pile has a surface area of 3.6 ha and an average depth of 15 m. Over a 30-yr period from 1966, sawdust and yard scrapings from timber milling in the region were dumped on the pile. Land around the pile has been engineered so that no surface or ground water enters the pile, and all leachate resulting from rainfall is collected in a small holding pond at the foot of the pile. In the past, vegetation has failed to

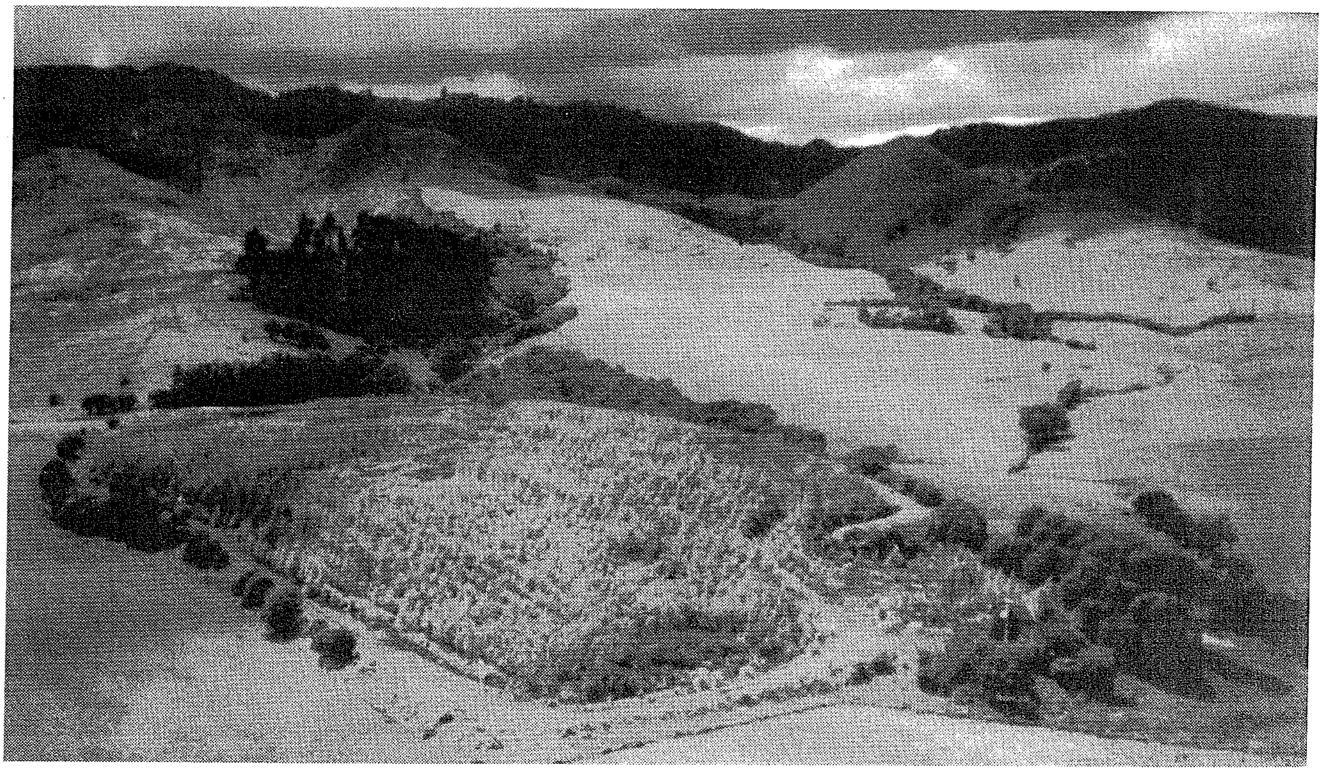

Fig. 1. Aerial photograph of the revegetated Kopu timber waste pile, October 2003.

establish and evaporation from the surface of the pile has been negligible, even in the summer months. This was demonstrated by the presence of saturated material at depths as shallow as 20 mm.

Leachate resulting from the annual rainfall of 1135 mm, as measured at a nearby meteorological station at Thames, regularly caused the holding pond to overflow and enter a local stream. This overflow elevated boron concentrations in the stream to levels that were in excess of 1.4 mg/L, the New Zealand drinking water standard, especially in the summer months when stream flow was low. In response to these breaches, the local environmental authority placed an order on the forestry company responsible for the site that the problem be remedied.

In July 2000, a 1-ha trial was established on the Kopu site using 10 poplar and willow clones, as well as two species of *Eucalyptus*. Two *Populus deltoides* hybrid clones were then chosen as the best candidates for phytoremediation based on survival, biomass production, and B uptake. The following year, the remainder of the pile was planted in these two clones at a density of 7000 trees/ha. Fertilizers were periodically added to the trees and a pump was installed near the holding pond at the foot of the pile for irrigation during the summer months. **Figure 1** shows tree growth on the Kopu pile after 3 yr. **Figure 1** demonstrates clearly how phytoremediation helps the contaminated site become part of the landscape by covering the bare pile with an actively growing green mantle.

