Restoring the soils of Nauru

Plants as tools for Ecological Recovery

by

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Abstract

The restoration of Nauru's mined areas is fundamental to the future wellbeing of the people and ecosystems of Nauru. Extensive open cast phosphate mining on Nauru over the last 100 years has led to soil losses and landscape degradation to the extent that over 70% of this South-Western Pacific island state is now uninhabitable and almost all productive land has been lost. Significant landscape degradation has occurred and as a consequence the soils that remain are insufficient in volume and quality to achieve the Government's restoration goals which support the long-term development of Nauru and the well-being of its people. The aim of this research is to evaluate aspects of cover-crop use as a means for soil restoration in Nauru. This research evaluates biomass production, phytoremediation potential, and germination success for a range of species in Nauruan soils. Field trials exploring biomass production and cadmium phytoextraction were performed, as was an experiment assessing the effects of cadmium on germination success. It was found that, in the circumstances assessed, biomass productivity was significantly determined by species, mulch use, soil type, and to a small degree – cadmium. Phytoextraction was significantly determined by tissue type. Germination success was not determined by soil cadmium, but soil type was a significant factor.

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Terms and Abbreviations

Black soil - Soil removed from the surface of mining areas which has been stockpiled for land rehabilitation.

Bottomside - The coastal fringe of land surrounding Topside. This is where most of the islands occupants reside.

Buada – The large interior lagoon or the district it is within

Cover crop – A crop which is planted to cover and protect the soil beneath

Ecological restoration – The process of modifying landscapes from a degraded ecological state into a more desired state; usually a historic state.

Ecosystems functions - Exchanges of energy and nutrients within ecosystems, involving decomposition and production of biomass.

Ecosystem services - Services to humanity provided by ecosystems functions.

Green manure – A crop which is grown to provide biomass, smother weeds, improve soil tilth, and possibly for nitrogen fixation.

Green mulch – A crop which is grown to suppress weeds, reduce soil erosion, enhance soil fertility, improve water infiltration and maintain soil moisture.

Hyperaccumulator – A plant species that accumulates high concentrations of soil toxins in its tissues. For cadmium the critical value above which a species is regarded as a hyperaccumulator is 100ppm.

ICP-MS - Inductively coupled mass spectrometry. ICP-MS provides accurate assessment of rare elements.

Karrenfield - An undulating landscape of vertical pillars of fossilised coral.

Land rehabilitation - The process of modifying landscapes so that they are suitable for human habitation.

Mollisol – A soil type containing high concentrations of organic matter. Considered to be the most productive soil for agriculture

NRC - Nauru Rehabilitation Corporation.

NPC - Nauru Phosphate Corporation.

Phytoaccumulation – The accumulation of contaminants in plant tissues.

Phytoextraction - The uptake by plants of contaminants from soil.

Phytoremediation – The use of plants to reduce the toxic potential of contaminants.

Species - The term is used in two ways within this document. The first refers to the biological definition of the word, to describe a genetically distinct grouping of organisms. The other is used in the chemical sense, to describe the diversity of chemical forms in which elements (in this case cadmium) can exist.

SOM – Soil Organic Matter - The total biologically derived organic material found in or on the soil, excluding the aboveground portion of live plants.

Topsoil - The raised plateau in central Nauru which is occupied by the phosphate mine

USP – University of the South Pacific.

Chapter One - Introduction and background to the rehabilitation of the soils of Nauru

INTRODUCTION

Open-cast mining of phosphate rock on Nauru has directly affected over 70 per cent of the land surface area of the island, in particular the raised central plateau known as Topside (Ferguson 1999). Topside has incurred the greatest impacts due to open-cast mining of the majority of the area. Topside comprises a raised plateau which is physically distinct from the coastal fringe area known as 'Bottomside' where the majority of the population resides (Manner, Thaman et al. 1984; Gowdy and McDaniel 1999).

Before mining began, Topside was thickly covered with tropical rainforest dominated in parts by the Pacific mahogany (Ijo or Tomano) tree (*Callophyllum inophyllum*), or pandanus (*Pandanus tectorius*) (Manner 1984; Thaman 1992; Thaman, Fosberg et al. 1994; Thaman, Hassall et al. 2008). Throughout most of the early 20th century Topside remained relatively undeveloped, despite a clear delineation of land ownership through inheritance, conquest, and customary use (Barker 2009). The land was managed by an agroforestry system, whereby productive tree species were planted, tended and cultivated within an environment that was otherwise largely unmodified (Weeramantry 1992).

Nauru is a 21km^2 raised limestone island 41km south of the equator at longitude 166° 56′ E in the Central Pacific (Fig. 1.1). It is surrounded by a fringing coral reef that sharply drops away 4,300m to the Pacific floor. "Bottomside" is the local name for the thin coastal plain surrounding the interior of the island, known as "Topside". Topside is a 1,620ha raised plateau that ranges from 20-60m in elevation, and is largely divided from Bottomside by a steep escarpment. A brackish lagoon, called "Buada" is in a large interior depression, and is hydraulically connected with the Pacific Ocean (Hunter, Harris *et al.* 1994; Kingston, P.A. 2004) (See Appendices I & II).

Figure 1.1 – Map of Nauru's position in the Pacific Ocean

Discovery of Phosphate Deposits

In 1886, Germany annexed the island. In 1900, Nauru was discovered to have phosphate of a quality surpassing all other sources then known (Gowdy and McDaniel 1999). By this time phosphate rock had come to be a valuable commodity due the following factors: its value as an essential macronutrient for plant based agriculture; the development of superphosphate (monocalcium phosphate), by treating rock phosphate with sulphuric acid thereby significantly increasing its availability to plants; and (laterly) aerial topdressing, which made widespread application of fertilisers economically feasible. With the phosphate discovery of 1900, Nauru suddenly gained international prominence.

From 1901 Germany proceeded to exploit the phosphate deposits (Weeramantry 1992). Meagre compensation was given to the Nauruan people in exchange for the extraction of what was a very valuable commodity (Weeramantry 1992; Fagence 1996). German rule in Nauru came to an end during World War I. After World War I, governance of Nauru was passed to the League of Nations. In 1919, at the Paris Peace Conference the island was entrusted to joint administration by the United Kingdom, Australia and New Zealand. Later that year, the Nauru Island Agreement was signed entitling the three administrative powers to the phosphate of Nauru at the cost of extraction rather than the international market price. After WWII governance of Nauru was passed to the UN, who re-established the UK, NZ and Australian administration (Drummond 1921; Macdonald 1988; Weeramantry 1992; CIA 2007). On the 31st of January 1968, Nauru gained independence and became a sovereign state (Weeramantry 1992). From this point, phosphate extraction was nationalised and the profits from the continued exports provided the Nauruan government with the vast majority of its revenue (Fagence 1996; Gowdy & McDaniel 1999). By 2005, 100 million tonnes of phosphate had been removed from Topside, Nauru (Morrison & Manner 2005).

Unlike other Small Island Developing States (SIDS) that have been reliant on international aid to a greater or lesser extent, Nauru was able to be economically self sustaining. Exploitation of Nauruan phosphate rock might have allowed for the state to achieve a form of economic sustainability were the mining profits effectively managed, however the capital has been substantially eroded (Gowdy & McDaniel 1999).

Open-cast mining of phosphate has resulted in substantially compromised ecosystems services, radically transforming the majority of the land of Nauru into an inhospitable landscape no longer suitable for human use (Manner *et al.* 1984). Bottomside and Buada are the only currently inhabitable and arable areas on the island. They are densely populated and cannot provide sufficient ecosystem services or resources for subsistence.

Unsustainable land use, notably mining, has greatly reduced soil quantity and quality on Nauru (Manner *et al.* 1984). In preparation for mining topsoil was cleared from mining sites and stored for later use in post-mining land rehabilitation. 650,000m^3 of soil has been stockpiled (Hunter, Harris *et al.* 1994). However, this volume of soil alone is insufficient to adequately rehabilitate the island (Carstairs 1994). Soil quality is also an issue. Low levels of organic matter and soil organisms mean that the remnant soils are infertile and have low water retaining qualities (Bhogal, Nicholson *et al.* 2009). Management practices which increase organic matter and soil organisms are likely to improve the quality of these soils.

Nauru Land Rehabilitation

In 1994, the Nauru Australia Cooperation Rehabilitation and Development Feasibility Study (RDFS) initiated the long term process of determining how to rehabilitate the mined areas of the island. The document provides an outline of how the landscape can be modified to achieve land rehabilitation goals. Further assessments by contractors and NRC staff have resulted in the development of the Pit 6 rehabilitation project (Burns 2007; Masters 2007; Debao 2009). The current plans for Pit 6 rehabilitation describe the engineering necessary to prepare the landscape for planting (levelling pinnacles, layering gravel and soil on top), but lacks guidance for the establishment of vegetative communities that will achieve rehabilitation goals. It will be necessary to re-establish ecosystems services essential for human habitation in Topside; for this to occur, ecosystem functions will need to be reinstated.

There are specific abiotic barriers in Topside which will need to be resolved in order to accelerate biotic succession for the re-establishment of ecosystem functions. Specifically these are lack of soil and water, and high levels of solar irradiance on the island. Desertification is an issue for the island, especially for Topside due to infrequent rainfall, lack of groundcover and ground porosity. An additional factor may be the presence of high levels of environmental cadmium which may affect community composition due to cadmium's toxic effects. Biotic factors include greatly reduced sources of propagules and invasive weed species.

The high level of solar irradiance is potentially an asset in landscape restoration if the incident energy can be effectively captured through photosynthesis. As the landscape is currently devegetated this quality is not being utilised for the benefit of the restoration process and instead, exposed soils are subject to dramatic temperature fluctuations and ultraviolet radiation. This leads to abiotic degradation of soil organic matter, desiccation, and ultimately, soils which are denuded of soil organisms. Accordingly, the degraded soils support little biomass and low soil biodiversity leading to poor fertility and plant growth.

Soil removed from the landscape prior to mining has been stockpiled, but is of reduced quality and limited in quantity. The author proposes that management of this soil resource is of fundamental concern to the success of Nauruan rehabilitation. This report provides a preliminary assessment of key components of the management of this resource: determining the potential for biomass production on different soils, the potential for selected species to contribute to cadmium phytoremediation and the effects of soil cadmium on germination success.

EXPERIMENTAL PLANNING AND DESIGN

The research involved three trips to Nauru. The first trip was from the 4th until the 12th of September 2008. The first trip involved meeting with a number of Nauruan officials and discussing prospects for research. The second trip from 31st March until the 1st of May 2009 was to establish field trials and conduct other experiments and site assessments. During the third trip from the 14th of November until the 7th of December 2009 samples required for analysis were collected.

A key part of the planning was making connections with relevant individuals and organisations to consult and collaborate, to benefit from their knowledge and ensure that the project design was relevant to the environment and community found in Nauru.

After consultation and a literature review of soil restoration techniques a field trial exploring the utility of plants for biomass accumulation and soil cadmium phytoremediation, and an experiment determining the effects of soil cadmium on germination success were planned. Unexpected results early on forced a significant re-evaluation of the direction of the research. The species trialled within the field plots were extirpated by the combination of severe environmental stresses and overcrowding by adventitious species that germinated from the soil seed bank. However, the success of the adventitious species provided a source of data relevant to the issues of biomass production and cadmium phytoremediation, as well as a valuable lesson in the utility of adaptive management principles in rehabilitation projects.

Soil

For over 30 years, when the mined areas of the island were cleared of vegetation and soil to access the phosphate rock beneath them, the covering vegetation and soil were lost. This continued until the 1930s, when a policy to stockpile soil cleared for later use in landscape restoration was implemented. 1,236ha requires soil of a total rehabilitation area of 1,405ha.

Topsoil stockpiles

Topsoil was deposited in two large stockpiles on Topside (Stockpiles A & B). The stockpiles are situated in exposed locations in Topside. Although only a small fraction of the soil that existed prior to mining, these stockpiles are a considerable asset to the rehabilitation process. However, long term stockpiling has reduced soil fertility, volume and quality. Stockpiling in large mounds has increased drainage and exposed the soil to dry winds, reducing levels of soil moisture, and leading to the loss of a significant proportion of the organic matter in the soil.

Stockpiles and more recently removed soils account for around 1,000,000m^3 of soil. Prior to mining, Nauru had an overall topsoil depth of 15-300mm (Carstairs 1994). Of the available soil left, if a soil depth of 150mm was to be used to rehabilitate the landscape, 700ha may be rehabilitable. This equates to less than half of the area (1404ha) that requires soil.

Soil organisms

Soil organisms thrive in well aerated soils with organic material and protection from fluctuations in temperature, moisture, pH, and gases. Stockpiling of soils has resulted in the formation of large anoxic areas leading to extensive loss of soil organisms. Desiccation due to exposure has further reduced soil organism populations.

Weeds

The Black soil stockpiles are colonised by weedy non-native species. Stockpile A is almost entirely dominated by *Leucaena leucocephala* while Stockpile B has a wider range of species. Weed species seed in the soil may pose ongoing issues if the soil is used in areas where non-natives are not desired. In Nauru, while weedy non-natives have been successful in colonising mined areas, native species tend to succeed the non-native species. Accordingly, these colonisers may promote the re-establishment of native vegetation, providing the soil with cover and leaf litter, initiating processes which establish soil structure.

Cadmium

Previous reports have identified that the topsoil deposits contain high levels of cadmium (Blake 1992; Hunter, Harris *et al.* 1994). Cadmium is toxic to a wide range of organisms and thus may affect restoration processes due to toxicity (Maksymiec and Krupa 2006; Lin, Wang et al. 2007; Dell'Amico, Cavalca et al. 2008; Sun, Zhou et al. 2008; Ci, Jiang et al. 2009). Additionally, soils used for agricultural purposes may pose risks to human health. Minimising the ecological effects of cadmium and the risk of cadmium exposure via contaminated soils is an important aspect of soil restoration.

Climate

The climate of Nauru is hot and humid due to its proximity to the equator. Temperatures are very stable, with monthly lows ranging from 24-26°C up to monthly highs of 29-31°C. Easterly winds predominate for most of the year, but stronger and gustier westerly winds are common toward the end of the year. The wet season is from December to March. Rainfall is highly variable between the wet and dry seasons, ranging from ~120mm in May to ~280mm in January. The El Niño-Southern Oscillation has a dominant effect on rainfall patterns. High rainfall consistently follows major El Niño events. Drought is common, extended periods without rain occur every other year (Hassall 1994; Hunter, Harris *et al.* 1994). Increases in cover of tall woody vegetation could significantly change the latent heat flux of the terrestrial biome on the island. Evapotranspiration and photosynthesis occurring in the forest ecosystems will result in less sensible heat (*cf.* latent heat) than without the forests. The loss of forests in a warm country like Nauru therefore increases the heating of the land surface and contributes to drying and water loss. Soil rehabilitation will be essential for increasing vegetation cover to mitigate these effects.

Climate change

Projected climate change impacts in Nauru may reduce rainfall due to increased frequency and intensity of El Nino events. This would result in more frequent and intense drought events for Nauru further threatening water security. Any increase in vegetation cover may help to mitigate the worst effects of future drought patterns. An effective and comprehensive programme to rehabilitate soils on this island will enable the reestablishment of forest cover and the related climate change mitigation effects. Research, careful monitoring, and adaptive management approaches to ecological restoration are current best practice and provide mechanisms by which future climate change can be integrated into existing management models (Harrington 1999; Lasch, Lindner *et al.* 2002; Cummings, Reid *et al.* 2005).

Freshwater

Nauru has limited freshwater resources. A brackish freshwater lens is supported within the substrate of the island and is replenished by rainfall infiltration (Ghassemi and Jakeman 1990). This freshwater resource is threatened by salination due to over-extraction, faecal coliforms from human waste, cadmium toxicity, and contamination from cemetery and landfill leachate (Marsh 1994). Hundreds of wells on Bottomside extract groundwater, a third of which are drawing water with higher dissolved salts than recommended by the World Health organisation (Nauru 2003). Infrequent and inconsistent rainfall is a significant obstacle to revegetation, which requires significant freshwater resources to ensure plant growth. Currently, most freshwater in Nauru is produced through desalination (Hunter, Harris *et al.* 1994). The desalination plant relies on imported diesel to function (NCCC 1999; Nauru 2004). Increasing international fuel prices and transport costs limit and are likely to further restrict freshwater production capacity.

MANDATE TO REHABILITATE

The Nauru National Sustainable Development Strategy (NSDS) is a high level guiding document providing an agenda for governmental reform and economic development in Nauru. The NSDS was prepared in 2005 through a consultative process with stakeholders. It emphasises the need for structural reform to enable Nauru to adjust to its changing economic, financial, social and environmental circumstances in a progressive manner. Its goals are listed in Table 1.1 including the components of each goal listed in order of priority. Because the symptoms of land degradation in Nauru are pervasive and burdensome almost all of the goal components listed in Table 1.1 are affected by Topside restoration.

Table 1.1 - Goals of the Nauru National Sustainable Development Strategy. (Emphasis added. *Italicised* goals refer specifically to land restoration in Nauru. Those components in bold are other goal components directly affected by landscape restoration.).

Stable, trustworthy, fiscally responsible government	Transparent and accountable governance practices Conducive legislative framework Efficient and productive public service Enabling and cooperative international relations Efficient and effective law and order system Increased community role in governance
Provision of enhanced social, infrastructure and utilities services	Broadened educational system **Alternative (including renewable) energy sources** **Improved access to water** **Preventative health service** **Improved sports and recreational facilities** Viable social welfare systems Well maintained infrastructure
Development of an economy based on multiple sources of revenue	**Phosphate mining** Fisheries resource management A developed SME sector **Efficient use of resources – people and natural** **Increased job opportunities locally and regionally** **National trust fund**

Rehabilitation of mined out lands for livelihood sustainability	*Land for agriculture development* *Land for conservation* *Land for water catchment* *Land for residential development* *Land for commerce & industry development*
Development of domestic food production	**Establishment of agricultural production** Enhance aquaculture farming Sustained use of inshore reef marine resources Promotion of pelagic fishery, in particular tuna fishing

Rehabilitation of mined land in Nauru is one of the five key goals identified by the NSDS, and of the remaining four, three are either dependent upon or positively associated with land restoration (refer to components of goals in bold above). Progress as defined by the NSDS was recently reviewed and several key areas, most notably Topside rehabilitation, were found to have progressed insufficiently.

A series of restoration plans have been developed through the Nauru Australia Cooperation (NAC) agreement and through consultants to the Nauru Rehabilitation Corporation (NRC), the organisation which is mandated with the task of rehabilitating the mined areas of the island.

The Rehabilitation and Development Feasibility Study (RDFS) 1994 produced by NAC is a landmark document presenting the work of a number of academics from Australia, and the Pacific focused exclusively on the issue of rehabilitation and development in Nauru. It is an extensive work, comprising seven documents covering waste management, Topside rehabilitation, forestry, housing, and human resources development. This document has played a key role in establishing the current post-restoration land-use plan. The NSDS states that soil is an essential component for 1236 of the 1405 ha of land which is to be rehabilitated and that the importation of soil is not a feasible option.

Soil is a central and integral factor in terrestrial ecosystem pathways. Action by the Nauru government to rehabilitate soils on Nauru will contribute to satisfying their local, regional, and international commitments. Healthy soils can provide a stable, dependable platform, contributing to the achievement of goals 1, 3, 4, 5, 6, 7 and 8 of the Millennium Development Goals, as well as the United Nations Convention to Combat Desertification (UNCCD), Convention on Biological Diversity (CBD), and climate change mitigation. The restoration of Nauru's soils will also support their regional commitments to the Convention for the Protection of the Natural Resources and Environment of the South Pacific Region, and their local commitments to the economic, social, and cultural well-being of the people of Nauru.

ECOLOGICAL RESTORATION

Davis and Slobodkin (2004) state that ecological restoration is "the process of restoring one or more valued processes or attributes of a landscape". Accordingly, while it employs scientific methods to achieve specific objectives, the objectives themselves are socially defined (Davis & Slobodkin 2004).

The natural variability of the ecosystems of Nauru has been lost due to the extensive and intensive perturbation of phosphate mining. The landscape has been thoroughly altered; it is unlikely that the historic conditions which preceded the mining can be re-established. Likewise, the historic environmental conditions of Nauru are unlikely to be regarded as socially ideal, given the dramatic cultural changes which have occurred in Nauru. Expectations have changed with regard to resource use, governance, property ownership, affluence, and maximal population to name a few, all of which contribute to a transformed relationship between people and land.

Nauruan society has radically changed in size and composition since pre-mining days, and as such it is unclear exactly what constitutes ideal ecological conditions for Nauru. What is clear is that the current conditions are less than ideal and that acting to transform the landscape cannot wait for a detailed understanding of that ideal due to the unsustainability of Nauru's current situation. Although a specific ecological goal may not be easily defined, there are a range of general goals that are definable. The author posits that these goals might be –

- rehabilitating the mined landscape to a state which is safe for human habitation
- increasing vegetative cover
- increasing soil organic matter (SOM)
- the preservation and cultivation of culturally significant species

- the preservation and cultivation of ecologically significant and endangered species
- the development of fertile soils for agriculture.

There is a need for explicit goals, a restoration programme developed with an awareness of local ecology, ongoing monitoring to provide quantitative data of change, and analysis of the results in order to adapt the design according to increasing knowledge of the ecology of the restoration landscape (Palmer, Falk *et al.* 2006). One of the outcomes from this model of experimental design is the development of 'knowledge targets'; ecological goals specific to the local conditions.

This report emphasises knowledge targets corresponding to the physiological challenges of land rehabilitation in Nauru, employing analytical research design. This report inevitably touches on many other ecological restoration knowledge targets as raised in the discussion (Chapter 5); however, they are not of central importance to this analysis. Part of the reasoning for the approach employed in this report is that the abiotic conditions found in Nauru are particularly severe and require initial attention. The relationship between soils and vegetation in the environmental conditions found in Nauru are assessed herein. Environmental cadmium is directly assessed and the general effects of the environmental conditions are assessed indirectly through measures of plant productivity and survival.