Robinson et al. *(1)* calculated the monthly water balance of the pile using a computer model similar to that described in Green et al. *(5)*. The model used

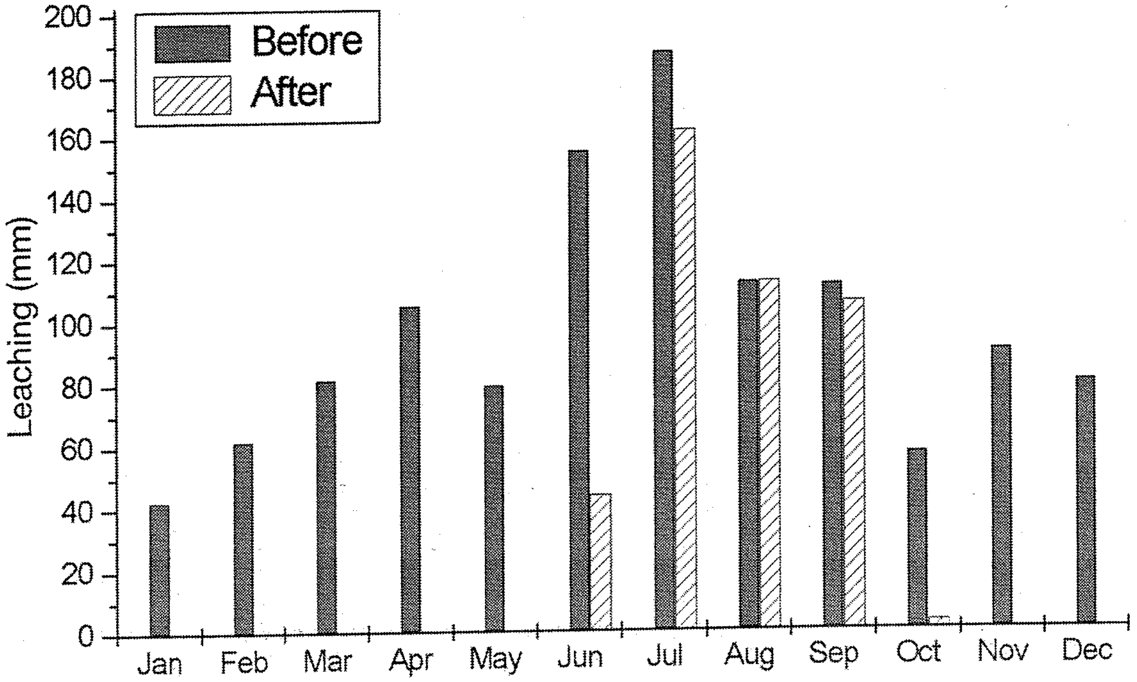

Fig. 2. Model calculations of average monthly leaching from the Kopu sawdust pile before and after phytoremediation.

daily weather data taken from a meteorological station at nearby Thames and other parameters obtained experimentally. Model calculations of leaching are shown in **Fig. 2**. As expected for such a high rainfall site, the bare pile leaches a considerable amount of drainage water through all months of the year. The impact of trees is to substantially reduce the drainage of water during the summer months when the trees are fully leafed and transpiring at their maximum. The summer months are of greatest concern for contamination of the local waterways because stream flows are lower and there is less dilution of the contaminants. The leaching that occurs during the winter months can be irrigated onto the trees in times of drought during the summer, or alternatively, released into a nearby stream at times of high flow when the risk of exceeding the New Zealand drinking water standard is minimal. Poplar leaves sampled from the sawdust pile contained Cu and Cr concentrations that were on average 6.6 and 4.9 mg/kg dry mass, respectively. Arsenic concentrations were below detection limits (1 mg/kg).

At the end of the growing season, the average leaf B concentration was nearly 700 mg/kg on a dry matter basis, over 28 times higher than the B concentration in the sawdust (40 mg/kg dry matter). Bañuelos et al. *(6)* have previously reported this B accumulation trait in poplars. The results indicate that in addition to controlling leaching at the site, poplars may also be able to reduce the B loading by phytoextraction. Unless the trees are harvested, most of the B is returned to the sawdust via leaf fall. Harvested material could, however, be used as an organic B supplement to trees in orchards that are B deficient in other parts of the country. The concentrations of other heavy metals in the leaves are unlikely to cause further environmental problems.

The cost of phytoremediation at Kopu is estimated to be New Zealand \$200,000 including a site-maintenance plan more than 5 yr. Half of this total cost was taken up as site assessment, involving scientist time to conduct the plant trial and chemical analysis. The alternative cost of capping the site was estimated by the local environmental authority to be over New Zealand \$1.2 million. Capping would also require ongoing maintenance to ensure its integrity.

3.2. Phytoremediation of a Disused Sheep-Dipping Site

Until 1966, there was a legal requirement that all sheep sold in New Zealand were free of pest infestations such as lice, blowflies, ticks, and mites *(7)*. The most effective means of dealing with this problem was dipping the sheep in a pesticide solution. The active ingredients of these solutions were arsenic, organochlorines, and organophosphates, the former two being persistent in the environment. Disposal of the pesticides after use resulted in areas adjacent to the sheep dip becoming contaminated. These areas pose a risk to human and animal health through groundwater contamination *(8)*, as well as direct ingestion of soil. Dipping sites were often located near wells or streams, to prepare the pesticide solution. The exact numbers and locations of historical dip sites in New Zealand are unknown, but there are probably many tens of thousands on both private and public land.

A disused sheep-dipping site in an asparagus field was discovered near the city of Hamilton, North Island, following the measurement of elevated dieldrin concentrations in a nearby well. Soil analyses revealed dieldrin concentrations from 10 to 70 mg/kg over 100 m^2. The Dutch intervention value for dieldrin in soil is 4 mg/kg. In late September 2001, the site was planted using HortResearch willow clones. In October 2003, the average height of the trees was over 3 m (**Fig. 3**). Soil collected from the site before planting was homogenized and placed in 12- to 15-L pots in HortResearch's plant-growth facilities. Willow clones were planted in eight of the pots. All pots were watered and fertilized equally. After 5 mo, soils from the pots were analyzed for dieldrin, as well as biological (dehydrogenase activity) activity. Substrate dehydrogenase activity is estimated from the rate of conversion of triphenyltetrazolium chloride to triphenylformazan (TPF). This is a measure of biological activity.

Figure 4 shows the biological activity in the root zones of grass and willows. The data shown in **Fig. 4** may approximate the surface of the site at Ngahinapouri before planting (i.e., when grass was growing on the site), and now after the planting of willows. Clearly, willows greatly enhance biological activity in the soil. Previous studies *(9,10)* have shown that biological activity

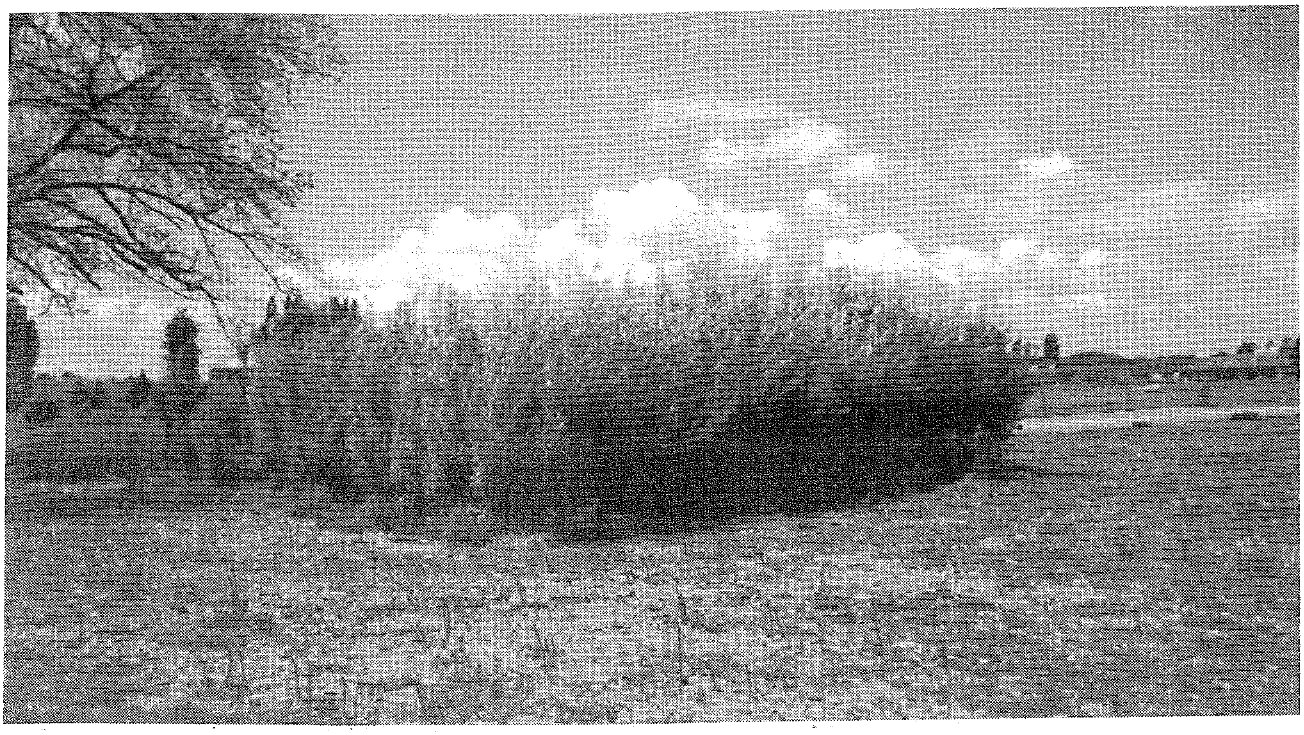

Fig. 3. Phytoremediation at the Ngahinapouri site.