SOIL RESTORATION

Ecological relevance

Soil is an active interface between abiotic and biotic systems combining geological, atmospheric, organic and living systems in intricate cycles (Richter & Markewitz 1995; Baskin 2005). The dynamic properties of soils are largely a consequence of the organisms which inhabit them. Soil organisms break down organic matter, store and cycle nutrients, renew soil fertility, filter and purify water, degrade and detoxify pollutants, and control plant pests and pathogens (Killham 1994). Soils provide anchorage for roots, oxygen and mineral nutrients, water, and buffering against the adverse effects of temperature and pH in an association of mineral particles dynamically linked with organic matter, water and gases (Donahue 1958; Wild 1993; Matson 1997; Sumner 2000; White 2006). Though many aspects of the dynamics of soils are still not well understood, it is clear that they provide essential and diverse services upon which human societies rely.

Nauru soil ecology

Morrison & Manner (2005) identified four historical soil types on Nauru – coastal fringe soils, deep and moderately deep Topside soils, steep-land soils with dolomite influence, and Buada soils. Generally, the soils of Nauru are coarse textured with low water retention, due to rapid water infiltration and transmission rates. Soil development is almost entirely due to the accumulation of organic material. The parent material is either resilient to weathering, in the case of apatite, or easily weathered, in the case of carbonates. With a substrate low in bioavailable minerals, Nauru's soil fertility is highly dependent upon organic matter to provide nutrients, lower soil pH, and retain water (Nauru 2003).

Increasing soil quantity and quality

Soil development strategies will need to be targeted to specific outcomes depending on landscape use, with different approaches to satisfy each outcome. Land uses proposed by the Rehabilitation and Development Feasibility Study include conservation areas, housing, agriculture, forestry, a municipal waste site, a cemetery, a water reservoir, recreational areas, industrial areas, government facilities, and roads. With the exception of roads, and possibly the municipal waste site, all other areas will need to have soil to a greater or lesser extent (Carstairs 1994).

Phosphate mining has resulted in the loss of almost all productive land in Nauru. There is now a paucity of land on which to produce food-crops on the island. This poses a significant challenge for the inhabitants who now rely heavily on imported foods. Land suitable for agricultural purposes requires that specific biophysical systems such as carbon cycling are functioning to support the production of useful agricultural products. In all cases increased humus content will have beneficial effects on the services provided by the soils.

Importation of soil

Soil importation to Nauru has been suggested as a method to replenish diminished soil stocks on Nauru (Carstairs 1994). While this method may satisfy the need for greater soil quantities, the costs, both in economic and biological terms, are considerable.

The economic costs associated with the importation of soils include; sourcing of appropriate soils, purchase of the soil stock from a willing seller, excavation, transportation to an appropriate port, loading costs, shipping costs, unloading, and distribution. This represents a net loss to the local economy of around $1,450,000 AUD per hectare (Carstairs 1994). It would be many years before the gains would offset the costs.

The potential environmental costs to Nauru of imported soils are also considerable. Soils are ecosystems in their own right, containing biologically distinct taxa, particular to their place of origin (Baskin 2005). Interactions within the soil system play a considerable role in characterising ecosystem biota, thus importation of soils from outside of Nauru poses a considerable risk to the biodiversity of native soil organisms, and their mutual reliance upon indigenous flora and fauna. Sterilisation of imported soils is potentially costly and will provide a 'dead' soil substrate, with properties which may not be ideally suited to native soil organisms. Consequently, the author does not consider soil importation to be a feasible or useful component of soil restoration on Nauru.

Soil development on Nauru

Recommendation 13 of the 'Recommendations used in Steering Committee Deliberations' states that "It is recommended that soil generation be achieved by utilising materials available on Nauru, using simple technology" (Hunter, Harris *et al.* 1994). Soil rehabilitation is dependent on raising soil volumes, fertility, and increasing microbial content. Composted organic inputs offer the best method for achieving these three outcomes. Under-utilised organic inputs are currently readily available on Nauru (Marsh 1994). Management systems should focus on sustaining soils through reintegrating the inputs that are already available.

Mineral inputs

Phosphates are an obvious source of locally available mineral fertiliser, although phosphate levels in Nauru soils are unlikely to become depleted except under intense agricultural pressure. It has been proposed that the use of phosphate be weighed against the opportunity cost of not selling it (Baines 1994).

Organic inputs

Organic inputs have been highlighted as the most promising method to raise soil fertility. Fortunately many sources of organic inputs already exist on the island. Facilitating their biodegradation will increase the rate at which organic materials become available in soils and thereby increase the rate at which the soils and vegetation can develop. Organic inputs increase the amount of water available to plants and reduce the density of the soil, facilitating plant growth (Bhogal, Nicholson *et al.* 2009). The use of locally available organic fertilisers offers fewer risks to groundwater quality than mineral fertilisers and reduces the incidence of stresses associated with water availability in soils (Duwig, Becquer *et al.* 1998). Organic inputs to soils result in significantly greater species richness in both bacteria and nematode communities (van Diepeningen, de Vos *et al.* 2006; Bhogal, Nicholson *et al.* 2009).

The natural accumulation of organic material is a consequence of production, slope and rate of decomposition. Rainfall is a limiting factor to vegetative growth, and is highly variable on Nauru, indicating that organic inputs to soils would vary considerably from year to year. With high humidity and aeration of soils, decomposition is likely to be rapid, leading to relatively low equilibrium levels of organic matter in the soils (Morrison & Manner 2005).

Soil organisms and mycorrhizae

Soil microorganisms increase the potential for soil biological activity and improve physiochemical soil properties, contributing to rapid humification of fresh organic matter and may be used as indicators of soil health (Valarini, Alvarez *et al.* 2002, Valarini 2003). Symbiotic associations between plants and mycorrhizae greatly increase growth productivity by enhancing nutrient availability and uptake and by maintaining and improving the physical, chemical and biological qualities of soils (Sen 2005; Cardoso & Kuyper 2006). Further research is necessary to identify soil organisms which may benefit native reforestation and agriculture on Nauru. Activity and abundance of soil organisms correspond to levels of organic material in soils (Baldock 2000).

Sourcing of organic inputs

Organic inputs on Nauru are available from human effluent, green waste, food and kitchen waste, and the growth of green manures (Marsh 1994). Cultivation of soil organisms will facilitate nutrient availability and improve overall soil development and productivity.

Biomass production

Cover crops and green mulches

While the terms are often used interchangeably, cover crops and green manures differ in their intended use. Cover crops are used, as the name implies, to cover the soil and thereby protect it, often in periods where seasonal weather patterns pose risks to exposed soils (Thurston 1997). Green manures are grown to be integrated into the soil after a period of growth to increase the organic content of the soil (Sullivan 2003). The terms are used interchangeably as it is often the case that both goals are expressed in a single crop.

Cover crops

Cover crops are primarily planted to cover and protect the soil from erosion. Other benefits may include –

- Potential nitrogen gains where legumes are used
- Organic matter content can significantly increase
- Protection from soil erosion
- Weed suppression
- Low labour costs
- Low expenses – seeds produced on site
- Potential for animal forage
- Reduction of photodegradation of soil organic matter

(Bunch 1994; Rutledge, Campbell *et al.* 2010)

Recent research shows that exposure of soil organic matter (SOM) to solar irradiance in dry environments results in substantial losses of SOM to the atmosphere by way of CO_2, produced by photodegradation (Rutledge, Campbell *et al.* 2010). Limiting this pathway by which organic matter is lost from the soil may be of considerable benefit when seeking to increase the organic content of soils. Living groundcover reduces photodegradation by limiting the amount of radiation incident upon soil organic matter.

Green manures & mulches

Green manures are cover crops grown to be reincorporated into the soil for the purpose of increasing soil fertility (Ghosh 2007; Liu, Gumpertz *et al.* 2007). Other advantages of green manures include soil profile development through root intrusion, protection of soils from environmental stresses by acting as living mulch (Elfstrand, Bath *et al.* 2007). Vegetation growth and productivity of native tree species such as the Tomago (*Calophyllum inophyllum)* would be greatly increased by the use of green manures (Moitra, Ghosh *et al.* 1994). Green manures are often species that harbour nitrogen fixing bacteria. The incorporation of green material from nitrogen fixing species minimises volatilisation of nitrogen (Thurston 1997).

Green mulches are grown for the benefits that they provide while growing (or during growth), including improvements to soil texture, and structure. Mulches are used to cover the soil, create a distinct layer between the soil and atmosphere and as such are akin to cover crops (Lal 1990).

Potential positive effects of green manures

- Decrease soil moisture evaporation, protecting against drought (Buckles, Ponce *et al.* 1994; Moreno & Sánchez 1994)
- Increase water infiltration (Ayanlaja & Sanwo 1991)
- Reduce erosion and water runoff (Ayanlaja & Sanwo 1991; Akobundu 1993; Buckles, Ponce *et al.* 1994; Moreno & Sánchez 1994)

- Reduce temperatures of soil
- Increase populations and activity of earthworms (Fragoso, Barois *et al.* 1993)
- Increase SOM (Ayanlaja & Sanwo 1991)
- Increase soil nutrients(Ayanlaja & Sanwo 1991; Buckles, Ponce *et al.* 1994; Moreno & Sánchez 1994)
- Protect young plants and seedlings from physical stressors such as wind and rain (Thurston 1992)
- Aid in weed management (Akobundu 1993)
- May reduce labour (Thurston 1992)
- Increase crop yields

- Potential negative effects of green manures
- Pests - eg. mice, rats, insects (Buckles, Ponce *et al.* 1994)
- Environment for some plant pathogens(Moreno & Sánchez 1994)
- Effects on C/N ratio (Jordan 1989)
- Nitrogen loss in some cases due to formation of ammonia (Costa, Bouldin *et al.* 1990)
- Increased labour costs in some cases (Thurston 1992)

Slashed shrubs or trees

While it is common to use grasses or other ground cover plants as cover-crops, there has been research into the use of shrub and tree species as sources of green manure. Various methods have been proposed for mulch produced from shrubs and trees including the lopping of foliage and coppicing (Brewbaker 1990). Often the land in question is organised so as to allow for multiple production sources, whereby trees provide material for integration into the soil, and protection for crops which are grown between. This has various names such as alley cropping, hedgerow cropping, avenue cropping, or hedgerow intercropping. It has been observed that coppicing is especially useful in the seasonally dry tropics where other forms of production may suffer (Nyerges 1989). Additional positive and negative aspects are listed below.

Other positive aspects of intercropped tree mulching systems

- Erosion control (Fernandes 1991; Akobundu 1993; Kang 1993)
- Improvement of soil physical properties by addition of SOM (Kang & Reynolds 1989; Fernandes 1991; Akobundu 1993; Kang 1993)
- Nutrient provisioning (esp. from legumes) (Kang & Reynolds 1989; Fernandes 1991; Kang 1993; Szott 1993)
- Firewood, poles, other wood products
- Fodder (Kang & Reynolds 1989)
- Weed suppression – shading and mulch (Kang & Reynolds 1989; Akobundu 1993)
- Beneficial microclimate effects
- Tree crops

Negative aspects of intercropped tree mulching systems

- Competition with crops for moisture, sunlight and nutrients
- Reduction of space available for other activities
- Disease issues caused by reduced air flow
- Risk of tree species becoming an invasive weed
- Labour inputs can be high
- Requires intensive management

Phytoremediation of soils

Cadmium liberation

An unfortunate consequence of phosphate mining on Nauru has been the liberation of substantial quantities of cadmium from subsoil deposits into the wider environment. Cadmium may have effects on ecological community structure in Nauru. Cadmium has negative effects on human health, thus cadmium bioavailability is a critical concern in agricultural soils.

Ecological effects of cadmium

Cadmium is classified as a toxic heavy metal. Contaminated areas are considered to be a threat to the well-being of humans and animals (Czeczot and Skrzycki, 2010). Cadmium affects the kidneys, liver, lungs, pancreas, skeleton and testis in humans due to disruptions of cellular adhesion, the immune system, the cellular antioxidant system, and cellular communication systems, inhibition of DNA repair and methylation, promotion of cell proliferation and apoptosis, and initiation of cell mutagenesis and carcinogenesis (Czeczot and Skrzycki, 2010; Dufresne et al., 2010; Satarug et al., 2010; Trzcinka-Ochocka et al., 2010). Cadmium has been demonstrated to have a wide variety of deleterious effects in ecological systems, negatively affecting soil microbial community structure and activities, affecting growth and causing severe physiological disorders in plants and animals, disrupting renal, hepatic systems, and endocrine system functioning, skeletal development, and fat storage in animals (Angenard et al., 2010; Ci et al., 2010; Czeczot and Skrzycki, 2010; Dufresne et al., 2010; Khan et al., 2010; Kumar et al., 2009; Lucia et al., 2010; Planelló et al., 2010; Van Campenhout et al., 2010). Cadmium bioaccumulates in food webs amplifying the risk to organisms at higher trophic levels (Sato et al., 2010; van den Brink et al., 2010).

Cadmium Bioavailability

Bioavailability is a complex term. It refers to the amount of contaminant in the soil which is available to an organism which may accumulate it. Dynamic equilibria of chemical species and their interactions with living organisms affect the rate and degree of bioavailability. Despite these difficulties in quantification, it is a useful qualitative concept, allowing for meaningful comparisons between different soil and plant interactions. In the context of this study, the terms bioavailability and phytoavailability refer to the heavy metals in the soil which are available for accumulation in plant tissues. The laboratory method employed in this report to assess the mobile fraction of cadmium in soil samples utilises $NaNH_3$, which is a weak extractant, to assess the free ionic concentration of cadmium in the soils. This fraction of the soil cadmium consists of a range of chemical species which are highly mobile and are readily available for uptake by plants.

Soil acidity

As soil pH affects precipitation of salts it is considered to be the single most significant factor determining solubility of heavy metals in the soil. Soil pH and solubility negatively correlate, meaning that all things being equal, acidic soils will have a greater availability of heavy metals than alkaline soils. Nauru's soils are alkaline due to the calcium carbonate substrate. Productive agricultural soils are typically more acidic than those found in Nauru, as acidity also increases the availability of soil nutrients. Accordingly, there will be conflicts for target pH of agricultural soils in Nauru, between increased productivity and cadmium bioavailability. Reducing the cadmium load in soils intended for agriculture will reduce that conflict.

Phytoremediation

It has been suggested that phytoremediation via phytoextraction may be an economically sensible tool for remediation of soils contaminated with heavy metals. It is a technique that employs plants as absorbers of inorganic contaminants for subsequent removal via harvesting.

Advantages of phytoremediation include:

- Can be performed in situ
- Less invasive than civil-engineering earth moving projects (Cunningham & Berti 1993; Cunningham, Berti et al. 1995; Wiltse, Rooney et al. 1998)
- Less expensive than civil-engineering earth moving projects (Cunningham & Berti 1993; Cunningham, Berti et al. 1995; Wiltse, Rooney et al. 1998; Garbisu & Alkorta 2001)
- Application over large surface areas (Wiltse, Rooney et al. 1998)
- Targets the bioavailable fraction of heavy metals in the soil
- Avoids further soil loss

Drawbacks include

- Long remediation time (years to decades)
- Perception of uncertainty and limits to performance predictability associated with biological remediation systems
- Elevated concentrations of heavy metals in aboveground plants parts may enter the food chain via herbivory.

Techniques employed in soil phytoremediation include

- Phytotransformation/phytodegradation
- The breakdown of contaminants through plant metabolic processes
- Phytostimulation
- The stimulation of fungal and microbial degradation of organic pollutants by plant exudates or enzymes
- Phytostabilisation
- The immobilisation of soil contaminants by plants limiting leaching, especially to groundwater
- Phytovolatilisation
- The formation and release of volatile forms of pollutants absorbed by plants
- Phytoextraction
- The extraction and accumulation of contaminants in harvestable plant parts

(Kumar, Dushenkov *et al.* 1995)

Of these, phytoextraction is the primary phytoremediation technique which will be evaluated as part of this research due to the relative accessibility of this technique for Nauru. Phytoextraction is cheap, low-tech and easier to employ over large areas than other phytoremediation techniques.

Phytoextraction

There are considerable incentives for the use of phytoextraction, including non-invasiveness, economics, aesthetics, soil stability, increased soil organic carbon, and the ability to use the land area during the rehabilitation process (Cunningham & Berti 1993; Cunningham, Berti *et al.* 1995; Salt, Blaylock *et al.* 1995; Garbisu & Alkorta 2001).

Recent research has focused on increasing extraction efficiency of heavy metals. Generally, two methods are pursued:

- The use of hyperaccumulating species (Baker, Reeves et al. 1994; Brown, Chaney et al. 1994; Nanda-Kumar, Dushenkov et al. 1995; Krämer, Smith et al. 1997; Zhao, Lombi et al. 2001)
- The use of soil amendments to stimulate the uptake and accumulation of heavy metals (Banuelos, Cardon et al. 1993; Huang, Chen et al. 1997; Ebbs & Kochian 1998; Huang, M.J. et al. 1998; Cooper, Sims et al. 1999; Lombi, Zhao et al. 2001; Shen, Li et al. 2002).

Other options include evaluating the benefits of genetically modified species (Gleba, Borisjuk *et al.* 1999; Kärenlampi, Schat *et al.* 2000) and rhizospheric associations between plants, mycorrhizae and bacteria (Killham & Firestone 1983; Khan 2001; Kunito, Saeki *et al.* 2001; Li, Chen *et al.* 2002; Bi, Li *et al.* 2003).

This research has focused on identifying locally available plant species which may act as hyperaccumulators, or at least serve the purpose of phytoextractors in the conditions found in Nauru. Many of the academic papers listed above deal with heavy metal contamination as the only significant limit to species viability; however, Nauru has various environmental factors other than heavy metal load which limit the viability of a wide range of species. Rather than focusing on hyperaccumulating species, or on soil amendments to increase heavy metal transport into plants, this research has focused on determining which species provide maximum yield *in situ*. Soil amendments to improve heavy metal transport have been of benefit to a number of soil restoration projects, however, the focus of this project has been on ascertaining the most basic and fundamental aspects of soil phytoremediation in Nauru, largely using the species and resources available on the island. Typically, the significant restrictions to efficient phytoextraction are bioavailability, the tolerance of each species to heavy metals, and translocation; however, the adverse growing conditions in Nauru pose their own set of physiological difficulties (Herzig, Rehnert *et al.* 2000).

Translocation

Aboveground accumulation of heavy metals in phytoaccumulating plants is limited by the translocation barrier formed by Casparian bands that separate the root cortex from the vascular bundle, forming a physiological barrier to heavy metals being transported from the roots to the shoots (Huang 1989). Various papers have described the differences in accumulated concentrations of cadmium between roots and shoot tissues (Kirkham 1978; Kastori, Petrovic *et al.* 1992; Guo & Marschner 1995; Salt, R.C. *et al.* 1995; Tack, Esteban-Mozo *et al.* 1998).

Accordingly, analysis of accumulated concentrations of cadmium in root, stem, and leaf tissue will be compared to determine which species have the greatest efficiency of transportation of cadmium to aboveground plant tissues.

Germination

Germination is a critical life process of plants whereby seeds take in water, rapidly increase respiratory activity, mobilise nutrient reserves, and initiate embryo growth (Bradbeer 1988; Fenner & Thompson 2005). Studies have found widely varied effects of cadmium on germination success describing either increased germination success with increased levels of cadmium, the opposite, or no effect (XinHong, YuXiu & RunJin; Zhang *et al.* 2010; Lefevre, 2009; Wang & Zheng, 2009; ZhiDe *et al.* 2009, Kumar *et al.* 2009; HuaBing, 2009; Farooqi *et al.* 2009). Nauru's rehabilitation project provides an interesting setting in which to explore the extent to which cadmium determines germination success. Firstly, the results may benefit the management of the rehabilitation process. Secondly, Nauru's cadmium levels are naturally elevated, in contrast to the artificially elevated levels assessed within the literature.

ADAPTIVE MANAGEMENT

Adaptive management (AM) is an approach to management in the face of uncertainty. AM has an iterative management approach, requiring that the results of management approaches are monitored and analysed, that the analysis is used to modify or update the management approach, and that any such modifications are subsequently employed and monitored (Walters & Hollings 1990; Gregory, Ohlson *et al*. 2006). By learning from management outcomes, AM systematically improves environmental management policies and practices (Gregory, Ohlson *et al.* 2006).

Two forms of AM exist – Active AM and Passive AM. Active adaptive management requires that several models are employed in such a way as to provide useful information for subsequent management. Experimentation is built into the management framework. Passive adaptive management employs one "best method" usually based on historical data. This method is trialled, the effects are monitored, and an updated management approach is implemented (Walters & Hollings 1990; Gregory, Ohlson *et al.* 2006). Active AM is more akin to scientific experimentation than passive AM and is consequently more likely to determine specific factors for shaping successful management approaches than Passive AM. This is due to controls and comparable treatments in Active AM to reduce the likelihood of measurement errors caused by stochastic effects, which might otherwise confound management and environmental effects (Walters & Hollings 1990). Typically, Active AM results in faster accumulation of information useful to environmental management. However, Active AM usually requires greater funding, preparation, and attention to the use of experimental design principles (Gregory, Ohlson *et al.* 2006).

The rehabilitation programme in Nauru cannot be expected to prescribe exacting methods by which rehabilitation can be achieved. Therefore, to be able to proceed with a reasonable expectation of success, adaptive management principles will need to be employed. This report explores some aspects of restoration in a manner that is consistent with an AM approach to restoration in Nauru. It does so by exploring biomass productivity, cadmium phytoremediation and germination success according to AM experimental design principles. In the cases of biomass productivity and cadmium phytoremediation, the experiments were conducted as field trials under conditions akin to those which are expected to be found in the rehabilitation areas.