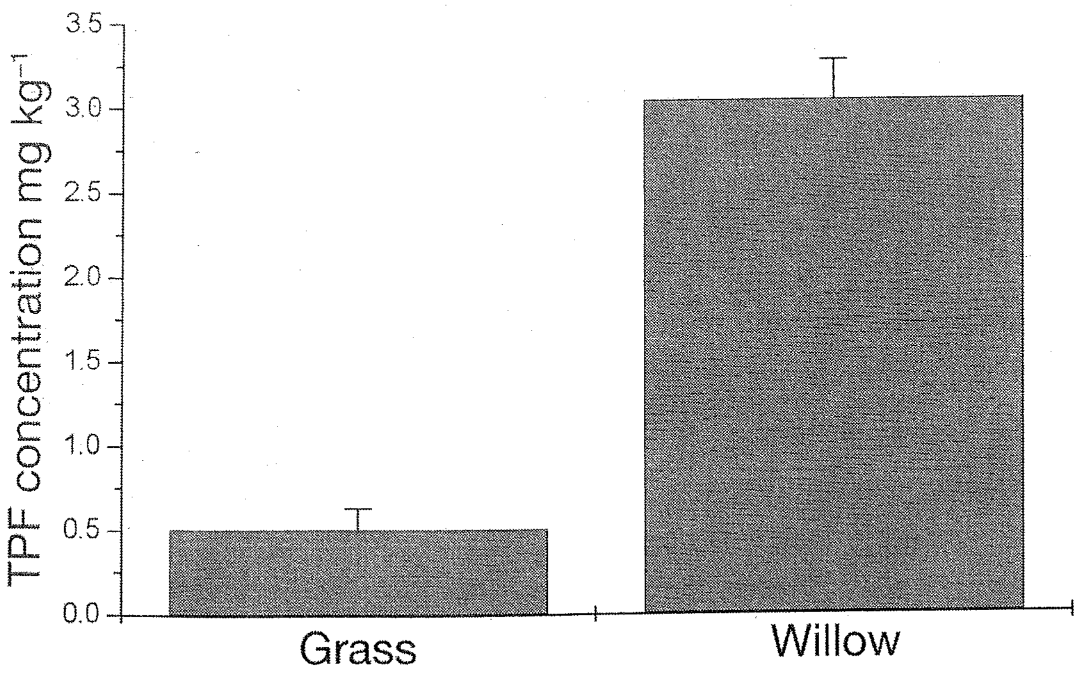

Fig. 4. Soil triphenylformazan (TPF) concentration under grass and willow vegetation.

leads to a greater rate of the decomposition of some contaminants. This increase in biological activity is caused by root exudates, such as sugars and organic acids, on which bacteria and fungi can feed. Willows have a much greater biomass production than grasses, and consequently have a greater quantity of root exudates. Willow roots also penetrate further than grass roots (up to 1 m) and improve soil aeration because of their high water use. The willows caused a significant decrease ($p < 0.05$) in the soil dieldrin concentration over the treatment

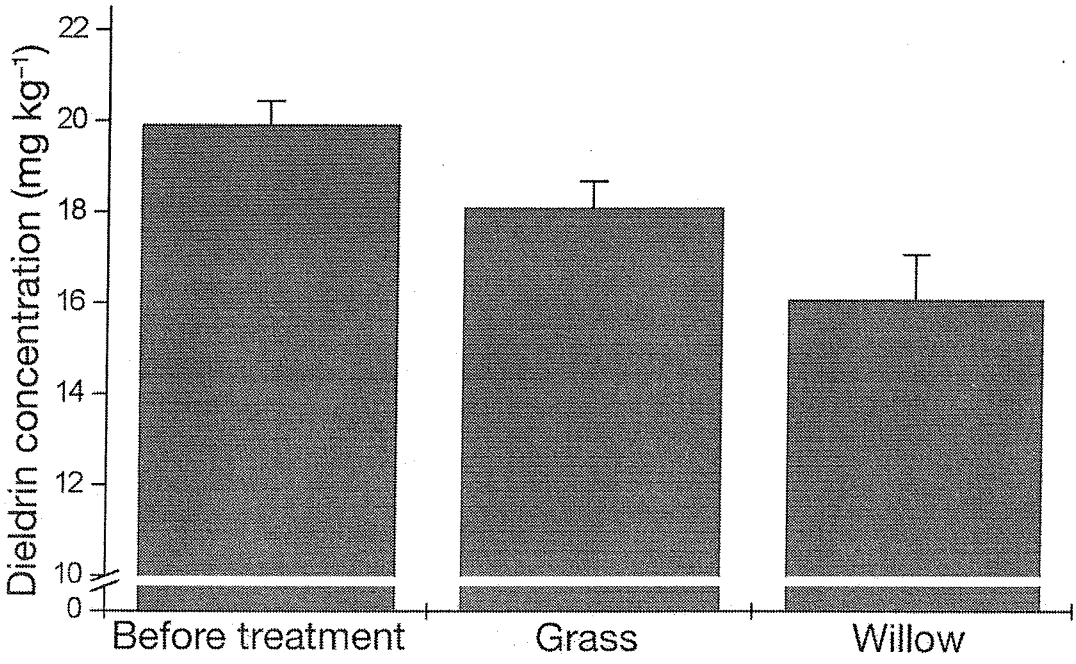

Fig. 5. Soil dieldrin concentration as affected by vegetation cover.

period (**Fig. 5**). This 20% reduction was achieved in only 5 mo of growth. The dieldrin degradation effected by the willows was greater than that by the grass species that may first colonize many disused sheep-dipping sites.