RESEARCH APPROACH AND THESIS CONTENT

The soil stockpiles on Nauru are an essential resource for rehabilitation which could be better managed than they have historically been. How best to manage this resource, however, is not clear. Determining, in greater detail, the potential impact of different management options would be useful as it will allow for more informed decision making.

Some key concerns are:

- the effects of cadmium on germination success of species in Nauru
- the impact of Nauruan growth conditions on various species that may be used for soil restoration
- whether phytoremediation techniques may be applicable in Nauru and to what extent.

This thesis aims to provide a preliminary exploration of these factors for rehabilitation through experimentation in Nauru. It must be noted that there were significant constraints to this process. Firstly, this is a Master's thesis and thus the scope of the research must be commensurate with the expectations of the examining body, both in terms of size and format. Secondly, it was only possible to visit Nauru three times and not for the full extent of the field trial, which meant that it was not possible to mitigate problems that arose between visits.

Chapters 2, 3 and 4 describe specific experiments that were performed to explore the issues of biomass accumulation, cadmium phytoremediation, and the effects of soil cadmium on germination success. The chapters have been written such that they individually perform the tasks of academic papers. Consequently there is some unavoidable repetition. Chapter 5 draws from each of the experimental chapters and integrates the information they individually report to inform the Nauru rehabilitation process. What follows are brief outlines of what the reader can expect from the following chapters.

Biomass production in Nauru

The environmental conditions found in Nauru are severely limiting to plant growth. It is useful to determine the biomass output *in situ* of potentially useful green mulch species under likely conditions in Nauru as a guide for nursery work and planting on the island. To this end, a field trial designed to explore biomass production was conducted on Nauru from April to October 2009.

This aspect of the restoration issue will be evaluated in greater depth in Chapter 2.

Cadmium bioremediation

Bioremediation of soil cadmium in Nauru may be of considerable use in ensuring that agricultural soils have levels of bioavailable cadmium which pose little to no threat to human health and well-being. A field trial designed to explore phytoremediation was conducted on Nauru from April to October 2009.

This aspect of the restoration issue will be evaluated in greater depth in Chapter 3.

Effects of cadmium on germination success

If elevated levels of cadmium are affecting germination rates then community composition may become altered through time. Testing the effects of soil cadmium on seed germination would provide useful information for the restoration process. An experiment designed to explore this issue was performed in Nauru in April 2009.

This aspect of the restoration issue will be evaluated in greater depth in Chapter 4.

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Chapter 2 - Biomass production in Nauru: A preliminary field trial

ABSTRACT

Nauru requires substantial volumes of organic matter to improve soils for landscape rehabilitation. This paper describes a preliminary field trial assessing the productivity of a range of species grown *in situ* in four local soils, with and without mulch. Total and exchangeable fractions of soil cadmium were also assessed with regard to effects on biomass production. Overall, productivity was highest - for three species - *Cajanus cajan*, *Leucaena leucocephala*, and *Calopogonium mucunoides*; for plants grown in the soil known locally as Black soil; when wood-chip mulch was used; and in soils containing lower levels of cadmium.

INTRODUCTION

Healthy functional soil systems are essential for human wellbeing. Soil infertility and toxicity are two examples of threats to the health of this system. Loss of soil fertility may lead to desertification in environments where biota are necessary to protect soils from environmental stresses. Soils containing toxic compounds pose health risks to humans and all organisms living on or near contaminated land. The severity of the risks are clearly illustrated in the Pacific Islands, where infertile or contaminated land can significantly exacerbate the shortage of available land (Gowdy & McDaniel 1999; van der Velde, Green *et al*. 2007). Few places demonstrate this situation more starkly than Nauru.

Nauru is a 21km^2 raised limestone island 41km south of the equator at longitude 166° 56′ E in the Central Pacific (Fig. 1.1). It is surrounded by a fringing coral reef that sharply drops away 4,300m to the Pacific floor. "Bottomside" is the local name for the thin coastal plain surrounding the interior of the island, known as "Topside". Topside is a 1,620ha raised plateau that ranges from 20-60m in elevation, and is largely divided from Bottomside by a steep escarpment. A brackish lagoon, called "Buada" is in a large interior depression, and is hydraulically connected with the Pacific (Hunter, Harris *et al.* 1994; Kingston, P.A. 2004) (See Appendices I & II).

Figure 2.1 – Map of Nauru's position in the Pacific

Mining of phosphate in Nauru has lead to various environmental effects, including deforestation, biodiversity loss, soil loss, liberation of toxic sub-soil cadmium deposits, soil degradation and desertification (Manner 1984; Morrison & Manner 2005). Nauru is facing various social, political, economic, and health issues which are exacerbated by soil degradation (Weeramantry 1992; Fagence 1996; Gowdy & McDaniel 1999). Rehabilitation of mined lands in Nauru constitutes one of the five goals of the Nauru National Sustainable

Development Strategy 2005-2025 (Nauru 2005). The 2009 review of the NSDS identified that objectives for the rehabilitation of mined land have thus far not been achieved according to its targets (Nauru 2009).

There are various reasons why NSDS targets have not been achieved:

- There is little knowledge of how to achieve specific goals in the ecological setting of Nauru.
- The amount of information which is potentially relevant to rehabilitation in this setting is vast.
- The scale and nature of the project is unlike any previous restoration project anywhere.
- Soil moisture is generally low, due to highly variable rainfall patterns, high rates of evaporation, and ready percolation through the porous underlying rock.
- Records of the historical ecology of Nauru, which could inform management decisions, are fragmentary (Morrison & Manner 2005).
- In Nauru there is a lack of human capital with experience and skills appropriate to landscape rehabilitation.

A range of goals for restoration were developed under the Nauru Australia Cooperation Rehabilitation and Development Feasibility Study 1994 (RDFS), many of which require the rehabilitation of soils for various land uses including housing, conservation, agroforestry/residential, sports/recreation/parks, an education complex, a public service complex, a cemetery, a municipal waste site, a hospital complex, and an industrial complex (Carstairs 1994; Hunter, Harris *et al.* 1994).

These land uses require soils, although they require them for different reasons and accordingly the properties required of the soils differ in relation to their intended purposes. Generally the soil purposes can be distinguished according to use as:

a) substrate, such as for hospital, education, public service and industrial complexes
b) growth media for food crops, as in the agroforestry/residential areas
c) growth media for vegetation cover for various purposes, as in the conservation, agroforestry/residential and sports/recreation/parks areas, as well as selected areas of the education, public service, hospital and industrial complexes and cemetery
d) media for containment and amelioration of biological hazards, as in the cemetery area and municipal waste site

(Baines 1994; Carstairs 1994).

Since 1970 mining operations have stockpiled soil for rehabilitation purposes (Baines 1994; Gowdy & McDaniel 1999). These soils have lost considerable amounts of material, organic content and biota while stockpiled, leaving the soils relatively infertile. Additionally, cadmium liberated through mining operations has contaminated the stockpiled soils limiting their value for rehabilitation.

Overall, it is required that the volume and fertility of soils available for landscape rehabilitation be increased. Soil provides plants with an anchorage for roots, supply of water, oxygen and mineral nutrients, and a buffering against the adverse changes of temperature and pH (Donahue 1958; Wild 1993; Matson, Parton *et al.* 1997). Increasing the organic carbon content of stockpiled soils is a viable method for increasing soil volume and fertility and may provide additional benefits to soils including increased water retention properties, increased soil biota and thus increased biological activity, and a carbon sink with potential benefits for the country with regard to carbon balance and associated carbon finance opportunities.

Of additional concern are the significant concentrations of cadmium in Nauruan soils. Cadmium is known to induce a range of severe physiological disorders in plants such as chlorophyll reduction, changes to phenols, oxidative stress and altered enzyme activity which ultimately retard plant growth (Maksymiec & Krupa 2006; Lin, Wang *et al.* 2007; Dell'Amico, Cavalca *et al.* 2008; Sun, Zhou *et al.* 2008; Ci, Jiang *et al.* 2009). It must be determined to what cadmium toxicity is of concern to the rehabilitation project.

This paper describes the first part of a two-part experimental field trial to assist in the developing a successful soil restoration programme through biomass production and cadmium phytoaccumulation for Nauru. The second paper entitled "Cadmium phytoaccumulation in Nauru: A preliminary field trial" assesses the cadmium phytoaccumulation capability of various species in a range of Nauruan soils as well as the impact of the addition of biomass through a locally produced wood chip mulch upon cadmium phytoaccumulation.

In this paper, biomass production capability is assessed for various species in a range of Nauruan soils as well as the impact of the addition of biomass through locally produced wood chip mulch. Total biomass accumulated according to soil-type, species, cadmium level, and use of mulch is described.

AIM

- To assess the biomass production capacity of a range of plant species for the rehabilitation of soils on Nauru

HYPOTHESES

- Soils with the greatest cadmium content will have the lowest biomass accumulation rates
- Mulch will increase biomass accumulation
- There will be variation in productivity between species
- Soil type will effect biomass production

METHOD

A selection of species were sown in a range of soils, watered and grown for a period of seven months whereupon they were to be assessed for their biomass production potential.

Field plots were established in Nauru within Topside, the elevated platform which constitutes the centre, and greater part of, the island.

Variables

Species

Five species were selected according to their suitability for soil rehabilitation on Pacific tropical islands– green mulches, drought tolerant, fast growth, and readily available seed as determined by the Centre for Tropical Agriculture and Human Resources (CTAHR) at the University of Hawai'i (Smith & Valenzuela 2002; Valenzuela & Smith 2002a; Valenzuela & Smith 2002b).

The species used were

- White oat - Avena sativa
- Black oat - *Avena strigosa* Schreb.
- Ryegrass - Lolium multiflorum
- Barley - Hordeum vulgare
- Hairy Vetch - Vicia villosa

Soil types

The soils used were

- Black soil
- Buada soil
- Topsoil
- Dolomite

Black soil

'Black soil' is the name given locally to soil from the soil stockpiles on Topside. Black soil is the remaining topsoil from across the central plateau, removed for phosphate mining access, and left stockpiled for several decades. This soil has lost significant amounts of organic material through stockpiling and exposure to the sun without substantial cover. Stockpiling also resulted in large anoxic areas within the piles which, along with desiccation and losses of soil organic matter, are likely to have reduced the populations of soil organisms within the soil. The soil used for this experiment was sourced from Stockpile A which has a greater variety of plant species growing on it than Stockpile B which is covered with a monoculture of *Leucaena leucocephala.*

Buada soil

'Buada soil' is soil from the Buada province of Nauru. Buada is a large depression containing a brackish lagoon and fairly fertile soils. Buada is protected from the hot salt laden winds that sweep across Nauru so the plants that grow there are less prone to desiccation. Buada soils are undisturbed compared with Black soil, and contain considerably higher volumes of organic material and soil organisms.

Topsoil

The 'Topsoil' is sourced from the Nauru Rehabilitation Corporation (NRC) nursery area in Topside which is located in an area that has operated as a sports oval and recreation area; the soil was part of the track and field area and was tended through use of fertiliser for many years. It was then used as the site of the Nauru detention centre for Australia, before becoming the site of the NRC nursery. This soil has been managed to some degree, having received applications of fertiliser and pesticides. The soil has been covered by pasture for many years, and is used preferentially in garden developments by the nursery staff.

Dolomite

The 'Dolomite' does not have all of the characteristics necessary to be accurately described as a soil. It is a mixed aggregate of fine to course material which has been mined containing a high proportion of rock phosphate. This material has been proposed as a medium for developing soil layers by the Nauru Rehabilitation Feasibility Study and other documents relating to landscape restoration on Nauru.

Mulch

Growing conditions on the Topside of Nauru are arid. Nauru experiences highly variable rainfall and large amounts of incident sunlight due to its location in the dry equatorial zone of the tropical Pacific Ocean. In these dry conditions, desiccation leads to increased plant mortality and reduced growth. Mulches can be used to protect soils from temperature fluctuation, to reduce soil moisture evaporation, and increase soil carbon content. Local production of wood-chip mulch from biomass was investigated within this experiment. Wood-chip was applied to a depth of 4-5cm on one of the two experimental beds. To ensure sufficient soil moisture, the beds were watered daily for the first month and then weekly unless rainfall meant that this was unnecessary.

Complications

The intention of the experiment was to test the viability of a range of selected species for phytoaccumulation in Nauru. Accordingly, a range of species of seeds were planted according to a randomised plan (Fig. 3.1). However, the resulting seedlings were unsuccessful as the adverse growing conditions found in the field in Nauru combined with the success of adventitious local seed from within the soils killed off the experimental species. This outcome posed significant issues for the original experimental design. However, though an unexpected outcome, this result revealed two factors important to the rehabilitation project; the significant challenges of the Nauruan growing environment, and the potential for using local flora which were evidently better suited for growth in adverse conditions. So we identified the species, measured their biomass production under the different treatments, and determined the cadmium levels in different parts of the plants.

Field plots

The seeds of a range of species were sown in randomly assigned mini-plots within larger plots of specific soil types. The larger plots were arranged into two beds, one with mulch, the other without. (Fig. 2.2). The beds were situated at the Nauru Rehabilitation Corporation nursery site (See Appendices I & II).

Seeds were sown as per standard sowing densities for each species, as recommended by the seed producers. The seeds were monitored for germination success for 10 days. For the following six months research obligations outside of Nauru, meant the beds were left in the care of the nursery staff. Due to the lack of access to telecommunications equipment on Nauru at the time, it was not possible to contact the nursery staff during this absence. Nursery staff observed during this period that adventitious species were germinating in the soils, with the Topsoil plots showing the greatest amount.

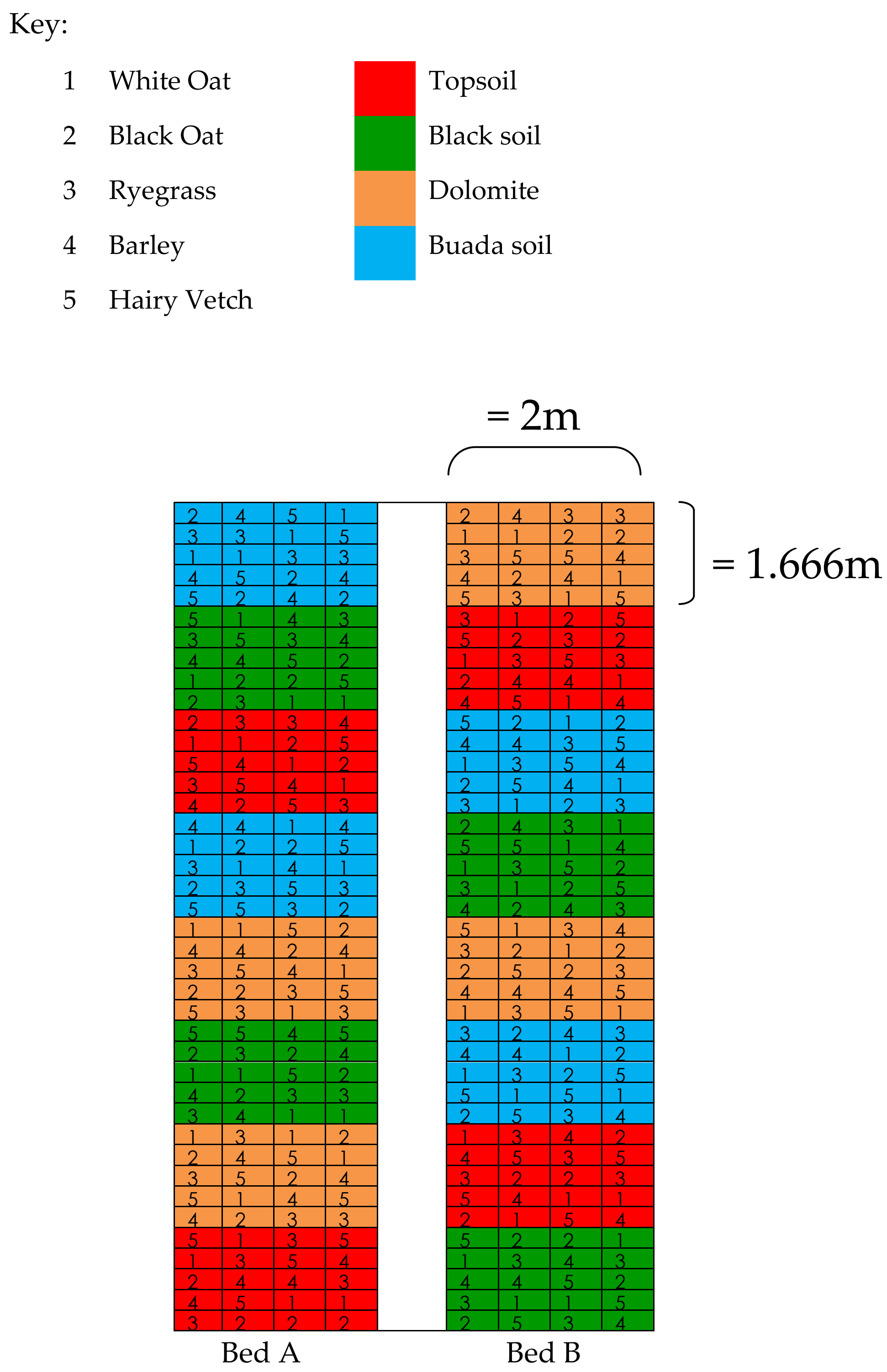

Figure 2.2 – Field trial plots

Preparation for sample collection

At the start of the third trip to Nauru, six months later in October 2008, it was found that weed species had overtopped and killed off the planted trial species. This posed several issues to the experimental design. The statistical power was reduced, as it was now not possible to produce a full factorial model. Nevertheless, it was determined that the circumstances could still provide valuable data for the development of a process for cadmium phytoaccumulation. At this point, the soils contained a large amount of seed of local weedy species which successfully germinated and grew in the adverse conditions found in Topside, Nauru. Accordingly, the germination and seedling success of the weedy species provides evidence of their adaptive suitability to the conditions found on Topside. It was decided to identify and sample the species which had grown, to assess their suitability for phytoaccumulation (Table 2.1).

The species which were identified were –

Table 2.1 – Weed species found in soils

Sampled species	Black soil	Topsoil	Buada soil	Dolomite
Calopogonium mucunoides	X	X	X	X
Cajanus cajan	X	X		X
Leucaena leucocephala	X	X	X	X

Indigofera hirsuta	X	X	X	X
Senna occidentalis		X	X	
Sida acuta	X		X	
Indigofera spicata	X	X		
Waltheria indica	X	X		
Phylanthus amarus			X	X
Ipomoea macrantha	X			
Scaevola taccada	X	X		
Unsampled species				
Chamaesyce hirta			X	
Tridax procumbens				X
Stachytarpheta jamaicensis			X	

Of note was the presence of Pigeon Pea *Cajanus cajan* which is listed by the College for Tropical Agriculture and Human Resources, University of Hawai'i, Mānoa as a beneficial green manure for the Pacific (Valenzuela & Smith 2002c). It is possible that the species arrived with asylum seekers who were detained on Nauru. This species has a global production of around 40,000 km^2, and is cultivated for its protein rich seed, as a cover crop and companion plant, for fodder and for firewood (Almeida, Furtunato *et al.* 2010; da Silveira, Ribeiro da Cunha *et al.* 2010; Eltayeb, Ali *et al.* 2010; Linares, Scholberg *et al.* 2010; Thampan & Remany 2010). It is a perennial nitrogen fixing legume used for producing biomass. *Cajanus cajan* grew successfully in conditions found on Topside Nauru that were limiting for other species.

Plant tissue sample collection

At the end of the trial period, all plant material from each soil plot was removed, washed, desiccated and weighed. Samples of leaf, stem and root tissue were taken for each species in each plot.

Sample Preparation and Analysis

Soil cadmium concentrations were analysed using Inductively Coupled Plasma Mass Spectrometry (IC-PMS). Samples were prepared according to the methodologies described below.

Soil samples were digested for exchangeable cadmium using the $NaNO_3$ extraction method described under Swiss legislation and by Meers, Samson *et al.* (VSBo 1986; Meers, Samson *et al.* 2007).

Extraction of total cadmium in soils

Total cadmium was extracted through total digestion of soil samples as described by Temminghoff & Houba in 2004. 15mL Teflon beakers were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3. 3 mL of sample was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. Following this, the beakers were cleaned with 3mL concentrated HNO_3 and 1mL concentrated HF and left sealed on a 120°C hotplate for 36 hours. The beakers were then triple rinsed with milli-Q water and dried.

Each sample was individually homogenised and approximately 130mg of each soil sample was placed in the 15mL Teflon containers and weighed. 4mL of concentrated HNO_3 was added to the Teflon containers and then left on a 120°C hotplate for 24 hours unsealed. This process was repeated and then 50 drops of concentrated HF and 30 drops of concentrated HNO_3 was added and sealed and placed on a 120°C hotplate for 36 hours. Two additional treatments with concentrated HNO_3 were performed to ensure that all organic compounds were chemically degraded. The product was then dissolved in 5mL of 5% HNO_3 and then weighed. 1mL was then extracted and diluted with 3mL of 5%HNO_3.

Extraction of exchangeable cadmium in soils

15mL Teflon beakers and 10mL c-tubes were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3. 3mL of sample was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. The beakers and tubes were then triple rinsed with milli-Q water and dried in preparation for extraction of bioavailable cadmium.

Each sample was individually homogenised and approximately 1g of soil sample was measured into the cleaned 15mL reaction tubes, and weighed on a calibrated Sartorius CP225D balance. 5mL of 0.1M $NaNO_3$ extractant was pipetted into each reaction tube and the total masses of the extractant and the soil were weighed. The soil extractant mixture was initially agitated to ensure full contact between the extractant and soil. The reaction tubes were then placed on a mixing plate to maintain full exposure of the soil to the extractant. After 2 hours on the mixing plate, the reaction tubes were placed in a centrifuge for 6 minutes at 3500rpm to settle out suspended particles.

5 mL of 5% HNO_3 was pipetted into the cleaned 10mL c-tubes, weighed and 300μL of sample were added to each tube from the centrifuged reaction tubes and weighed. This product constituted the material to be analysed by the ICP-MS.

This standard procedure was employed for each of the 18 soil samples and 3 cadmium deposit samples. For error testing, five samples were made up to three times the volume of the other samples to provide sufficient quantities for multiple analyses and data consistency checks. This applied to five samples: four soils and one cadmium deposit.

Additionally, 1ppb and 2ppb standards were made up from a 10ppb standard of toxic metals for calibration of ICP-MS output data. These standards were made to greater volumes than the samples and with volumes of 5% HNO_3 and 0.1M $NaNO_3$ in equivalent proportions to that of the samples to ensure that the viscosity of the standards would be equivalent to that of the samples. This was done to ensure consistency of analysis in the ICP-MS as fluid viscosity affects the rate of delivery to the nebuliser of prepared samples.

Inductively Coupled Plasma Mass Spectrometry analysis

Exchangeable fractions of soil cadmium in solution were then determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). ICP-MS uses inductively coupled plasma to ionise samples that are then recorded by a mass spectrometer. This method allows for highly precise measurements of elemental concentrations (Hokura, Matsuura *et al.* 2000). Samples in solution are nebulised into plasma which ionises the elements contained therein. The ions are then passed through a system of electromagnets and are directed to detectors which register the characteristics of individual ions.

Samples were delivered to the ICP-MS nebuliser for 60 seconds followed by milli-Q water for 30 seconds; a 5% HNO_3 wash for 90 seconds; then 60 seconds of a 1% HNO_3 wash, before the next sample was analysed. 1 ppb standards were used at the start, end and at frequent intervals throughout the analyses. 2ppb standards were used as secondary standards within the analysis to test the standardisation process. Additionally, multiple analyses of some samples and "blank" tubes were performed to ensure that both the sample preparation and ICP-MS analysis were accurate and effective.

RESULTS

The results of the analysis of cadmium concentrations in experimental soils, and biomass productivity are as follows.

Soil cadmium

Measurements of total and exchangeable soil cadmium were statistically analysed to determine differences in cadmium concentration between soil types

Total cadmium

The soils differed in total cadmium concentrations ($p=0.001$, $F=16.257$, (3, 12 df), $R^2=0.859$, adj. $R^2=0.806$). Figure 2.3 illustrates the grouping of soils according to concentration of total cadmium. The dolomite gravel has the lowest concentration; Topsoil and Black soil together form an intermediate group; Buada soil has the greatest concentration of total cadmium.

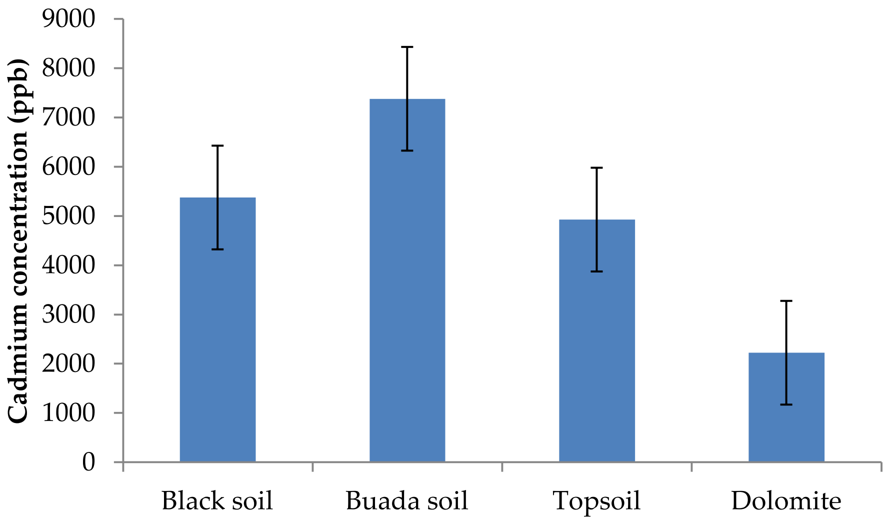

Figure 2.3 – Total cadmium concentrations in Nauruan soils

Exchangeable fraction

Soils differed significantly in concentration of exchangeable cadmium ($p<0.001$, $F=64.509$, (3, 20 df), $R^2=0.924$, adj. $R^2=0.909$). Soil exchangeable cadmium differed significantly between soil types (Fig. 3.4). Black soil, Topsoil and Buada soils contain equal concentrations of exchangeable cadmium but significantly higher concentration than dolomite.

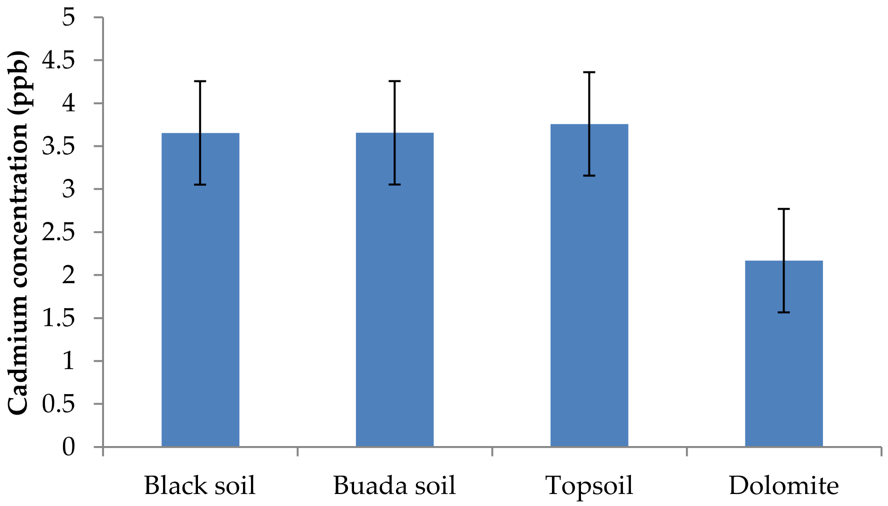

Figure 2.4 – Concentrations of exchangeable cadmium in Nauruan soils

Biomass productivity

Measurements of produced biomass were statistically analysed to determine which, of a range of predictive factors, were significant.

Biomass by Total Cd

Biomass production was found to not be significantly determined by total soil cadmium ($p=0.546$, $F=0.366$ (1, 181 df.), $R^2=0.262$, adj. $R^2=0.156$).

Biomass by exchangeable Cd

Biomass production was found to be significantly determined by exchangeable soil cadmium ($p=0.031$, $F=4.766$ (1, 176 df.), $R^2=0.377$, adj. $R^2=0.288$). The β value for exchangeable soil cadmium was found to be -0.043, $\sigma=0.020$, indicating that as exchangeable soil cadmium increases by 1ppb, biomass production is reduced by 0.043g per m^2.

Total biomass per m^2 by soil type

This analysis assessed the differences between soil types, according to the total mass of plant material produced per m^2, comparing between plots. Soil type is a significant determiner of total m^2 biomass productivity ($p=0.002$, $F=9.410$ (3, 16 df.), $R^2=0.702$, adj. $R^2=0.627$). Topsoil has the greatest productivity and variability, followed by Black soil, then Buada soil and Dolomite (Fig. 2.5).

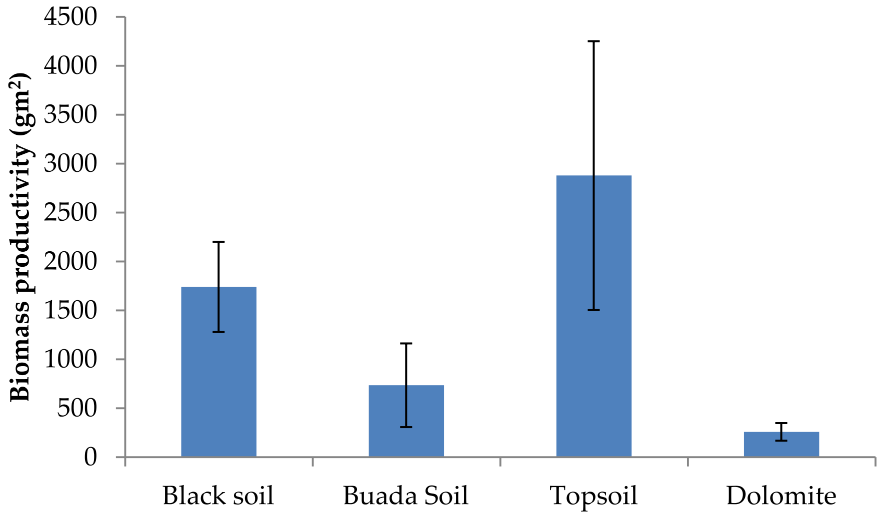

Figure 2.5 – Productivity by soil type – Total m² productivity

Mean Biomass per m² by Soil type

This analysis assessed the difference between soil types, according to the mean mass of plant material per m², comparing between plots. Soil type is a significant determiner of biomass productivity ($p<0.001$, $F=13.493$ (1,88 df.), $R^2=0.892$, adj. $R^2=0.785$). Topsoil has the greatest productivity, followed by Black soil, then Buada soil and Dolomite (Fig. 2.6).

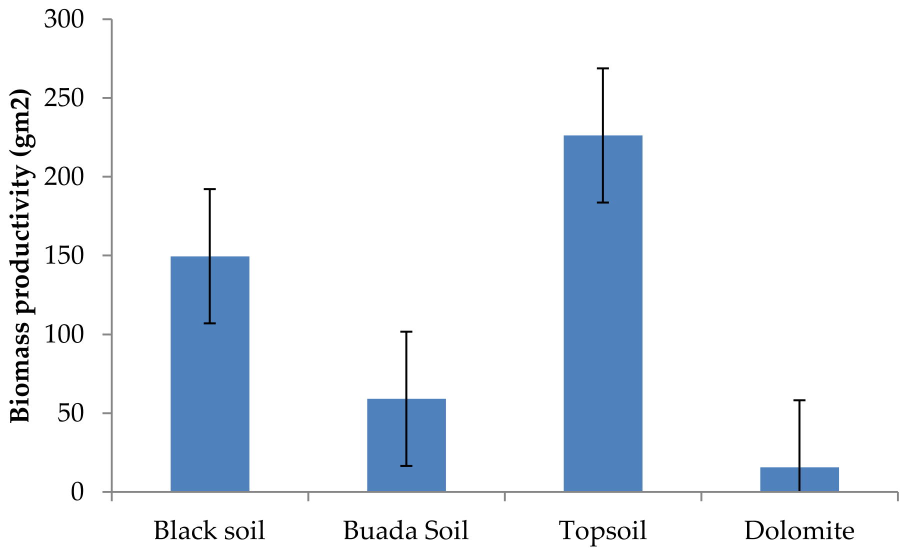

Figure 2.6 – Mean Productivity by soil type

Biomass by species

Species was a significant determinant of biomass production ($p<0.001$, $F=4.161$ (10, 176 df.), $R^2=0.377$, adj. $R^2=0.288$). *Cajanus cajan* and *Calopogonium mucunoides* produce the highest biomass followed by *Leucaena leucocephala*, and then *Indigofera hirsuta*. The remaining species averaged relatively low levels of biomass production (Fig.2.7).

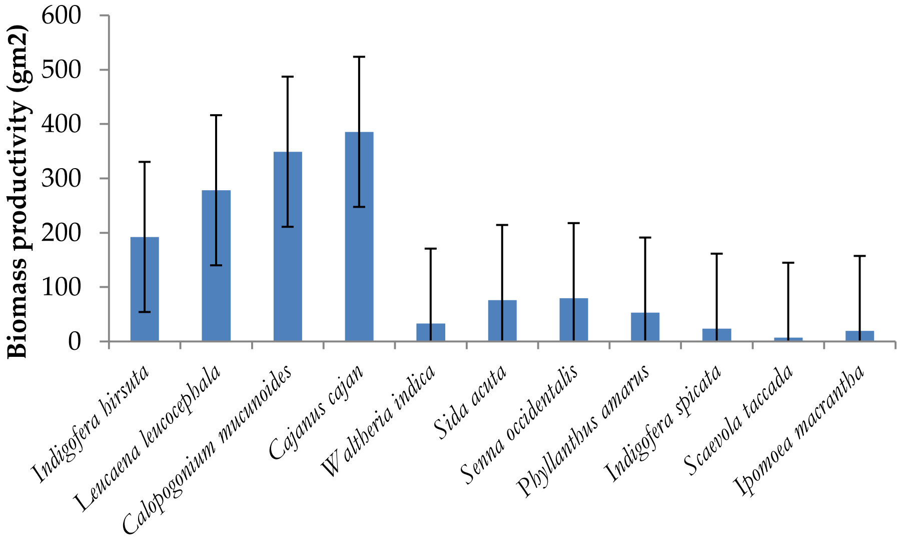

Figure 2.7 – Mean biomass productivity per species

Mean biomass production as affected by use of mulch

Mulch was a significant determinant of biomass production ($p=0.013$, $F=6.307$ (1, 176 df.), $R^2=0.377$, adj. $R^2=0.288$). Use of mulch produced 330gm^{-2} of biomass, by comparison with 120gm^{-2} produced for plots that lacked mulch (Fig.2.8).

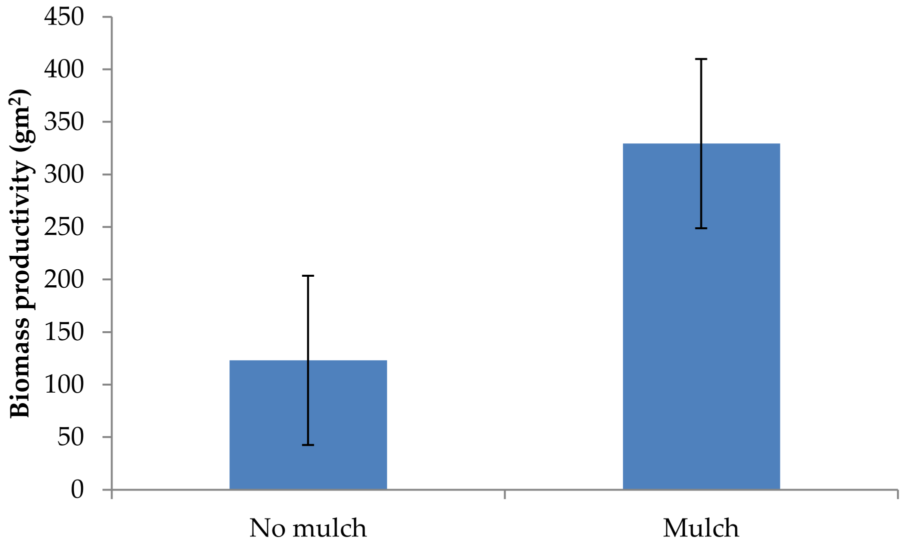

Figure 2.8 – Mean productivity with and without mulch

Biomass productivity of specific soil types

Due to significant variation in species and biomass production between soil types, the significance of species and mulch were statistically tested for specific soil types.

Black soil biomass productivity per species

Species was a significant determinant of biomass production in Black soil ($p<0.001$, $F=5.757$ (8, 27 df.), $R^2=0.630$, adj. $R^2=0.521$), however mulch use did not produce a significant effect ($p=0.682$, $F=0.171$ (1, 34 df.), $R^2=0.005$, adj. $R^2=-0.024$).

In the Black soil, *Calopogonium mucunoides* was most productive, followed by *Cajanus cajan*. *Indigofera hirsuta* had relatively low levels of production, while the remaining species produced negligible biomass (Fig. 2.9).

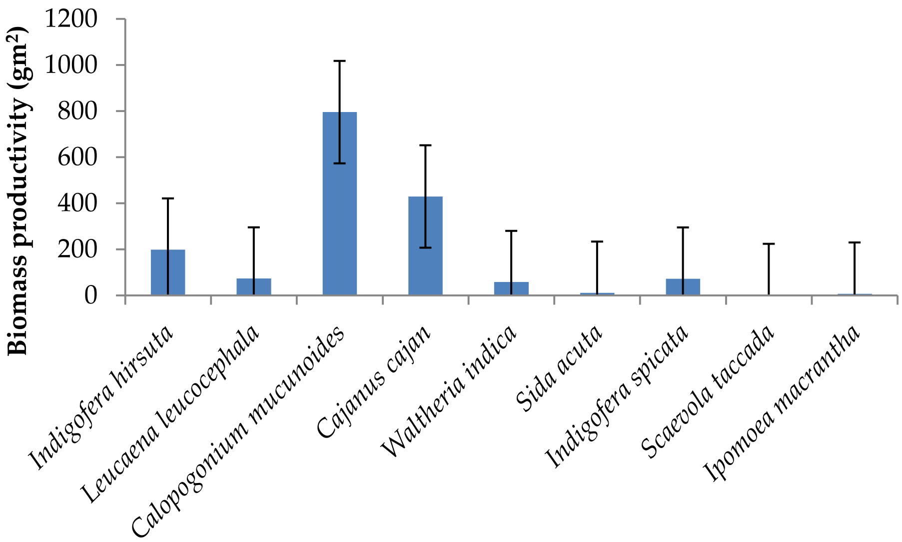

Figure 2.9 – Mean Black soil biomass productivity per species

Topsoil biomass productivity per species

Species was not a significant determinant of biomass production in Topsoil at the 5% level, but was at the 10% level (p=0.077, F=2.147 (7, 24 df.), R^2=0.385, adj. R^2=0.206), and mulch use did not produce a significant effect (p=0.164, F=2.038 (1, 30 df.), R^2=0.064, adj. R^2=0.032).

In the Topsoil, *Cajanus cajan* and *Leucaena leucocephala* produced the greatest biomass. *Senna occidentalis* and *Indigofera hirsuta* produced moderate to low levels of biomass, while the remainder were negligibly productive (Fig. 2.10).

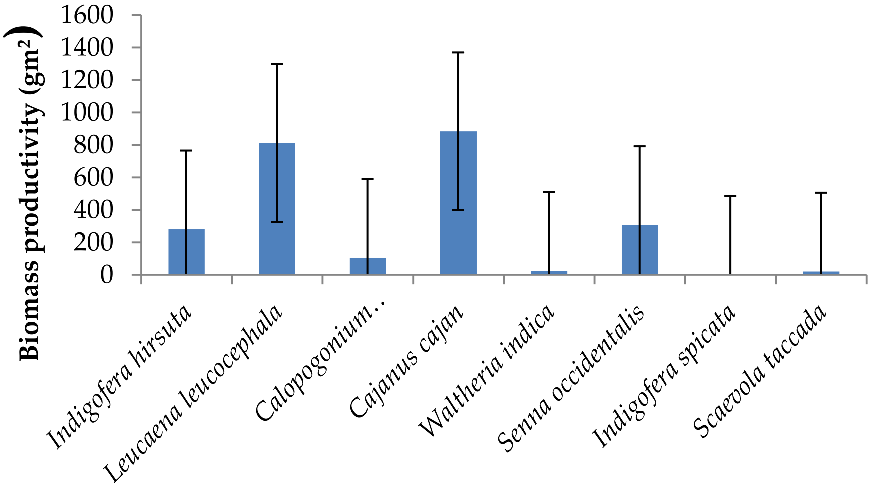

Figure 2.10 – Mean Topsoil biomass productivity per species

Buada soil productivity per species

Species was not a significant determinant of biomass production in Buada soil (p=0.705, F=0.594 (5, 18 df.), R^2=0.142, adj. R^2=-0.097), mulch use also did not produce a significant effect (p=0.187, F=1.858 (1, 22 df.), R^2=0.078, adj. R^2=0.036).

In the Buada soil only *Sida acuta* was significantly productive, and only to moderate to low levels (Fig. 2.11).

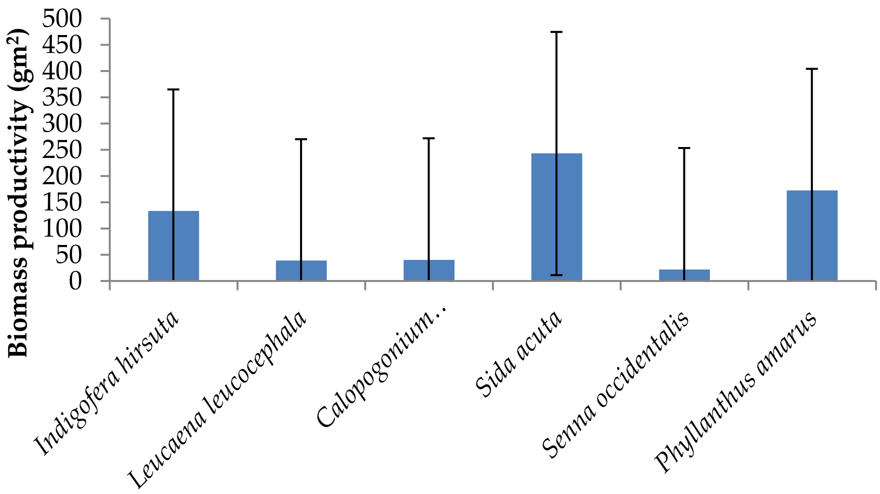

Figure 2.11 – Mean Buada soil biomass productivity per species

Dolomite biomass productivity per species

Species was not a significant determinant of biomass production in Dolomite at the 5% level but was at the 10% level ($p=0.057$, $F=2.917$ (4, 15 df.), $R^2=0.437$, adj. $R^2=0.287$), and mulch use did not produce a significant effect ($p=0.698$, $F=0.155$ (1, 20 df.), $R^2=0.009$, adj. $R^2=-0.047$).