3.3. Phytoremediation of the Tui Mine Site

The Tui mine tailings near Te Aroha, is considered New Zealand's worst environmental disaster caused by mining activities *(11)*. The site consists of a 1.5-ha tailings dam containing 100,000 m^2 of toxic mining waste, principally sulfide minerals with high concentrations of lead (0.5%), cadmium (26 mg/kg), and mercury (8 mg/kg). Continual oxidation of the sulfide produces sulfuric and sulfurous acids that result in a pH <3.0 for the surface material. The low pH mobilizes heavy metals that leach out of the tailings dam into a nearby stream. Analyses of the stream water and sediments reveal that both are above the allowable limits for lead and cadmium set by the World Health Organization *(12)*.

Although the site has been abandoned for more than 30 yr, no vegetation has established itself on the tailings as a result of a low pH and the high concentration of heavy metals. During the summer months, dust containing high concentrations of heavy metals is blown around, contaminating nearby areas. Adjacent to the tailings dam is a car park used by hikers. Children have been observed playing on the tailings, their parents unaware of the risk of heavy metal poisoning. The goal of phytoremediation at Tui is to mitigate heavy metal leaching, prevent erosion and dust movement, and to return the area to native vegetation. Plant accumulation of heavy metals is not desirable because this may provide an exposure pathway for metals to enter the food chain via herbivore browsing. The pH and plant nutrient status of the tailings had to be modified so that

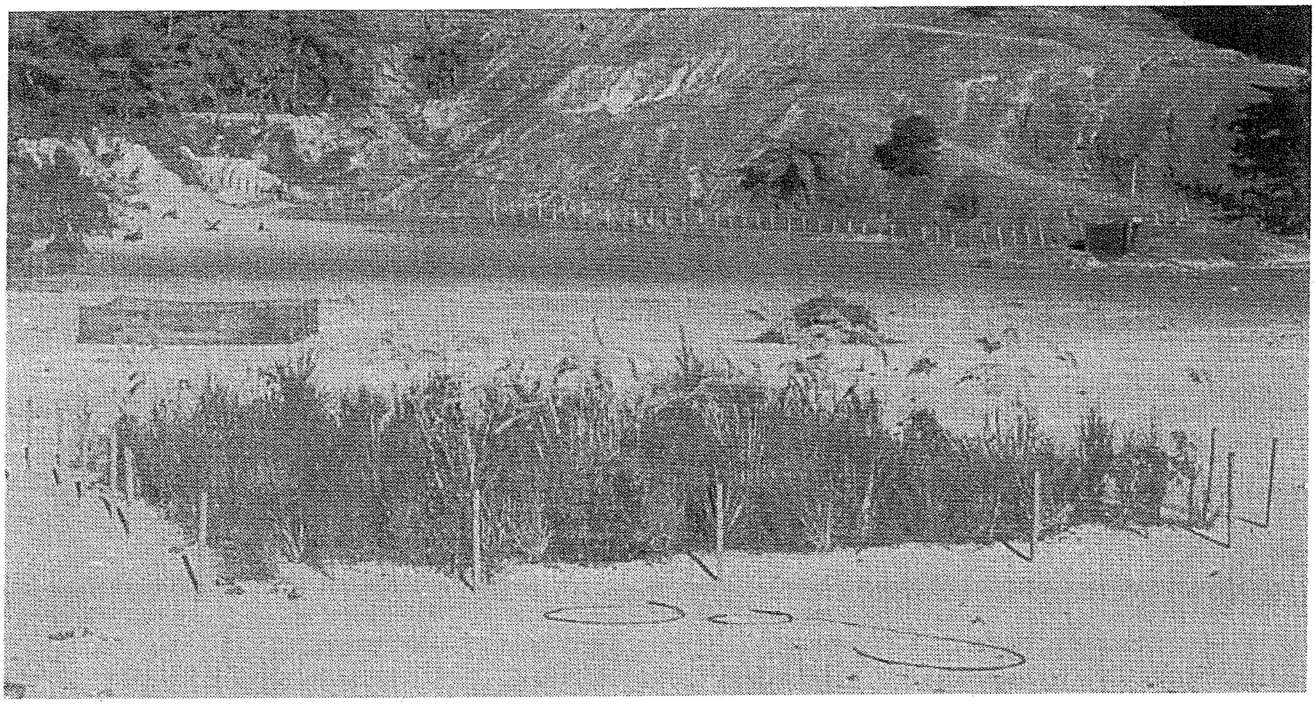

Fig. 6. Experimental plot on the Tui mine tailings, September 2002.

Table 1
Metal Concentrations in Tui Tailings and Supported Plant Species

	Cd	Cu	Fe	Hg	Pb	Zn
Tailings	0.7	27 (3)	1581 (180)	8 (1)	5410 (923)	83 (7)
Phormium tennax	<0.15	12 (1)	179 (6)	<0.1	102 (52)	67 (10)
Hebe stricta	<0.15	11 (1)	221 (63)	<0.1	314 (71)	32 (7)
Leptospermum scoparium	<0.15	14 (1)	285 (18)	<0.1	454 (87)	43 (13)
Populus sp.	<0.15	8 (1)	122 (15)	<0.1	148 (23)	74 (26)
Cortaderia toetoe	<0.15	14 (2)	525 (368)	<0.1	226 (94)	30 (2)

vegetation could be established. Experiments conducted at Massey University determined the optimal rate of liming and organic matter addition to permit plant growth on the Tui tailings. A 100-m^2 plot was established on the Tui tailings in April 2001. Several indigenous species were planted as well as lupin to fix nitrogen.

The plants established rapidly (**Fig. 6**), with other plants and animals colonizing the plot area over time. Chemical analyses of leaf material from the plants that were grown on the plot at the Tui mines indicated low levels of bioaccumulation (**Table 1**). Elevated lead levels may be the result of surface contamination of the leaves with dust from adjacent nonvegetated areas. Greenhouse experiments with the Tui tailings, where there is no risk of dust contamination, demonstrated that leaf lead levels never exceeded 50 mg/kg. Samples of surface material on and off the vegetated plot were analyzed for TPF, an indicator of

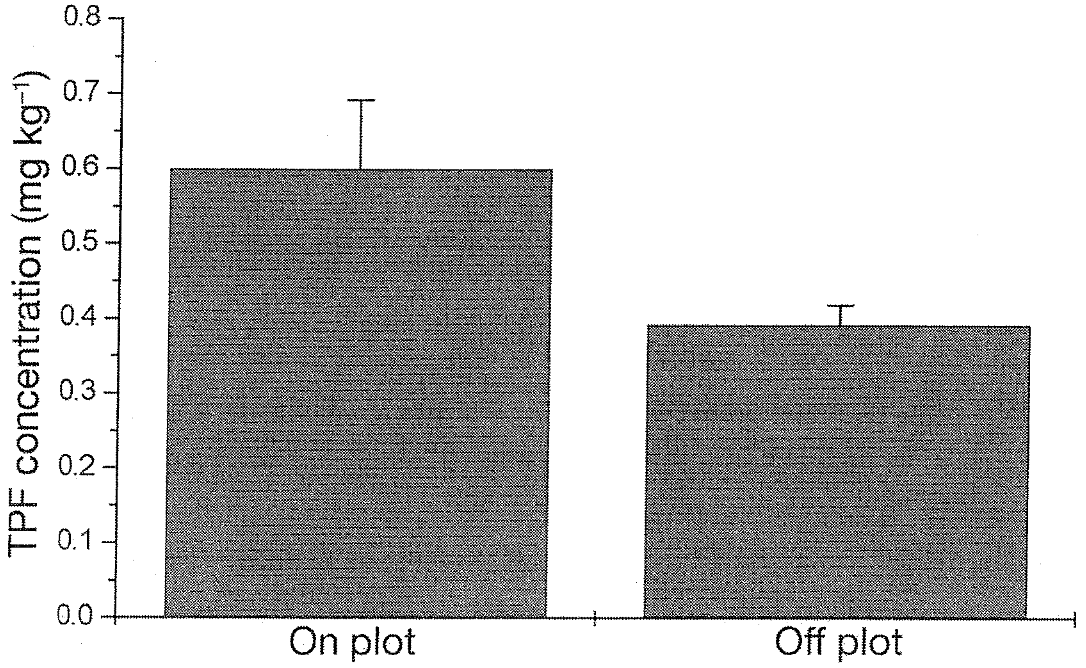

Fig. 7. Biological activity in the surface of the Tui mine tailings, as measured by triphenyl farmazan (TPF) concentration, on and off the phytoremediation plot.

microbial activity (**Fig. 7**). Microbial activity was significantly higher under the vegetated areas. The measurable TPF concentrations off the plot may be a result of the presence of *Thiobacillus* bacteria that are responsible for sulfide oxidation.

Clearly, it is possible to establish vegetation on the Tui mine tailings. Full-scale phytoremediation would eliminate lead-laden dust, reduce the visual impact of the mine, and reduce leaching by re-evaporating some of the rainfall through transpiration. Phytoremediation of the Tui tailings can be considered a revegetation operation. Quantification of the environmental benefit afforded by phytoremediation can be made through analysis of the biological activity of the substrate.

3.4. Phytostabilization of Biosolids, Western Treatment Plant, Victoria, Australia

The storage of biosolids, the solid fraction of sewerage waste, is a contentious subject for any developed area. Fresh biosolid or oxidation pond sludge waste has a water content of approx 70% by weight. When disposed of on land, natural drying will generate a crust of approx 15 cm; less than 15 cm minimal drying will occur. Mechanical drying of the fresh waste is possible, but is costly and is certainly not applicable to previously deposited volumes of waste. Every major populated area in New Zealand and Australia has large volumes of unstable, semiliquid waste stored on potentially valuable land.

Melbourne Water is the largest water utility in Melbourne, with a sewerage system of 380 km and two water treatment plants, the Western and Eastern Treatment Plants. Melbourne produces on average 900 million liters of sewage a day, 54% of which is treated by The Western Treatment Plant (WTP) situated on the western shore of Port Philip Bay near the city of Geelong ***(13)***. The WTP covers 11,000 ha of valuable land, and discharges approx 600 L of treated water daily into Port Philip Bay. Three treatment methods are used for incoming sewage. An extensive lagoon system is used for peak daily and year-round wet weather flow. Land filtration is used during periods of high evaporation between October and April. Grass filtration is used during periods of low evaporation between April and October. Extensive land contamination with organic and inorganic contaminants has occurred at the WTP as a result of sewage disposal practices over the past 100 yr. Commercial and governmental groups in Melbourne have developed a "Vision for Werribee," a long-term plan that aims to turn solid and liquid sewerage waste into valuable revenue streams, and that will release decontaminated land to capital development. The Vision for Werribee brings together several environmental technologies to achieve the desired objective. One of these technologies is phytoremediation.