Leucaena leucocephala was the most productive species in dolomite, however productivity was low for it and all other species (Fig. 12).

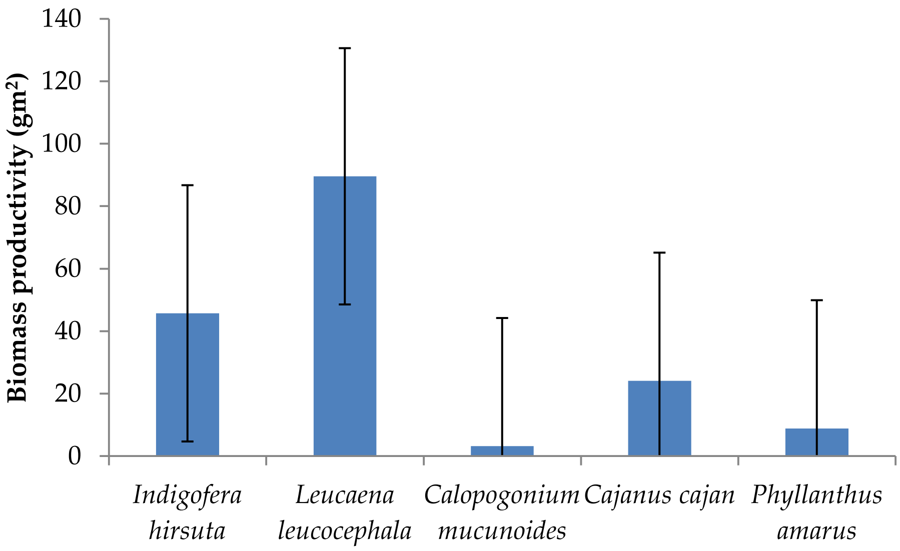

Figure 2.12 – Mean Dolomite biomass productivity per species

DISCUSSION

Research outcomes

Exchangeable soil cadmium was negatively correlated with biomass production. This suggests cadmium inhibits plant growth. As exchangeable soil cadmium increased by 1ppb, biomass production reduced by 0.043g per m^2 ($\sigma=0.020$) However, as there is low variation in exchangeable cadmium concentration between soils (~2ppm), the size of the effect is insignificant.

Soil type was a significant predictor of total and mean biomass production (Figs. 2.5, 2.6). Topsoil had the highest and most varied productivity, followed by Black soil, Buada soil, and then dolomite. Black soil productivity was 1,740±460gm^{-2} over a 6 month period. Assuming that this figure can be extrapolated this equates to productivity of 34.8±9.2 tonnes of biomass per hectare per year.

Biomass production differed significantly between species, with *Cajanus cajan* and *Calopogonium mucunoides* producing the highest biomass followed by *Leucaena leucocephala*, and then *Indigofera hirsuta*.

Biomass production increased with use of mulch. Mulch maintains soil moisture, increases SOM, protects soil from erosion, suppresses weeds and in doing so supports more robust communities of soil organisms any or all of which may have promoted biomass production. This effect was particularly pronounced for *Leucaena leucocephala* and *Cajanus cajan*, which were more than 10 times as productive when mulch was used. Use of mulch was not a significant factor with regard to biomass production when the soils were assessed separately. However, the sample sizes (two for each factor) were too low to provide certainty. It is more reasonable to accept the conclusions provided by the aggregated analysis in this case.

Species productivity varied considerably between soils. In Black soil *Calopogonium mucunoides* had the highest productivity, followed by *Cajanus cajan.* In Topsoil, *Cajanus cajan* and *Leucaena leucocephala* shared the highest productivity. Productivity in the Buada and Dolomite soils was generally low.

Research limitations

In determining the significance of the biomass results three factors must be taken into consideration. Firstly, the plots consisted of mixed species, and so the values reflect biomass production with competition and allelopathic effects. Secondly, each species was not found in every plot, as the plants grew from seed present in the soils. This seed distribution was unlikely to be homogenous, as reflected in the selection of species that grew in each of the soils. Thirdly, there were no controls on seed density or distribution, so stochastic effects are likely to have played a significant role. Accordingly, the results must be accepted as preliminary. This research does not fully explore the potential of each of these species in each of the soils.

Another factor not tested was the effects of different regimens of soil moisture and watering on biomass production. As freshwater is a very limited resource in Nauru, ensuring low water use in biomass production is of critical concern. It is recommended that this aspect of rehabilitation be examined.

Relevance to academic literature

Soil organic matter and its interactions with soil organisms underpin the ecological functions of soil fertility, maintenance of soil structure and biodegradation of wastes (Hopkins & Gregorich 2005). Over time, the accumulation of carbon in soils is a consequence of differing rates of production and decomposition and is associated with an increase in soil microbial biomass (Hopkins & Gregorich 2005). Soil organic matter also has a key role in determining the volume and distribution of moisture in the soil, a characteristic which significantly affects soil organism function (Young & Ritz 2005).

Pre-mining soil fertility in Nauru was high for a Pacific atoll, but nevertheless fertility was limited (Morrison & Manner 2005). The dominant process for soil formation and fertility in Nauru is the accumulation of organic material (Morrison & Manner 2005). Somewhat remarkably for a Pacific atoll, Nauru had mollisols (Morrison & Manner 2005). Mollisols have a very rich organic layer in their dark-coloured A horizon (Gardiner & Miller 2001). Mollisols are considered the most productive soils for agriculture due to their structure and high organic content (Gerrard 2000; Dubbin 2001). Mulch has been used effectively to increase soil fertility in the rehabilitation of phosphate mining areas (Best, Wallace *et al.* 1988).

Buada soil, with its high SOM is locally regarded as a good growth medium however, biomass productivity in Buada test soils was low. While this may have been due to seed source, both incidentally occurring seed and seed sown as part of this experiment produced a low yield in Buada soil. This suggests that the growing conditions inhibited growth more than competition from weed species.

Conclusion

Biomass production and integration into soils must be emphasised as an integral component of soil restoration in Nauru. Protecting soils with highly productive vegetation will be critical. This research has identified several species which may be used for the purposes of biomass production in the difficult growing conditions on Nauru. *Cajanus cajan* and *Calopogonium mucunoides* produced the highest biomass followed by *Leucaena leucocephala,* and then *Indigofera hirsuta*.

Biomass produced in the rehabilitation project could be used to produce mulch, thereby improving subsequent biomass production rates. An alternative may be the use of biomass as feedstock for biochar production to produce useful volatile gases and stable forms of carbon for soil rehabilition.

This research provides evidence that wood-chip mulch use has a significant impact on biomass production and that soil cadmium has a significant but minimal effect on biomass production. The fastest and most effective method for rehabilitating Nauruan soils will be to ensure that vegetation is managed to promote productivity. Regular crop thinning and mulching of the soil surface will increase soil organic matter, soil microbial life, and vegetative productivity.

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Chapter 3 - Cadmium phytoaccumulation in Nauru: A preliminary field trial

ABSTRACT

This paper reports the findings of a field trial experiment which assessed how locally grown plants could be used to bioaccumulate soil cadmium in Nauru. A range of species were grown in different soils, with and without mulch. Cadmium concentrations in root, stem and leaf tissues were assessed using ICP-MS. *Senna occidentalis* and *Indigofera hirsuta* accumulated the greatest concentration of cadmium (both around 200ppm) There was some evidence to suggest that cadmium was found in the greatest concentration in root tissues, followed by leaf tissues; and that the use of mulch had a positive effect on cadmium concentration in plant tissues, however limited data restricted the statistical power of the analysis.

INTRODUCTION

Healthy functional soil systems are essential for human wellbeing. Soil infertility and toxicity are two examples of threats to the health of this system Loss of soil fertility may lead to desertification in environments where biota are necessary to protect soils from environmental stresses. Soils containing toxic compounds pose health risks to humans and all organisms living on or near contaminated land. The severity of the risks are clearly illustrated in the Pacific Islands, where infertile or contaminated land can significantly exacerbate the shortage of available land (Gowdy & McDaniel 1999; van der Velde, Green *et al*. 2007). Few places demonstrate this situation more starkly than Nauru.

Nauru is a $21km^2$ raised limestone island 41km south of the equator at longitude 166° 56′ E in the Central Pacific (Fig. 1.1). It is surrounded by a fringing coral reef that sharply drops away 4,300m to the Pacific floor. "Bottomside" is the local name for the thin coastal plain surrounding the interior of the island, known as "Topside". Topside is a 1,620ha raised plateau that ranges from 20-60m in elevation, and is divided from Bottomside by a steep escarpment in most places. A brackish lagoon, called "Buada" is in a large interior depression, and is hydraulically connected with the Pacific (Hunter, Harris *et al.* 1994; Kingston, P.A. 2004) (See Appendices I & II).

Figure 3.1 – Map of Nauru's position in the Pacific

Mining of phosphate in Nauru has lead to various environmental effects, including deforestation, biodiversity loss, soil loss, liberation of toxic sub-soil cadmium deposits, soil degradation and desertification (Manner 1984; Morrison & Manner 2005). Nauru is facing various social, political, economic, and health issues which are considerably affected by soil degradation (Weeramantry 1992;

Fagence 1996; Gowdy & McDaniel 1999). Rehabilitation of mined lands in Nauru constitutes one of the five goals of the Nauru National Sustainable Development Strategy 2005-2025 (Nauru 2005). The 2009 review of the NSDS identified that objectives for the rehabilitation of mined land have thus far not been achieved according to its targets (Nauru 2009).

There are various reasons why NSDS targets have not been achieved:

- There is little knowledge of how to achieve specific goals in the ecological setting of Nauru.
- The amount of information which is potentially relevant to rehabilitation in this setting is vast.
- The scale and nature of the project is unlike any previous restoration project anywhere.
- Soil moisture is generally low, due to highly variable rainfall patterns, high rates of evaporation, and ready percolation through the porous underlying rock.
- Records of the historical ecology of Nauru, which could inform management decisions, are fragmentary (Morrison & Manner 2005).
- In Nauru there is a lack of human capital with experience and skills appropriate to landscape rehabilitation.

A range of goals for restoration were developed under the Nauru Australia Cooperation Rehabilitation and Development Feasibility Study 1994 (RDFS), many of which require the rehabilitation of soils for various land uses including housing, conservation, agroforestry/residential, sports/recreation/parks, an education complex, a public service complex, a cemetery, a municipal waste site, a hospital complex, and an industrial complex (Carstairs 1994; Hunter, Harris *et al.* 1994).

These land uses require soils, although they require them for different reasons and accordingly the properties required of the soils differ in relation to their intended purposes. Generally the soil purposes can be distinguished according to use as:

a) substrate, such as for hospital, education, public service and industrial complexes
b) growth media for food crops, as in the agroforestry/residential areas
c) growth media for vegetation cover for various purposes, as in the conservation, agroforestry/residential and sports/recreation/parks areas, as well as selected areas of the education, public service, hospital and industrial complexes and cemetery
d) media for containment and amelioration of biological hazards, as in the cemetery area and municipal waste site

(Baines 1994; Carstairs 1994).

Since 1970 mining operations have stockpiled soil for rehabilitation purposes (Baines 1994; Gowdy & McDaniel 1999). These soils have lost considerable amounts of material, organic content and biota while stockpiled, leaving the soils relatively infertile. Additionally, cadmium liberated through mining operations has contaminated the stockpiled soils limiting their value for rehabilitation.

Cadmium is classified as a toxic heavy metal. Contaminated areas are considered to be a threat to the well-being of humans and animals (Czeczot & Skrzycki, 2010). Cadmium affects the kidneys, liver, lungs, pancreas, skeleton and testis in humans due to disruptions of cellular adhesion, the immune system, the cellular antioxidant system, and cellular communication systems, inhibition of DNA repair and methylation, promotion of cell proliferation and apoptosis, and initiation of cell mutagenesis and carcinogenesis (Czeczot & Skrzycki, 2010; Dufresne *et al.*, 2010; Satarug *et al.*, 2010; Trzcinka-Ochocka *et al.*, 2010). Cadmium has been demonstrated to have a wide variety of deleterious effects in ecological systems, negatively affecting soil microbial community structure and activities, affecting growth and causing severe physiological disorders in plants and animals, disrupting renal, hepatic, and endocrine system function; skeletal development; and fat storage in animals (Angenard *et al.*, 2010; Ci *et al.*, 2010; Czeczot & Skrzycki, 2010; Dufresne *et al.*, 2010; Khan *et al.*, 2010; Kumar *et al.*, 2009; Lucia *et al.*, 2010; Planelló *et al.*, 2010; Van Campenhout *et al.*, 2010). Cadmium bioaccumulates in food webs amplifying the risk to organisms at higher trophic levels (Sato *et al.*, 2010; van den Brink *et al.*, 2010). Phytoextraction, the utilisation of plants to extract toxic compounds from soils, is a low technology method which may be used to reduce cadmium concentrations in contaminated soils. Cadmium is known to induce a range of severe physiological disorders in plants such as chlorophyll reduction, changes to phenols, oxidative stress and altered enzyme activity which ultimately retard plant growth (Maksymiec & Krupa 2006; Lin, Wang et al. 2007; Dell'Amico, Cavalca et al. 2008; Sun, Zhou et al. 2008; Ci, Jiang et al. 2009).

The quality and quantity of stockpiled soil is insufficient for restoration. Far greater volumes of soil will be needed to restore the mined areas. The issues of infertility and contamination will need to be resolved.

Increasing the organic carbon content of stockpiled soils is a viable method for increasing soil fertility and may provide additional benefits to soils including increased water retention properties, increased soil biota and thus increased biological activity, and a carbon sink with potential benefits for the country with regard to carbon accounting and accreditation.

An additional concern is the lack of soils sufficiently low in cadmium for safe food production. Phytoextraction, the utilisation of plants to extract toxic compounds from soils, is a low-technology method which may be used to achieve this outcome.

This paper describes the second of a two-part experimental field trial to assist in developing a successful soil restoration programme through biomass production and cadmium phytoaccumulation for Nauru. The first paper entitled "Biomass production in Nauru: A preliminary field trial" assesses the biomass production capability of various species in a range of Nauruan soils as well as the impact of the addition of biomass through a locally produced wood chip mulch upon plant productivity.

Concentrations of cadmium in soil and plant tissues were assayed to determine:

- What effect soil cadmium has on cadmium phytoaccumulation

- Whether any of a range of factors (use of mulch, tissue type, species, or soil type) had significant effects on cadmium phytoaccumulation.

Soil cadmium was measured for both total cadmium, and the free ionic fraction, using $NaNH_3$ solution as the extraction agent.

AIM

- To determine the cadmium phytoaccumulation potential of a range of green mulch species.

HYPOTHESES

- Plant species will accumulate differing concentrations of cadmium in their roots, stems and leaves
- Cadmium accumulation will be influenced by soil type and use of mulch.

METHOD

A selection of species were sown in a range of soils, watered and grown for a period of seven months to be assessed for their cadmium phytoaccumulation potential. Field plots were established in Nauru on the central plateau known as Topside.

Variables

Species

Five species were selected for their suitability for soil rehabilitation on Pacific tropical islands – drought tolerance, fast growth, appropriateness for use as green mulches, and seed availability, as determined by the Centre for Tropical Agriculture and Human Resources (CTAHR) at the University of Hawai'i (Smith & Valenzuela 2002; Valenzuela & Smith 2002a; Valenzuela & Smith 2002b).

The species used were:

- White oat - Avena sativa
- Black oat - *Avena strigosa* Schreb.
- Ryegrass - Lolium multiflorum
- Barley - Hordeum vulgare
- Hairy Vetch - Vicia villosa

Soil types

The soils used were

- Black soil
- Buada soil
- Topsoil
- Dolomite

Black soil

'Black soil' is the name given locally to soil from the soil stockpiles on Topside. Black soil is the remaining topsoil from across the central plateau, removed for phosphate mining access, and left stockpiled for several decades. This soil has lost significant amounts of organic material through stockpiling and exposure to the sun without substantial cover. Stockpiling also resulted in large anoxic areas within the piles which, along with desiccation and losses of soil organic matter, are likely to have reduced the populations of soil organisms within the soil. The soil used for this experiment was sourced from Stockpile A which has a greater variety of plant species growing on it than Stockpile B which is covered with a monoculture of *Leucaena leucocephala.*

Buada soil

'Buada soil' is soil from the Buada province of Nauru. Buada is a large depression containing a brackish lagoon and fairly fertile soils. Buada is protected from the hot salt laden winds that sweep across Nauru so the plants that grow there are less prone to desiccation. Buada soils are undisturbed compared with Black soil, and contain considerably higher volumes of organic material and soil organisms.

Topsoil

The 'Topsoil' is sourced from the Nauru Rehabilitation Corporation (NRC) nursery area in Topside which is located in an area that has operated as a sports oval and recreation area; the soil was part of the track and field area and was tended through use of fertiliser for many years. It was then used as the site of the Nauru detention centre for Australia, before becoming the site of the NRC nursery. This soil has been managed to some degree, having received applications of fertiliser and pesticides. The soil has been covered by pasture for many years, and is used preferentially in garden developments by the nursery staff.

Dolomite

The 'Dolomite' does not have all of the characteristics necessary to be accurately described as a soil. It is a mixed aggregate of fine to course material which has been mined containing a high proportion of rock phosphate. This material has been proposed as a medium for developing soil layers by the Nauru Rehabilitation Feasibility Study and other documents relating to landscape restoration on Nauru.

Mulch

Growing conditions on the Topside of Nauru are arid. Nauru experiences highly variable rainfall and large amounts of incident sunlight due to its location in the dry equatorial zone of the tropical Pacific Ocean. In these dry conditions, desiccation leads to increased plant mortality and reduced growth. Mulches can be used to protect soils from temperature fluctuation, to reduce soil moisture evaporation, and increase soil carbon content. Local production of wood-chip mulch from biomass was investigated within this experiment. Wood-chip was applied to a depth of 4-5cm on one of the two experimental beds. To ensure sufficient soil moisture, the beds were watered daily for the first month and then weekly unless rainfall meant that this was unnecessary.

Complications

The intention of the experiment was to test the viability of a range of selected species for phytoaccumulation in Nauru. Accordingly, a range of species of seeds were planted according to a randomised plan (Fig. 3.1). However, the resulting seedlings were unsuccessful as the adverse growing conditions found in the field in Nauru combined with the success of adventitious local seed from within the soils killed off the experimental species. This outcome posed significant issues for the original experimental design. However, though an unexpected outcome, this result revealed two factors important to the rehabilitation project; the significant challenges of the Nauruan growing environment, and the potential for using local flora which were evidently better suited for growth in adverse conditions. So we identified the species, measured their biomass production under the different treatments, and determined the cadmium levels in different parts of the plants.

Field trials

Field plots

The seeds of a range of species were sown in randomly assigned 33cm by 50cm plots within 1.66m by 2.0m plots of specific soil types. The larger plots were arranged into two beds; Bed A with mulch, Bed B without (Fig. 3.2). The beds were situated at the Nauru Rehabilitation Corporation nursery site, (See Appendices I & II).

Seeds were sown as per standard sowing densities for each species, as recommended by the seed producers. The seeds were monitored for germination success for 10 days. For the following six months research obligations outside of Nauru, meant the beds were left in the care of the nursery staff. Due to the lack of access to telecommunications equipment on Nauru at the time, it was not possible to contact the nursery staff during this absence. Nursery staff observed during this period that adventitious species were germinating in the soils, with the Topsoil plots showing the greatest amount.

Key:

1	White Oat		Topsoil
2	Black Oat		Black soil
3	Ryegrass		Dolomite
4	Barley		Buada soil
5	Hairy Vetch		

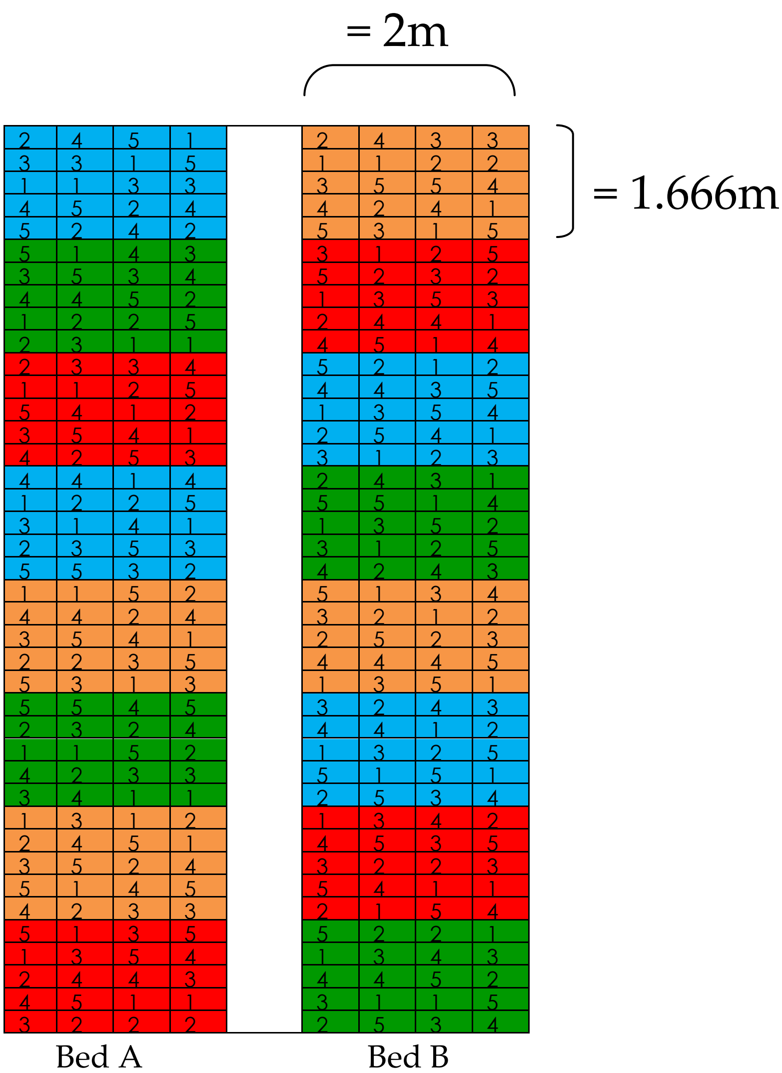

Figure 3.2 – Field trial plots

Preparation for sample collection

At the start of the third trip to Nauru, six months later in October 2008, it was found that weed species had overtopped and killed off the planted trial species. This posed several issues to the experimental design. The randomisation of planting was reduced, and it was now not possible to produce a full factorial model. Nevertheless, it was determined that the circumstances could still provide valuable data for the development of a process for cadmium phytoaccumulation. At this point, the soils contained a large amount of seed of local weedy species which successfully germinated and grew in the adverse conditions found in Topside, Nauru. Accordingly, the germination and seedling success of the weedy species provides evidence of their adaptive suitability to the conditions found on Topside. It was decided to identify and sample the species which had grown, to assess their suitability for phytoaccumulation (Table 3.1).