3.4.1. Establishing the Field Trial

The concept of plants as biopumps has been field tested at Werribee to assess the dewatering potential that phytoremediation may have on stockpiled biosolids. Biosolids have potential use as a soil amendment or energy source (as a renewable "brown coal"), however, high water content limits this potential. For the period between 1973 and 1979 (the only period when climatic data was collected), average annual rainfall at Werribee was 641 mm, whereas average annual evaporation for this period was 1386 mm (**Fig. 8**). For no month did rainfall exceed evaporation and this indicates that if water can be removed using plants then no rainfall-induced recharge should occur. An experimentally derived biosolid water-retention curve shows that, in theory, the water content could be lowered to approx 20% (10 bars) by plant transpiration. Interpretation of this physical and climatic data suggests that plants should be able to dewater the Werribee biosolids. Chemical analysis of the biosolids indicated that elevated concentrations of Cu could possibly affect plant growth, however, no signs of phytotoxicity were observed during experimental work (**Table 2**).

A 1-yr demonstration trial was initiated in May 2002 on a biosolids storage tank. The relative growth performance of 10 plant species was tested during the trial. Core samples (0–20 cm) collected from across the plot area at the time of trial setup and then again 1 yr later allowed for estimation of the level of de-watering.

3.4.2. Dewatering Potential of Eucalyptus *sp. and Vetiver Grass*

Figure 9 summarizes the end of trial performance of two of the trialed species, *Eucalyptus saligna* and vetiver grass, in dewatering the biosolids.

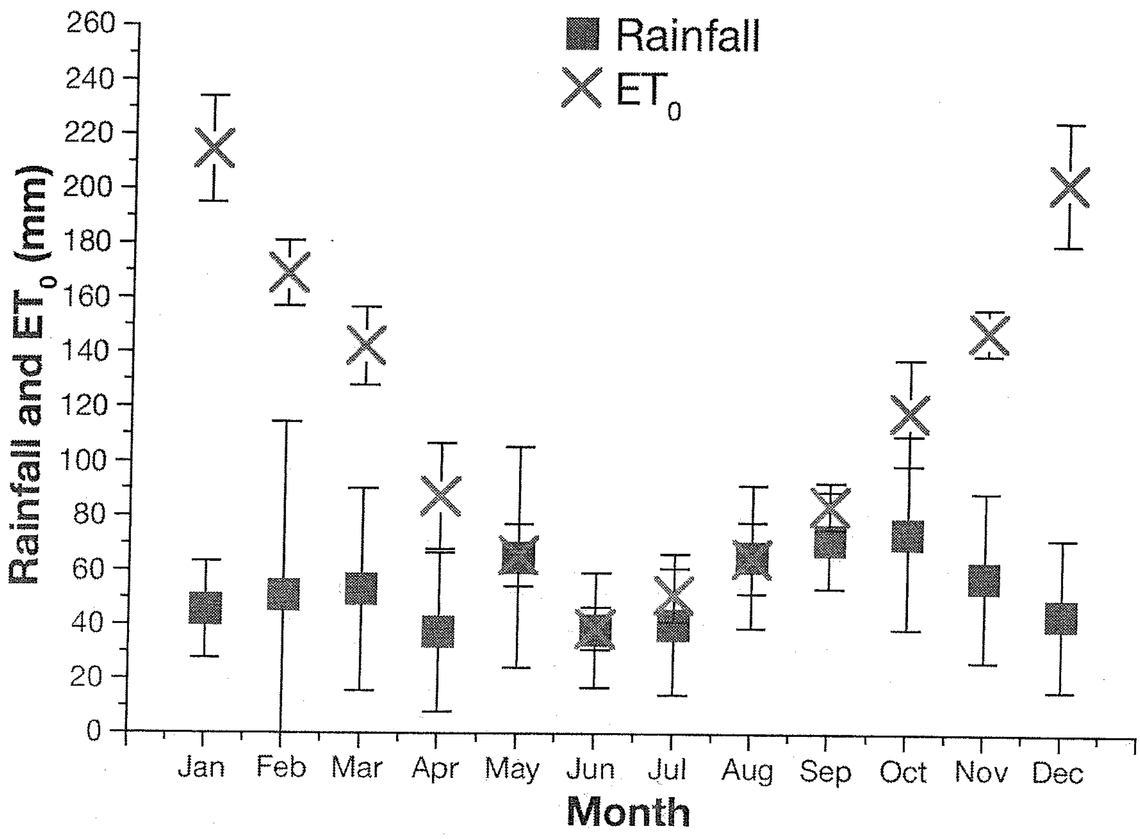

Fig. 8. Average monthly values of rainfall and potential evapotranspiration (ETo) at Werribee.