The species which were identified were:

Table 3.1 – Weed species found in soils

Sampled species	Black soil	Topsoil	Buada soil	Dolomite
Calopogonium mucunoides	X	X	X	X
Cajanus cajan	X	X		X
Leucaena leucocephala	X	X	X	X
Indigofera hirsuta	X	X	X	X
Senna occidentalis		X	X	
Sida acuta	X		X	

Indigofera spicata	X	X		
Waltheria indica	X	X		
Phylanthus amarus			X	X
Ipomoea macrantha	X			
Scaevola taccada	X	X		
Unsampled species				
Chamaesyce hirta			X	
Tridax procumbens				X
Stachytarpheta jamaicensis			X	

Of note was the presence of Pigeon Pea *Cajanus cajan* which is listed by the College for Tropical Agriculture and Human Resources, University of Hawai'i, Mānoa as a beneficial green manure for the Pacific (Valenzuela & Smith 2002c). It is possible that the species arrived with asylum seekers who were detained on Nauru. This species has a global production of around 40,000 km^2, and is cultivated for its protein rich seed, as a cover crop and companion plant, for fodder and for firewood (Almeida, Furtunato *et al.* 2010; da Silveira, Ribeiro da Cunha *et al.* 2010; Eltayeb, Ali *et al.* 2010; Linares, Scholberg *et al.* 2010; Thampan & Remany 2010). It is a perennial nitrogen fixing legume used for producing biomass. *Cajanus cajan* grew successfully in conditions found on Topside Nauru that were limiting for other species.

Plant tissue sample collection

At the end of the trial period, all plant material from each soil plot was removed, washed, desiccated and weighed. Samples of leaf, stem and root tissue were taken for each species in each plot.

Sample Preparation and Analysis

Soil and plant cadmium concentrations were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Samples were prepared according to the methodologies described below.

Soil samples were digested for exchangeable cadmium using the $NaNO_3$ extraction method described under Swiss legislation and by Meers, Samson *et al*. (VSBo 1986; Meers, Samson *et al*. 2007).

Extraction of total cadmium in soils

Total cadmium was extracted through total digestion of soil samples as described by Temminghoff & Houba in 2004. 15mL Teflon beakers were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3. 3 mL of sample was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. Following this, the beakers were cleaned with 3mL concentrated HNO_3 and 1mL concentrated HF and left sealed on a 120°C hotplate for 36 hours. The beakers were then triple rinsed with milli-Q water and dried.

Each sample was individually homogenised and approximately 130mg of each soil sample was placed in the 15mL Teflon containers and weighed. 4mL of concentrated HNO_3 was added to the Teflon containers and then left on a 120°C hotplate for 24 hours unsealed. This process was repeated and then 50 drops of concentrated HF and 30 drops of concentrated HNO_3 was added and sealed and placed on a 120°C hotplate for 36 hours. Two additional treatments with concentrated HNO_3 were performed to ensure that all organic compounds were chemically degraded. The product was then dissolved in 5mL of 5% HNO_3 and then weighed. 1mL was then extracted and diluted with 3mL of 5%HNO_3.

Extraction of exchangeable cadmium in soils

15mL Teflon beakers and 10mL c-tubes were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3. 3mL of sample was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. The beakers and tubes were then triple rinsed with milli-Q water and dried in preparation for extraction of bioavailable cadmium.

Each sample was individually homogenised and approximately 1g of soil sample was measured into the cleaned 15mL reaction tubes, and weighed on a calibrated Sartorius CP225D balance. 5mL of 0.1M $NaNO_3$ extractant was pipetted into each reaction tube and the total masses of the extractant and the soil were weighed. The soil extractant mixture was initially agitated to ensure full contact between the extractant and soil. The reaction tubes were then placed on a mixing plate to maintain full exposure of the soil to the extractant. After 2 hours on the mixing plate, the reaction tubes were placed in a centrifuge for 6 minutes at 3500rpm to settle out suspended particles.

5 mL of 5% HNO_3 was pipetted into the cleaned 10mL c-tubes, weighed and 300μL of sample were added to each tube from the centrifuged reaction tubes and weighed. This product constituted the material to be analysed by the ICP-MS.

This standard procedure was employed for each of the 18 soil samples and 3 cadmium deposit samples. For error testing, five samples were made up to three times the volume of the other samples to provide sufficient quantities for multiple analyses and data consistency checks. This applied to five samples: four soils and one cadmium deposit.

Additionally, 1ppb and 2ppb standards were made up from a 10ppb standard of toxic metals for calibration of ICP-MS output data. These standards were made to greater volumes than the samples and with volumes of 5% HNO_3 and 0.1M $NaNO_3$ in equivalent proportions to that of the samples to ensure that the viscosity of the standards would be equivalent to that of the samples. This was done to ensure consistency of analysis in the ICP-MS as fluid viscosity affects the rate of delivery to the nebuliser of prepared samples.

Samples of vegetation assessed for cadmium content

Due to time and financial limitations not all samples available for analysis were analysed. Representative samples were selected from those available so as to produce sufficient overlap for comparative analysis.

Vegetation samples were cleaned onsite and dried as per requirements of the New Zealand Department of Conservation (DoC) allocated importation licence. On arrival in New Zealand, where the laboratory analysis was performed, the samples were cleaned once more using milli-Q water and dried in a dehydrator for 2 hours at 40°C. For each measurement, approximately 200mg of dry plant tissue was measured into the cleaned 15mL Teflon beakers, and weighed on a calibrated Sartorius CP225D balance. 3mL of concentrated (6-7 mol) sub-boiled HNO_3 was then added to each beaker to digest the samples. The beakers were placed on a hotplate at 120°C without lids and monitored for the first 40 minutes to ensure that the reactions were not so volatile as to lead to cross-contamination. Once reaction rates had settled sufficiently, the samples were left to evaporate. 3 mL of 1 mol sub-boiled HNO_3 was then added to the digested residue and enclosed for a further period of digestion. The subsequent solution was transferred to cleaned c-tubes, weighed, and centrifuged at 6000rpm for 10 minutes to remove any sedimentitious contaminants from suspension. 1mL of solution was pipetted into cleaned c-tubes and weighed. 5mL of milli-Q water was added to dilute the solution and the final solution was again weighed.

Additionally, 1ppb and 2ppb standards were made up from SRM 1575 Pine Needle standard for toxic metals for calibration of ICP-MS output data (Hokura, Matsuura *et al.* 2000). The standards were processed in the same manner as the experimental samples.

Inductively Coupled Plasma Mass Spectrometry analysis

Exchangeable fractions of soil cadmium in solution were then determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). ICP-MS uses inductively coupled plasma to ionise samples that are then recorded by a mass spectrometer. This method allows for highly precise measurements of elemental concentrations (Hokura, Matsuura *et al.* 2000). Samples in solution are nebulised into plasma which ionises the elements contained therein. The ions are then passed through a system of electromagnets and are directed to detectors which register the characteristics of individual ions.

Samples were delivered to the ICP-MS nebuliser for 60 seconds followed by milli-Q water for 30 seconds; a 5% HNO_3 wash for 90 seconds; then 60 seconds of a 1% HNO_3 wash, before the next sample was analysed. 1 ppb standards were used at the start, end and at frequent intervals throughout the analyses. 2ppb standards were used as secondary standards within the analysis to test the standardisation process. Additionally, multiple analyses of some samples and “blank” tubes were performed to ensure that both the sample preparation and ICP-MS analysis were accurate and effective.

RESULTS

The results of the analysis of cadmium concentrations in Nauruan soils, and cadmium phytoaccumulation are presented.

Soil Cadmium

Measurements of total and exchangeable cadmium were statistically analysed to determine differences in cadmium concentrations between soil types

Total cadmium

The soils differed in total cadmium concentrations ($p=0.001$, $F=16.257$, (3, 12 df), $R^2=0.859$, adj. $R^2=0.806$). Figure 3.3 illustrates the grouping of soils according to concentration of total cadmium. The dolomite gravel has the lowest concentration; Topsoil and Buada soil together form an intermediate group; Black soil has the greatest concentration of total cadmium.

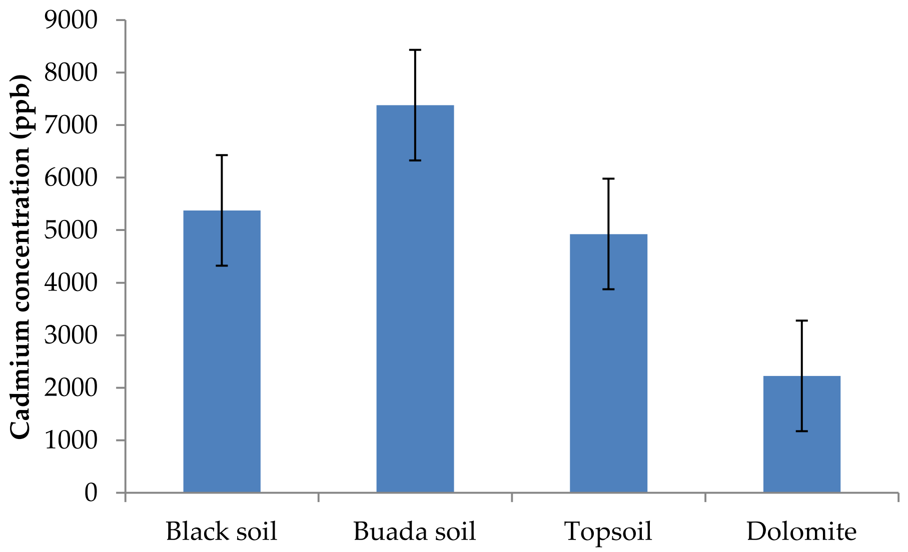

Figure 3.3 – Total cadmium concentrations in Nauruan soils

Exchangeable fraction

Soils differed significantly in concentration of exchangeable cadmium ($p<0.001$, $F=64.509$, (3, 20 df), $R^2=0.924$, adj. $R^2=0.909$). Soil exchangeable cadmium differed significantly between soil types (Fig. 3.4). Black soil, Topsoil and Buada soils contain equal concentrations of exchangeable cadmium but significantly higher concentration than the dolomite.

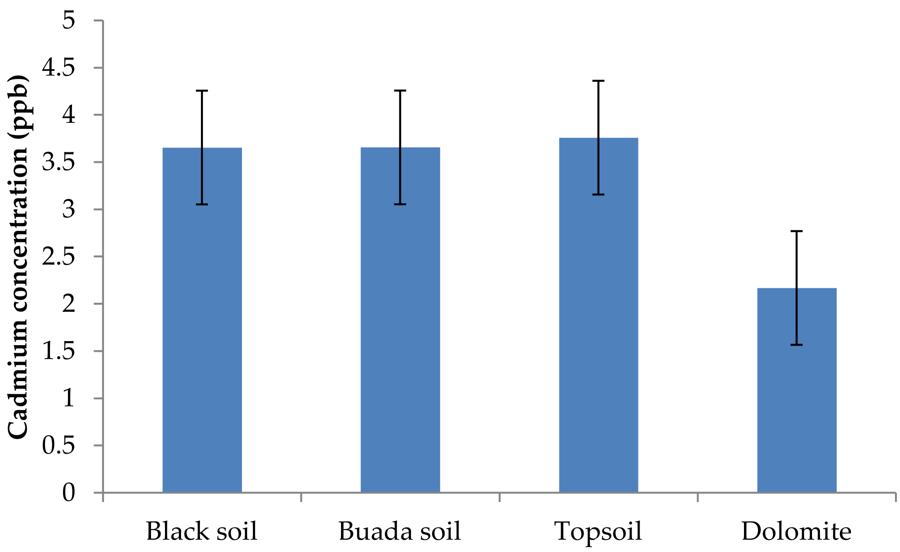

Figure 3.4 – Concentrations of exchangeable cadmium in Nauruan soils

Cadmium phytoaccumulation

Measurements of cadmium concentration in plant tissues were statistically analysed to determine which, of a range of predictive factors, were significant.

Phytoaccumulation by total and exchangeable cadmium

Two general univariate analyses were conducted, using alternatively, total soil cadmium concentration data, or exchangeable cadmium concentration of the acquired plant tissue data with post hoc Tukey and LSD analysis. This included species, mulch use, and tissue type as factors, with interactions between species and tissue type, and species and soil. Both soil total cadmium (p=0.955, F=0.005 (1, 1 df.), R^2=0.998, adj. R^2=0.919) and soil exchangeable cadmium (p= 0.957, F=0.005 (1, 1 df.), R^2=0.998, adj. R^2=0.911) were found to not be significant predictors of plant tissue cadmium concentrations.

Additionally, soil type was not a significant predictor of plant tissue cadmium concentrations (p=0.559, F=0.699 (3,33 df.), R^2=0.060, adj. R^2=-0.026).

Cadmium concentration by species

Species type did not significantly predict cadmium concentrations in plant tissues (p=0.154, F=5.769 (5, 2 df.), R^2=0.989, adj. R^2=0.794) (Fig.3.5).

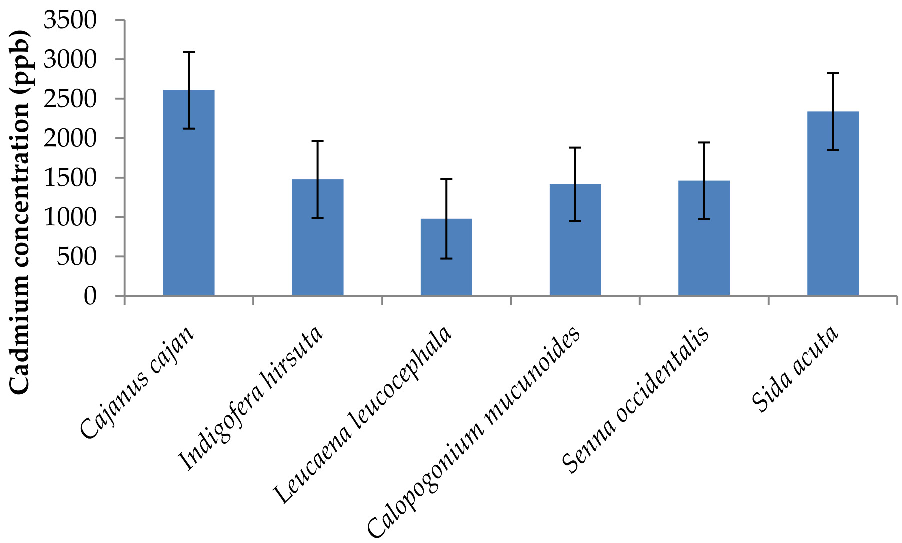

Figure 3.5 – Cadmium concentrations in tested plant species

Cadmium concentrations by tissue type

Tissue types did significantly differ with regard to cadmium concentrations (p=0.037, F=26.183 (2, 2 df.), R^2=0.989, adj. R^2=0.794) (Fig.3.6).

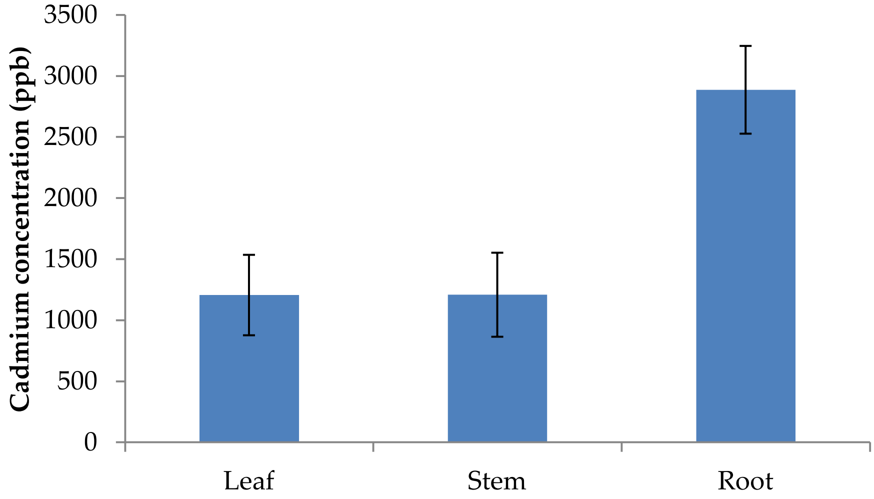

Figure 3.6 – Cadmium concentrations by tissue type

Cadmium concentrations by use of mulch

There was no significant difference in cadmium concentrations between plants grown with or without mulch (p=0.425, F=0.986 (1, 2 df.), R^2=0.989, adj. R^2=0.794) (Fig. 3.7).

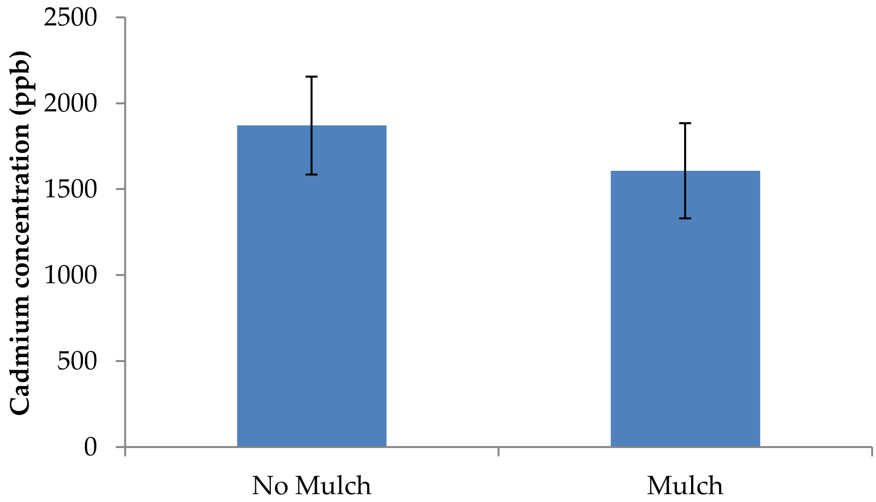

Figure 3.7 - Cadmium concentrations as determined by use of mulch

Plant cadmium accumulation by soil type

Plant cadmium concentrations by soil type was not significant ($p=0.334$, $F=1.190$ (3, 25 df.), $R^2=0.504$, adj. $R^2=0.286$) (Fig.3.8).

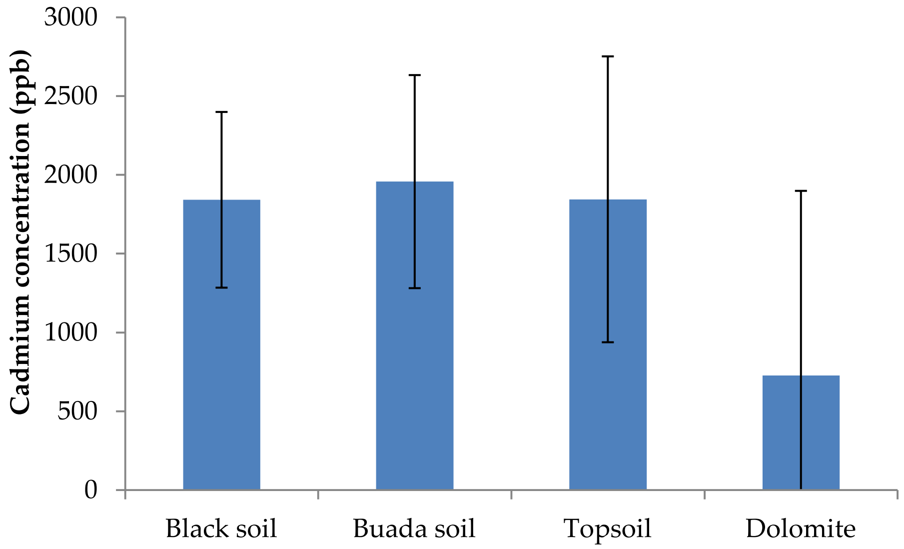

Figure 3.8 – Plant cadmium concentrations by soil type

Plant cadmium accumulation by species and tissue type

The interaction of species and tissue type was not significant ($p=0.221$, $F=3.900$ (10, 2 df.), $R^2=0.989$, adj. $R^2=0.794$) (Fig.3.9).

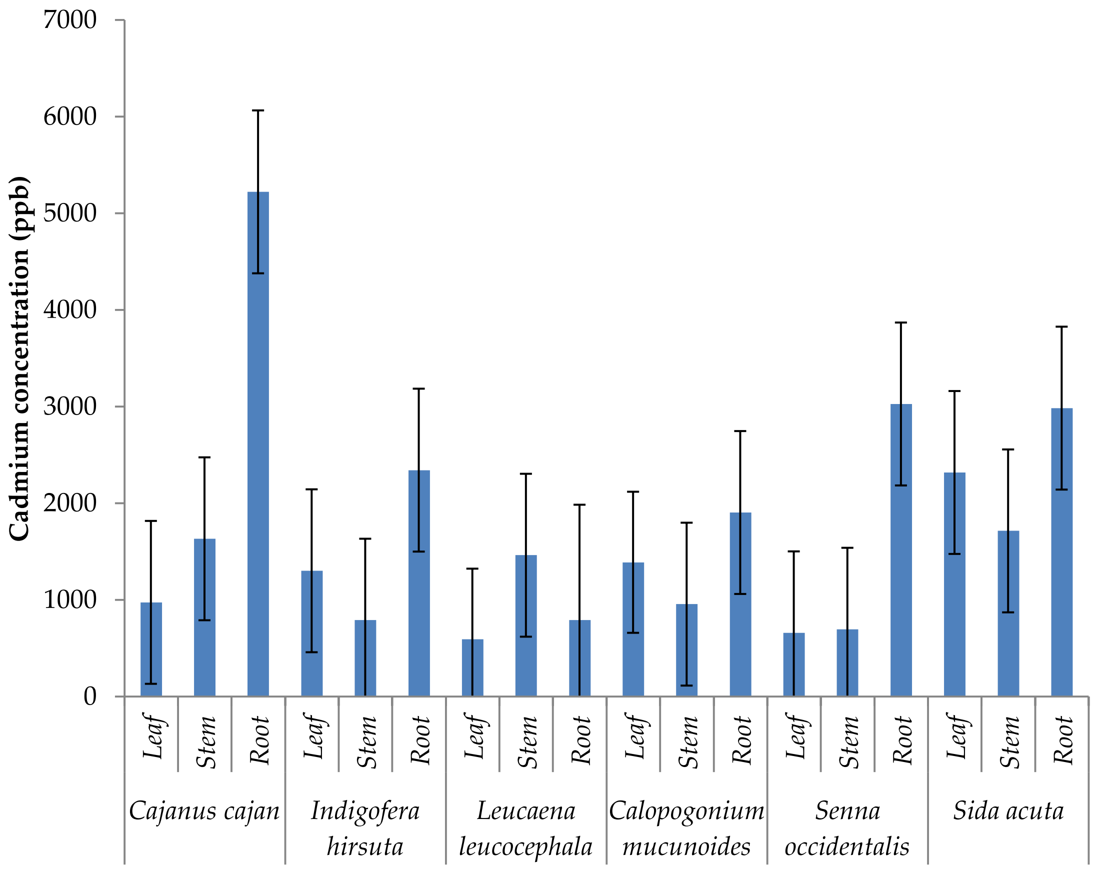

Figure 3.9 – Cadmium concentrations in tissues of plant species

DISCUSSION

Research outcomes

Soil types differed significantly in their total cadmium and exchangeable fractions. The exchangeable fraction of cadmium was typically around 3 orders of magnitude less than the concentration of total cadmium. The levels of exchangeable cadmium differed significantly across soil type – with the Buada soil, Topsoil and Black soil containing ~4ppb, and Dolomite ~2ppb.

Plant tissues accumulated concentrations of cadmium (1000-2500ppb) that were considerably greater than the concentration of exchangeable cadmium available in the soil (2-3.5 ppb). While we may expect bioaccumulation to account for some of this difference, it is also possible that the $NaNH_3$ extraction method does not sufficiently account for all of the exchangeable cadmium in the soils. The cadmium levels found in the plants are high (Figs. 3.5, 3.9), though not sufficiently so to be categorised as hyperaccumulators (>100ppm) (Kamel & Sakr 2009).

The concentration of cadmium in root tissues differed significantly from cadmium concentrations in stem and leaf tissues (Fig. 3.6). This is unsurprising as one of the effects of the Casparian bands is to limit the transportation of cadmium into above-ground plant parts (Yamaguchi, Mori, *et al.* 2009).

Research limitations

Due to time and financial constraints it was not possible to analyse a larger number of samples to increase the statistical power of the analysis. This is a significant issue with this analysis as insufficient data limited the outcomes of this analysis considerably.

A further limitation was caused by limited equipment in the field. This meant it was not possible to determine the weight of each of the plant parts (leaf, stem and root) for each species in each plot. Having done so would have allowed for an analysis of the total amount of cadmium extracted from the soils by the plant species.

The experimental design was not intended to accommodate the drastic changes which occurred due to the success of the "weed" species. Redesigning this experiment to assess the phytoaccumulative capacity of the weed species would allow a more robust evaluation of their potential.

$NaNH_3$ extraction assesses the most mobile chemical species of soil cadmium. Accordingly, it does not reflect the full extent of the exchangeable fraction of cadmium in the soil. An analysis to determine the chemical species in which cadmium occurs in Nauruan soils may assist in determining a more suitable chemical extractant.

Relevance to academic literature

The concentrations of total soil cadmium found in this report differ significantly from earlier analyses. Blake (1992) recorded stockpiled Black soil cadmium levels of between 214.9 and 353.4 ppm, and an NRC (1991) report provides estimates of between 93.8 and 95.3 ppm. These measurements are considerably more than was recorded in this report (~5.5ppm). The duration between measurements (12/13 years) may account for this variation. Table 3.3 presents a summary of Blake's measurements of cadmium in the Black soil stockpiles. What is unclear from both Blake's and the NRC analyses is the methodology employed to assess the cadmium load in the soils. While Blake describes the methods employed for sample collection and cadmium extraction, he omits the method of measurement. The NRC analysis merely states the recorded levels without any description of methodology.

Table 3.3 – Cadmium concentrations in stockpiled soils from Blake (1992)

Site	Cd (ppm)
1	214.9
1	243.8
1	263.5
1	299.3
1	282.9
2	326.3
2	307.7
2	353.4

Conclusion

While this research does not provide an exhaustive assessment of phytoaccumulation in Nauru, there are some research outcomes which may be of benefit for rehabilitation processes in Nauru. Firstly, the species assessed were successful colonisers of arid, infertile and cadmium enriched soils. Secondly, cadmium phytoaccumulation differed between plant parts. Thirdly, measured cadmium levels in stockpiled soils were dramatically lower than those found by Blake (1992) and in NRC (1991). This may indicate that there are methodological differences in cadmium assessment between researchers and/or changes in cadmium concentration through transportation away from the cadmium waste deposits.

In six months the experimental species grew in dense clusters up to ~2.4m in height, providing good protection to the soils beneath.

Given the success of these species, they may be useful in the rehabilitation process. They may be grown to achieve specific rehabilitation outcomes such as biomass production. Understanding the differences in cadmium concentrations between plant parts may be useful to determine how and where each of those tissues is best used post-harvest.

Due to the association of cadmium with phosphate in Nauru, the contemporary soil cadmium load is considered to be significantly higher than in pre-mining soils and represents a significant abiotic change to the Nauruan environment. Heightened soil cadmium levels may threaten the health of Nauru's flora and fauna, in particular, species currently in decline or with restricted distributions. Such effects, however, shall remain unresolved until comparative studies with non-contaminated soils are able to demonstrate or rule out such ecological effects.

Other areas for further research include;

- Assessment of biodegradable physicochemical agents such as chelating agents or micronutrients, to increase bioavailability and subsequent cadmium uptake in hyperaccumulator species
- Assessment of stimulated microbiological uptake of cadmium
- Assessment of the chemical species containing cadmium in Nauruan soils to provide further insight into the chemical dynamics of the soil system, and better predict the long term effects of phytoaccumulation on exchangeable cadmium.

It is likely that biochemical processes during phytoaccumulation alter the cadmium chemical species and consequently the degree to which cadmium is mobile in the soil system. Changes to cadmium mobility due to phytoaccumulation may influence soil rehabilitation management of accumulated biomass. Multi-generational studies of cadmium bearing chemical species may provide insight into how phytoaccumulation processes can lower concentrations of exchangeable cadmium through removal of phytoaccumulated cadmium and/or reduce the chemical mobility of the toxic element.

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Chapter 4 - Germination success in Nauruan soils: The effects of different cadmium bearing soils on selected species.

ABSTRACT

This paper assesses the effects of cadmium in native soils on the germination success of a selection of plant species which have been identified as having potential roles in soil rehabilitation in Nauru. The soils of Nauru have historically had relatively high levels of cadmium. Phosphate mining on the island has liberated substantial amounts of previously buried cadmium which has further increased the cadmium concentration in soils. Germination is a critical stage of plant development which may be affected by bioavailable cadmium in growth media. The seeds of ten species were planted in a selection of native soils, and native soils with altered cadmium levels, and then monitored for germination success. Germination varied between species and was also significantly affected by soil type but not cadmium concentration.

INTRODUCTION

The soils of Nauru contain relatively high levels of cadmium due to liberation of subterranean cadmium through phosphate mining (Blake 1992). It is useful to determine the ecological effects of soil cadmium in order to develop rehabilitation guidelines suited to the conditions found on Nauru. Germination is a critical stage in the life cycle of plants and thus in community assemblage (Fenner & Thompson 2005). This paper seeks to determine whether cadmium in Nauruan soils has effects on the germination success of various native and non-native species.

Studies have found widely varied effects of cadmium on germination success describing either increased germination success with increased levels of cadmium, the opposite, or no effect (XinHong, YuXiu & RunJin 2009; Zhang *et al.* 2010; Lefevre, 2009; Wang & Zheng, 2009; ZhiDe *et al.* 2009, Kumar *et al.* 2009; HuaBing, 2009; Farooqi *et al.* 2009).

Cadmium in soils can exist in a wide range of chemical forms. When used to refer to cadmium and other toxic metals found in soil the terms 'bioavailable', 'bioavailable fraction', 'phytoavailable' are inadequate as the complexity of dynamics between toxic metals, soil chemistry and species effects prevent us from defining a single figure which defines the mobile proportion of toxic material within the soil system (Meers, Unamuno *et al.* 2005; Meers, Samson *et al.* 2007). However, the terms are useful as they describe a concept of importance, namely that a proportion of the total amount of the toxic material is mobile in the soil system and it is this exchangeable fraction which is potentially problematic for plant life. Accordingly I have used a method of assessment of the exchangeable fraction of soil cadmium (hereafter referred to as Exchangeable Cadmium) which is used under Swiss legislation (VSBo 1986; Meers, Samson *et al.* 2007). This method uses 0.1M Sodium Nitrate as a leaching agent to extract Cadmium from prepared soil samples.

Currently the effects of soil cadmium on ecological processes in Nauru are unknown. Determining the effects of soil cadmium on seed germination may provide information of significant value to the land rehabilitation programme in Nauru.

The experimental design employed utilised locally available soils which are intended for use in the restoration of the Nauruan landscape. The soils used are listed below. They are listed according to the names which were most commonly used on the island by the Nauru Rehabilitation Corporation (NRC) Plant Nursery staff.

AIM

- To determine the effect of soil cadmium on germination success for a range of species in Nauruan soils.

HYPOTHESES

- Cadmium content in soils will have a negative effect on seed germination of species selected for their potential use in land rehabilitation.
- Soil type will influence germination success of species selected for their potential use in land rehabilitation.
-

METHODS

Seeds of a range of species were sown in a selection of soils in Nauru with either natural or increased cadmium levels and monitored for germination success.

Variables

Soil Types

- Black soil
- Topsoil
- Black soil with Dolomite rock mix.

Black soil

'Black soil' is the name given locally to soil from the soil stockpiles on Topside. Previous to mining this soil was spread across the landscape and was accumulated into the stockpiles as mining progressed. This soil has lost significant amounts of organic material through stockpiling and exposure to the sun without substantial cover. Stockpiling also resulted in large anoxic areas within the piles which, along with desiccation and losses of soil organic matter, are likely to have reduced the populations of soil organisms within the soil. The soil used for this experiment was sourced from Stockpile A which has a greater variety of plant species growing on it than Stockpile B which is covered with a monoculture *Leucaena leucocephala.*

Topsoil

The 'Topsoil' is sourced from the NRC nursery area Topside which is located on an area that has operated as a sports oval and recreation area; the soil was part of the track and field area and was tended through use of fertiliser for many years. It was then used as the site of the Nauru detention centre for Australia, before becoming the site of the NRC nursery. This soil has been managed to some degree, having received applications of fertiliser and pesticides. The soil has been covered by pasture for many years. This soil is used preferentially in garden developments by the nursery staff.

Black soil with Dolomite rock mix.

Due to insufficient volumes of stockpiled soil available for landscape rehabilitation, relatively fine dolomite rock aggregate, which is readily available from mine sites, has been proposed as a resource for bulking out the available soils, either as a substrate, or directly incorporated into the soil. This trial utilised a 50:50 blend of Black soil with Dolomite rock to determine whether the use of this material would affect germination success.

Species

Ten species of plants were selected for trial based on their availability and suitability according to various characteristics.

Species A through F were selected due to suitability for use as green mulch species. The species used come from a list of species identified as appropriate for use in Pacific islands by the College of Tropical Agriculture and Human Resources at the University of Hawai'i, Mānoa (Smith & Valenzuela 2002; Valenzuela & Smith 2002; Valenzuela & Smith 2002).

Species G through I were selected with guidance from nursery workers employed by NRC according to availability and growth characteristics, including success as ruderal species in the mined areas known as the Topside.

Species J was selected due to seed availability to nursery staff. The Japanese government had supplied large volumes of seed to Nauru to assist the land rehabilitation process. The seed had been stored on Nauru for a period of at least two years, and as such was not in ideal condition for assessment.

- A - Barley - *Hordeum vulgare*
- B - White Oat - *Avena sativa*
- C - Black Oat - *Avena strigosa* Schreb.
- D - Ryegrass - *Lolium multiflorum*
- E - Fiji Feathers Pea - *Pisum sativum*
- F - Hairy Vetch - *Vicia villosa*
- G - Wild Tamarind – *Leucaena leucocephala*
- H - Red Bean – *Adenanthera pavonina*
- I - Flame Tree - *Delonix regia*
- J - Millet - *Pennisetum glaucum*

Added Cadmium

Cadmium levels were manipulated by the addition of cadmium waste sourced from a cadmium dump site in Buada to produce two levels - natural cadmium concentration and raised cadmium. The cadmium waste is a distinctive, silty, blue-grey substance produced as a by-product of the phosphate manufacturing process. While the volumes of soil and cadmium waste used to prepare the cadmium enriched soils were estimated due to the variability of inputs and the lack of laboratory resources on Nauru, cadmium concentrations of the resulting soils were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Experimental Process

Soils and cadmium waste were collected from various locations around Nauru. Mixed soil and cadmium waste treatments were prepared. Soils were put into seed raising trays in preparation for seed. Scarification of the seed testa of *Delonix regia* was performed to improve germination success by cutting back the testa with a knife. Seeds of the selected species were sown in seedling trays in experimental soils to provide 15 repetitions of each treatment. They were watered twice daily, and monitored for germination success for a period of 30 days. Germination success was recorded.

Issues

Millet was excluded from the data as it was assumed to be non-viable as in all circumstances no seed germinated. The seed had been stored in the Nursery for at least two years prior to the experiment. Its history prior to this was unclear.

Sample Analysis

Soil cadmium concentrations were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Samples were prepared according to the methodologies described below.

Soil samples were digested for exchangeable cadmium using the $NaNO_3$ extraction method described under Swiss legislation and in various research papers (VSBo 1986; Meers, Samson et al. 2007).

Extraction of total cadmium in cadmium waste

Total cadmium was extracted through total digestion of cadmium waste samples as described by Temminghoff & Houba in 2004. 15mL Teflon beakers were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3. 3 mL of sample was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. Following this, the beakers were cleaned with 3mL concentrated HNO_3 and 1mL concentrated HF and left sealed on a 120°C hotplate for 36 hours. The beakers were then triple rinsed with milli-Q water and dried.

Each sample was individually homogenised and approximately 130mg of each cadmium sample was placed in the 15mL Teflon containers and weighed. 4mL of concentrated HNO_3 was added to the Teflon containers and then left on a 120°C hotplate for 24 hours unsealed. This process was repeated and then 50 drops of concentrated HF and 30 drops of concentrated HNO_3 was added and sealed and placed on a 120°C hotplate for 36 hours. Two additional treatments with concentrated HNO_3 were performed to ensure that all organic compounds were chemically degraded. The product was then dissolved in 5mL of 5% HNO_3 and then weighed. 1mL was then extracted and diluted with 3mL of 5%HNO_3.

Extraction of Exchangeable Cd in Soils

15mL Teflon beakers and 10mL c-tubes were cleaned by initial triple rinse with milli-Q water followed by soaking in 5% HNO_3 for a minimum of 2 weeks. The beakers were treated to additional cleaning using concentrated (6-7 mol) sub-boiled HNO_3, 3 mL of which was placed in the beakers which were then sealed and placed on a hot plate at 120°C for 48 hours. The HNO_3 was then removed from the beakers and the process was repeated a second time. After treatment with HNO_3 the samples were thoroughly rinsed with milli-Q water and treated with concentrated (6-7 mol) sub-boiled HCl in the same manner as used with the HNO_3 treatment. The beakers and tubes were then triple rinsed with milli-Q water and dried in preparation for extraction of bioavailable cadmium.

Approximately 1g of soil was measured into the cleaned 15mL reaction tubes, and weighed on a calibrated Sartorius CP225D balance. 5mL of 0.1M $NaNo_3$ extractant was pipetted into each reaction tube and the total masses of the extractant and the soil were weighed. The soil-extractant mixture was initially agitated to ensure full contact between the extractant and soil. The reaction tubes were then placed on a mixing plate to maintain full exposure of the soil to the extractant. After 2 hours on the mixing plate, the reaction tubes were placed in a centrifuge for 6 minutes at 3500 rpm to settle out suspended particles.

5 mL of 5% HNO_3 was pipetted into the cleaned 10mL c-tubes, weighed and 300µL of sample were added to each tube from the centrifuged reaction tubes and weighed. This product constituted the material to be analysed by the ICP-MS.

This standard procedure was employed for each of the 18 soil samples and 3 cadmium deposit samples. For error testing, a selection of samples was made up to three times the volume of the other samples to provide sufficient quantities for multiple analyses and data consistency checks. This applied to five samples: four soils and one cadmium deposit.

Additionally, 1ppb and 2ppb standards were made up from a 10ppb standard of toxic metals for calibration of ICP-MS output data. These standards were made to greater volumes than the samples but with volumes of 5% HNO_3 and 0.1M $NaNO_3$ in equivalent proportions to that of the samples to ensure that the viscosity of the standards would be equivalent to that of the samples. This was done to ensure consistency of analysis in the ICP-MS, as fluid viscosity affects the rate of delivery of the sample fluid through the nebuliser.

Inductively Coupled Plasma Mass Spectrometry analysis

Exchangeable fractions of soil Cd in solution were then determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). ICP-MS uses inductively coupled plasma to ionise samples that are then recorded by a mass spectrometer. This method allows for precise measurements of elemental concentrations (Hokura, Matsuura et al. 2000). Samples in solution are nebulised into plasma which ionises the elements contained therein. The ions are then passed through a system of electromagnets and are directed to detectors which register the characteristics of individual ions.

Samples were delivered to the ICP-MS nebuliser for 60 seconds followed by milli-Q water for 30 seconds; a 5% HNO_3 wash for 90 seconds; then 60 seconds of a 1% HNO_3 wash, before another sample was analysed. 1 ppb standards were used at the start, end and between every sample. 2ppb standards were used as secondary standards within the analysis to test the standardisation process. Additionally, multiple analyses of some samples and "blank" tubes were performed to ensure that both the sample preparation and ICP-MS analysis were accurate and effective.

RESULTS

The results of the analysis of cadmium concentrations in experimental soils, and germination success are presented.

Soil Cadmium

Measurements of total and exchangeable cadmium were statistically analysed to determine differences in cadmium concentration between soil types

Exchangeable Cadmium in Experimental Soils

The exchangeable fractions of cadmium in the soils differed significantly ($p=0.002$, $F=10.732$ (2, 12 d.f.), $R^2 = 0.956$, adj. $R^2 = 0.938$). The concentration of bioavailable Cd in each soil type is shown in Figure 4.1

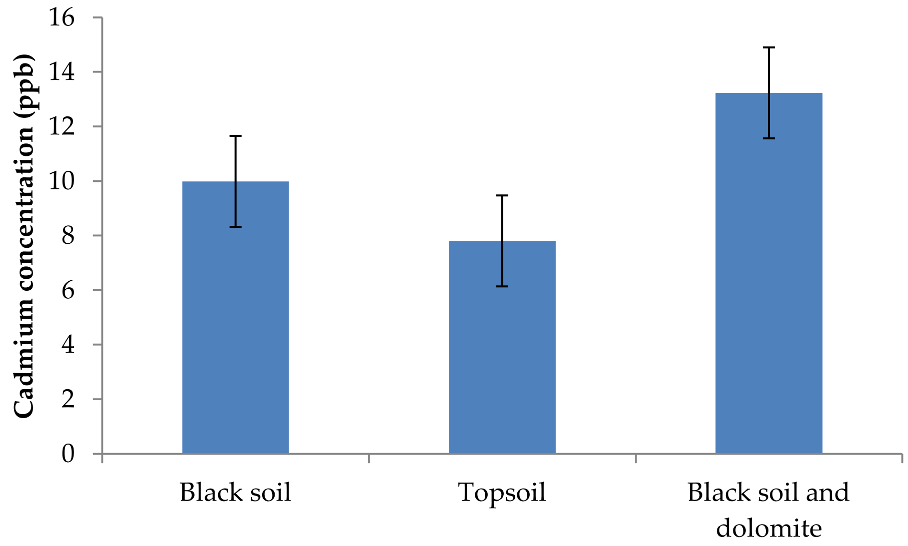

Figure 4.1 – Concentrations of exchangeable cadmium in soils

Soils with Cadmium Added

The addition of cadmium waste had a significant effect on the concentration of exchangeable cadmium in the soil ($p<0.001$, $F=214.599$ (1, 12 d.f.) $R^2 = 0.956$, adj. $R^2 = 0.938$). When averaged across soils, those with added cadmium contained nearly five times the amount of exchangeable cadmium (17.4 ± 1.4 ppb for soils with added cadmium, 3.3 ± 1.4 ppb for soils without) (Fig.4.2).