Table 2
Select Geochemical Parameters of the Werribee Biosolids

Metal	Extractable metal concentration (mg/L)	Total metal concentration (mg/kg)
As	0.04	9
Ca	464	8620
Cd	0.0008	9
Cr	0.002	646
Cu	0.16	1001
Fe	3.8	10943
K	84.6	1601
Na	272	1837
P	1.6	6724
Zn	7	1174

[a]Extractable concentrations determined by ICP analysis of 12,000*g* centrifuge soil solution extracts. Total concentrations determined by ICP analysis of aqua regia digest solutions.

Clearly, both species affected a significant decrease in the water content of the biosolids to 30–40% in the 5- to 10-cm sampled horizon. This is relative to a 55% water content for control sampling in May 2003 and a pretrial water content of 65% at May 2002. Dewatering was so effective that it was not possible

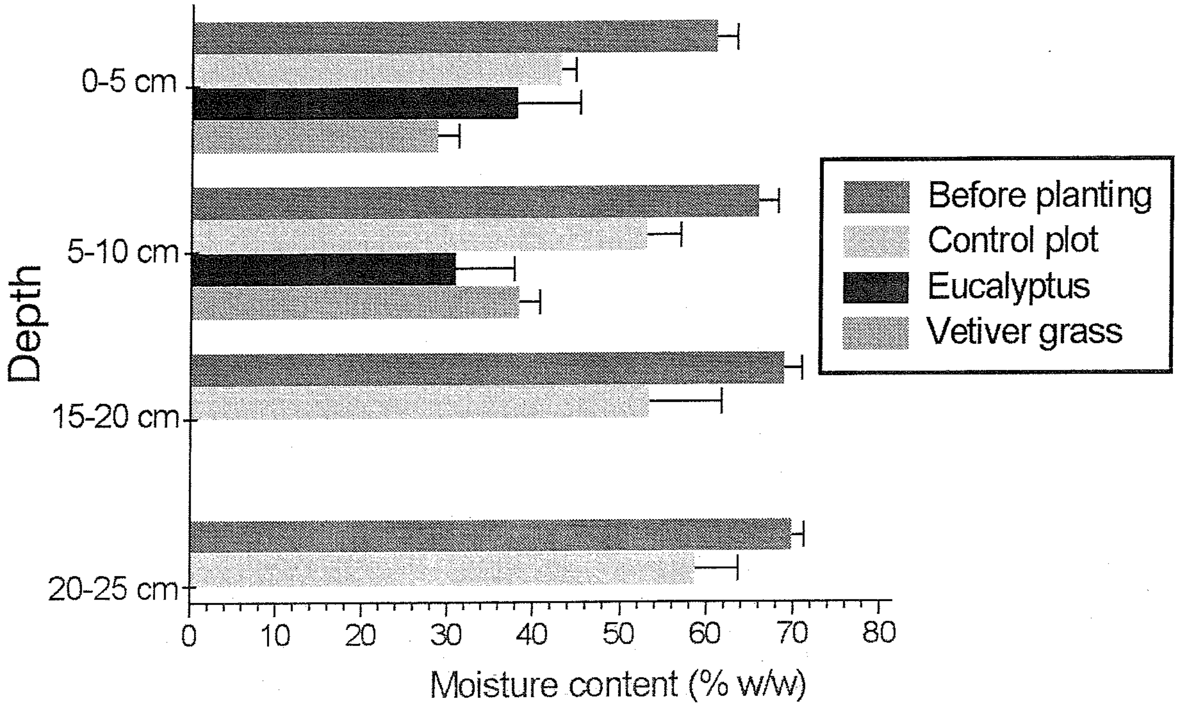

Fig. 9. Water contents of the sludge at Werribee under select plantings.

to push the soil corer into biosolids below a 10-cm depth for all cores sampled in proximity to vegetation.

There was a decrease in water content for control cores, sampled away from areas of vegetation. However, we expect that this water will have recharged because of the rainfall of late winter 2003; the timeline of the trial (May 2002 to May 2003) was particularly dry. Dewatering results indicate that in a single growing season, either *Eucalyptus* or vetiver grass could be used to dewater the top 15 cm of sludge stabilizing the material and potentially allowing reuse of the substrate. A 15-cm dewatering scenario is conservative and based on observed results; the plants had not been able to reach their maximum biomass over the trial because of cattle and sheep grazing. The true dewatering depth may be much greater, as modeled using HortResearch's Phytoextraction Decision Support System.

4. Conclusion

Ongoing research and commercial activities in New Zealand and Australia continue to apply phytoremediation to contaminated and degraded land. Four examples have been presented in this chapter; wood waste, acid mine tailings, a disused sheep-dip site, and sewage sludge. In addition, phytoremediation to promote revegetation has been successfully tested on a cyanide heap-leach pad in Victoria, Australia, and at a serpentinite waste-rock pile in the Waikato, New Zealand. Quantification of the benefits of phytoremediation is possible through analysis of variables such as biological activity and species diversity, as well as by examining the reduction in contaminant values promoted by plants. Phytoremediation is likely to remain a fertile subject for research and commercial development in New Zealand. The technology is well suited to the clean up of low-level contamination and land degradation associated with the commodity-driven economies of Australasia.

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