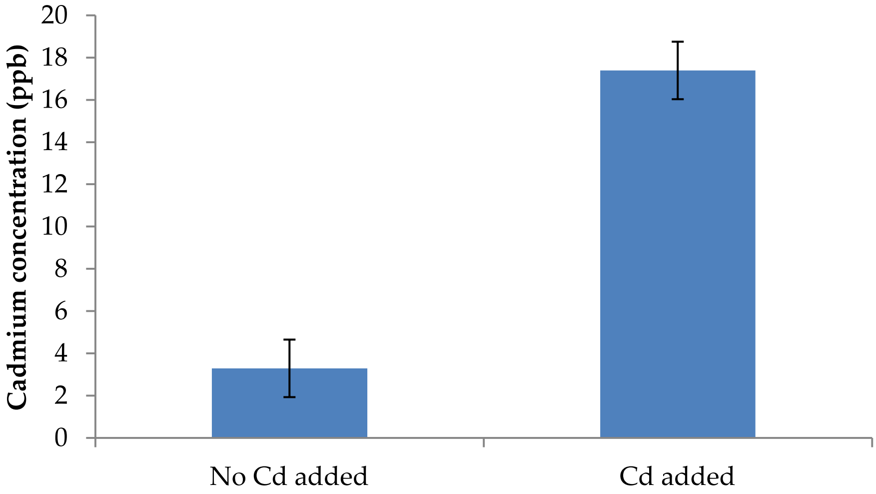

Figure 4.2 – Mean concentrations of exchangeable cadmium between samples with and without added cadmium.

Interaction between Soil Type and Added Cadmium

There was a significant interaction between the factors of soil type and cadmium addition ($p=0.001$, $F=13.398$ (2, 12 d.f.) $R^2 = 0.956$, adj. $R^2 = 0.938$) (Fig.4.3).

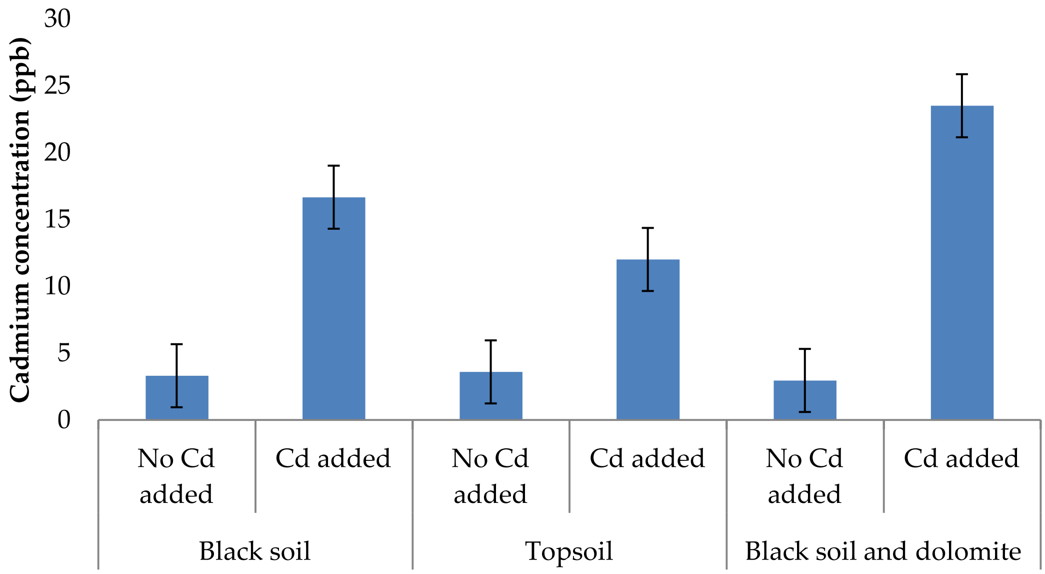

Figure 4.3 – Concentration of exchangeable cadmium in three soils with and without added cadmium. Error bars indicate two standard errors.

Analysis of Germination Success

A stepwise forward likelihood binary logistic regression was performed on the germination data. Soil cadmium concentration was not significant (p=0.458), so was excluded as a factor and replaced with categorical factors for soil and added cadmium. The categorical cadmium factor was not significant (p=0.719). Species (p<0.001) and soil type (p<0.001) were significant factors in determining germination success. Univariate analysis determined that germination success of the trial species differed significantly (Table 4.1). Topsoil had the highest germination success rate at 95%, as shown in Table 4.2. A test of the full model versus an intercept only model showed that species and soil type were statistically significant factors ($\chi^2(10, N = 900) = 347.27, p < 0.001$). The model was able to correctly classify 74% of seeds which failed to germinate and 86.5% of seeds which successfully germinated, for an overall success rate of 81.6%.

Table 4.1 – Germination success of experimental species

Species	Percent germination
Barley - *Hordeum vulgare*	93
Black Oat - *Avena strigosa Schreb.*	62
Flame Tree - *Delonix regia*	54
Fiji Feathers Pea - *Pisum sativum*	94
Red Bean - *Adenathera pavonina*	9
Ryegrass - *Lolium multiflorum*	98
Tamarind - *Leucaena leucocephala*	83
Vetch - *Vicia villosa*	46
White Oat - *Avena sativa*	95

Table 4.2 – Germination success in Soils

Soil type	Percent germination
Black soil with Dolomite	86
Black soil	89
Topsoil	95

Table 4.3 shows the logistic regression coefficient, Wald test, and significance for each of the predictors. Using a 0.05 criterion of significance, all soil types and six of the nine species types had significant effects. White Oat was the reference variable for species type. Black Oat, Flame Tree, Red Bean, Tamarind and Vetch were

all significantly different with respect to White Oat. Both Black Soil and Topsoil were significantly different with respect to Black Soil with Dolomite.

Table 4.3 – Logistic regression predicting decisions from Species and Soil Type

Predictor	*B*	Wald χ^2	*p*
Species			
Barley	-0.43	0.83	0.360
Black Oat	-2.47	35.00	<0.001
Flame Tree	-2.81	44.48	<0.001
Fiji Feathers Pea	-0.23	0.23	0.633
Red Bean	-5.23	78.89	<0.001
Ryegrass	0.88	1.99	0.158
Tamarind	-1.33	9.76	0.002
Vetch	-3.12	53.34	<0.001
Predictor	*B*	Wald χ^2	*p*
Soil			
Black soil	-1.14	22.89	<0.001
Topsoil	-0.86	13.25	<0.001
Constant	2.95	56.18	<0.001

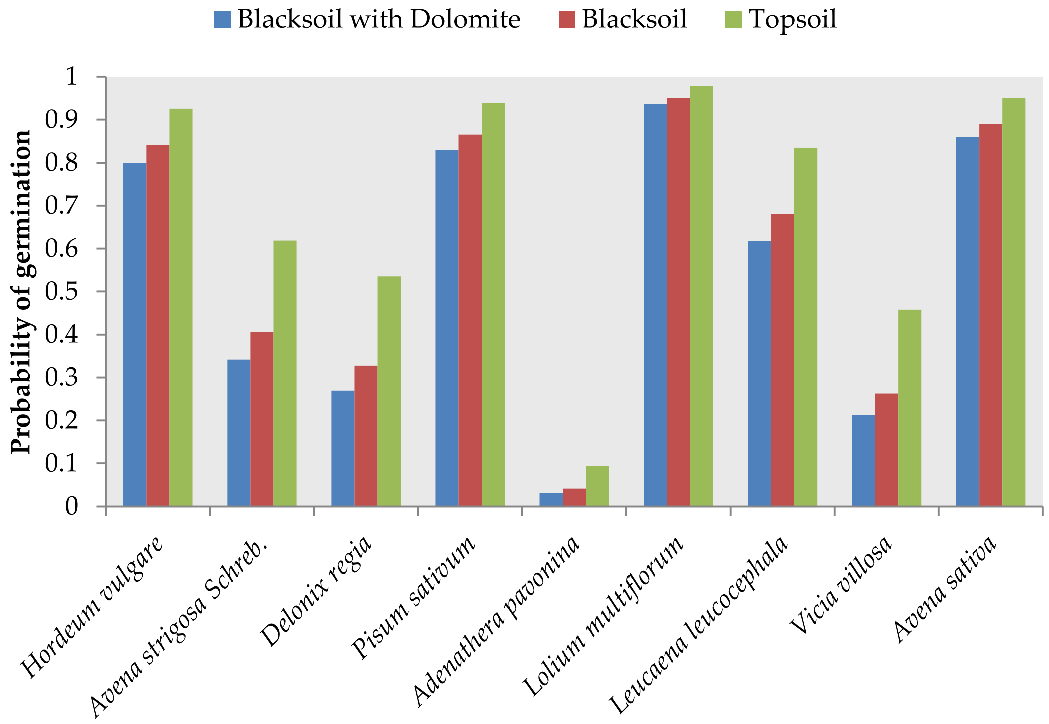

Figure 4.4 - Probability of germination success of seeds grown in three soils

Cadmium concentrations in cadmium waste

Measured values of cadmium concentrations in cadmium waste are listed in Table 4.4. Cadmium concentrations in the cadmium waste ranged from ~19 - ~21 ppm.

Table 4.4 – Cadmium concentration in Cadmium waste.

Sample	Cd concentration (ppb)
1	21360 ± 30
2	18880 ± 60
3	19420 ± 30

DISCUSSION

Research outcomes

The results of this report confirm that for the species tested, and with the treatments employed, cadmium concentration does not have a statistically significant effect on germination success. This finding was reinforced by the statistical insignificance of added cadmium on germination success.

Soil type was a significant factor affecting germination success, indicating that soil characteristics other than cadmium concentration play a role. Black soil, which is available for restoration in far greater quantities than Topsoil, showed significantly lower germination rates than Topsoil across all species and the addition of dolomite rock further reduced germination success (Table 4.2, Figure 4.4).

Species was a significant factor affecting germination success, which is to be expected as it is known that species have differing germination success rates (Bradbeer 1988; Fenner & Thompson 2005). The analysis showed that the order of rates of germination success from highest to lowest were – Ryegrass > White Oat > Fiji Feathers Pea > Barley > Tamarind > Black Oat > Flame Tree > Vetch > Red Bean (Table 4.1).

Research limitations

Time Constraints

Limits to time in the field as well as other financial and temporal restrictions, to some extent, restricted this research. The duration of the experiment was shorter than the germination periods of *Delonix* *regia* and *Adenathera pavonina* which is likely to have affected recorded rates of germination (Alam, Basak *et al.* 1996; Vozzo Unpubl.). We would expect to have higher rates of germination for these species if the experiment had run longer.

Sample analysis limitations

High operational costs, lengthy sample processing times and logistical constraints using ICP-MS reduced the data available for analysis, thereby limiting the robustness of the statistical analysis. Due to this, the total cadmium concentrations of the experimental soils were not measured nor the significance of their effects. It is tempting to assume, as the exchangeable fraction of cadmium did not significantly influence germination success, and the concentrations of total and exchangeable soil cadmium are likely to be proportionate across the experimental soils, that measures of total soil cadmium would also produce statistically insignificant results.

Species knowledge limitations

Knowledge of appropriate seed pre-treatment may have reduced germination times for *Leucaena leucocephala* and *Adenathera pavonina*, which may be improved by scarification; for example, immersion in very hot water for a short period of time, followed by soaking in cold water for an extended period. This information was not known by the NRC nursery staff and will be valuable if either of these species is used in the rehabilitation process.

Methodological limitations

It is possible that the method for measuring concentrations of exchangeable cadmium used may not accurately reflect the exchangeable fraction of the soils. As soil characteristics play a significant role in determining cadmium mobility, the measured exchangeable fraction may not reflect a proportion of the available soil cadmium which is consistent when relating between the different soils and may thus have produced a falsely negative significance for the effect of cadmium concentration on germination success.

Logistical constraints limited this experiment to 10 species. It cannot be concluded that the effects found for the tested species will hold true for all species of interest or value for Nauru. It may be worth assessing the influence of cadmium on germination success for other species relevant for rehabilitation and/or conservation.

Relevance to other studies

Researchers have found positive, negative and an absence of effects of cadmium on germination success (XinHong, YuXiu & RunJin 2009; Zhang *et al.*, 2010; Lefevre, 2009; Wang & Zheng, 2009; ZhiDe *et al.*, 2009, Kumar *et al.* 2009; HuaBing, 2009; Farooqi *et al.* 2009). This experiment found no significant effect of cadmium on germination success. In the context of the academic literature, this result indicates that the effects of cadmium on germination success vary depending on circumstances, or that stochastic effects are influencing experimental outcomes. It is known that cadmium does have effects on other aspects of plant growth and development (Maksymiec and Krupa 2006; Lin, Wang et al. 2007; Dell'Amico, Cavalca et al. 2008; Sun, Zhou et al. 2008; Ci, Jiang et al. 2009). In the associated paper assessing biomass production (Chapter 2), exchangeable cadmium had a significant but minimal negative impact on plant biomass production.

Cadmium waste

Levels of cadmium in cadmium waste deposits measured in 1992 by Blake ranged from 169.7ppm to 781.9ppm, down from original estimates of 2,000ppm when the cadmium waste was deposited in the cadmium slimes dam (Baines 1994). Measurements of cadmium concentrations in cadmium waste for this report were around 20ppm (Table 4.4). This may represent methodological differences in cadmium assessment and/or changes in cadmium concentration through transportation away from the cadmium waste deposits. If cadmium has been lost from the cadmium waste, its absence is of concern as it is unclear where the transported cadmium has gone. If cadmium has been transported away from the waste deposits it is likely that water has been the method of transportation. As overland flow is unlikely in Nauru, cadmium is likely to have moved down in the soil profile, possibly into the porous underlying rock, or even into the freshwater lens. It is recommended that there be ongoing monitoring of cadmium concentrations in cadmium waste and groundwater.

Impacts for restoration

Soil type had an effect on germination success for all species assessed. Topsoil had the highest rates, followed by Black soil, followed by the lowest rates in the Black soil Dolomite mix. It is evident that biophysical properties other than cadmium concentration are influencing germination success. Soil moisture retention may be playing a role. The experiments were conducted in the NRC nursery in a roofed, open walled structure affording no humidity control. The nursery is situated in the midst of the phosphate mine karrenfield. The location results in a nursery climate that is very hot and dry, elevating the potential for soil desiccation. A new enclosed plant nursery has recently been built which provides better control over the ambient conditions of cultivated plants. It may be of use to experiment with the different soils in the new nursery to determine whether the differences in germination success between soil types persist.

The differences in germination success between soil types are relevant to landscape rehabilitation in Nauru due to the relative availability of the soils and the current rehabilitation plan. The rehabilitation plan intends to use Black soil due to the volume available in soil stockpiles. The Black soil in the soil stockpiles will be used, along with dolomite gravels as media for developing soils on rehabilitation areas. The Nursery is currently using Topsoil as the preferred medium for raising seedlings from seed, largely due to the Topsoil available at the nursery site. Given the availability of the soil, and greater germination success, it is recommended that this practice is continued. Costs associated with raising seedlings in the nursery require that germination success be taken into consideration to ensure that the work is performed efficiently.

Black soil, with dolomite rock, is to be used in the rehabilitation areas. The reduced germination success of seed in the rehabilitation areas may not be of significant concern, given sufficient viable seed.

While the effect of cadmium on germination success was absent for the assessed species, this may not be the case for other ecologically significant species. There will be value in monitoring seed production and community composition to determine larger scale effects.

The dramatically lower measured concentrations of total cadmium in the cadmium waste in this study compared with Blake (1992) and Baines (1994) require reconciliation. It is recommended that additional, and ongoing assays of cadmium concentrations in the cadmium waste be performed to determine whether this study, Blake's, and/or Baines' present inaccurate measurements, whether methods of analysis of cadmium differed significantly between studies, and/or whether cadmium concentrations in the cadmium waste are dropping as rapidly as these studies suggest. If cadmium levels in the cadmium waste are dropping, as suggested by the measured data, determining the transport mechanisms and destinations of the cadmium is strongly recommended. To protect the health and safety of the people of Nauru it is necessary to ensure that vectors for exposure to dangerous levels of cadmium are understood and mitigated.

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Chapter 5 - Discussion

INTRODUCTION

This chapter is a summary of the results of the biomass, cadmium phytoaccumulation and germination experiments which were performed as part of this research. The implications of these results for the soil rehabilitation process are discussed within the conceptual frameworks of ecological restoration and adaptive management.

RESULTS

Seedbank

Nauruan soils contain seed. Some of the species of seed found in the soils were able to grow in the taxing conditions found on Topside. *Calopogonium mucunoides*, *Leucaena leucocephala,* and *Indigofera hirsuta* were successful in Black soil, Topsoil, Buada soil and dolomite. As none of these were among the five trial species, This indicates that the soils contained their seed, and that the soils were adequate to promote their germination and growth.

Biomass

Analysis of biomass production of a range of plant species in different Nauruan soils revealed that, in the conditions of the field trial:

- Soil types differed significantly in biomass productivity; Black soil and Topsoil were substantially more productive than Buada soil or dolomite
- Black soil productivity was 1,740±460gm^{-2} over a 6 month period. Assuming that this figure can be extrapolated this

equates to productivity of 34.8±9.2 tonnes of biomass per hectare per year.

- *Calopogonium mucunoides* and *Cajanus cajan* were the most productive species in Black soil
- *Cajanus cajan* and *Leucaena leucocephala* were the most productive species in Topsoil
- Use of woodchip mulch had a large positive effect on biomass production
- Exchangeable soil cadmium had a small negative effect on biomass productivity.

Cadmium

Analysis of cadmium phytoaccumulation by a range of plant species in different Nauruan soils revealed that, in the conditions of the field trial:

- Total cadmium concentrations in the tested soils differed significantly; Buada soils contained the highest concentrations at 4ppm, followed by Black soil and Topsoil with 2ppm, and the lowest concentrations were found in the dolomite at 1ppm
- Plant tissue concentrations of cadmium differed according to tissue type; concentrations of cadmium were highest in root tissues.

Germination

Analysis of germination success of seed from a range of plant species in different Nauruan soils revealed that, in the conditions of the germination trial:

- Exchangable soil cadmium levels did not determine germination success

- Soil type had a significant effect on germination success; Topsoil had the highest success rate, followed by Black soil. The lowest rates of success were for the Black soil dolomite mix
- Species was a significant factor determining germination success.

SIGNIFICANCE FOR SOIL REHABILITATION

Seedbank

The success of species which grew from seed in the experimental soils provides information which is valuable for rehabilitation planning. Firstly, there must be recognition of the soil seedbank; the soils cannot be regarded as being devoid of vegetation propagules. Secondly, within the seedbank are seed of species which can successfully germinate and develop into mature plants in rehabilitation conditions. Thirdly, judging from their germination and growth rates, the species present in the seedbank appear to be well adapted to the conditions found in Topside, Nauru. The best use of stockpiled soils requires a management approach that considers land use. The stockpiled soils should not be used for land uses where the presence of viable seed stock is problematic. Allowing the seed to germinate and systematically removing plants prior to seed set will be a suitable option in many cases. In soils that contain large amounts of undesired seed other management options may be more appropriate.

Calopogonium mucunoides, Leucaena leucocephala, and *Indigofera hirsuta* successfully germinated and grew in all four soils. Their success indicates their potential to be widespread pest species. However, it may also be the case that these coloniser species will establish environmental conditions which promote the successional establishment of a wider range of species, significantly benefiting rehabilitation. Accordingly, monitoring of developing vegetation patterns in rehabilitation areas should be conducted to determine to what extent these species may assist or hinder the rehabilitation process.

Biomass

There were significant differences in biomass production between soil types. Topsoil and Black soil were far more productive than either the Buada soil or dolomite. This is a positive outcome as the Black soil is to be used for land rehabilitation, and the Topsoil is used as a seed raising and potting medium for plants in the nursery. The low rates of biomass production in the Buada soil may be due to lower levels of seed in the soil, especially of species suited to growing on Topside. The use of woodchip mulch doubled biomass production. This provides some support for the idea that increasing soil organic matter will improve the fertility of Nauruan soils through the various mechanisms discussed in Chapter 1. Likewise, biomass produced in rehabilitation areas could be used for woodchip mulch production, to be returned to the site for subsequent accumulation of organic matter to provide further benefits for biomass production.

Black soil productivity was 1,740±460gm^{-2} over a 6 month period. Assuming that this figure can be extrapolated this equates to productivity of 34.8±9.2 tonnes of biomass per hectare per year. It is likely that, as soil fertility improves, biomass production will increase.

Calopogonium mucunoides and *Cajanus cajan* were the most productive species in Black soil. Both species are likely candidates for use in the rehabilitation area for increasing biomass available for mulch production to improve soil fertility. *Calopogonium mucunoides* is a twining or trailing short-lived perennial herb which grows in a dense mat up to 50cm thick. It is a valuable leguminous pioneer species, grown as a cover crop to reduce erosion and improve soil fertility. It will associate with a wide range of mycorrhizae in its rhizobia, and cowpea inoculants can be used where soils are sterile (Chen & Aminah 1992; Veasey *et al.* 1999). *Cajanus cajan* is a leguminous shrub that can grow to heights of 5m. It is hardy, widely adaptable and tolerant of drought and high temperatures. It produces peas which are used throughout the world for food, and is an important source of biomass for household fuel in many parts of the world (Sheldrake & Narayanan 1979; Willey *et al.* 1981; Sheldrake 1984). The growth forms of *Calopogonium mucunoides*, and *Cajanus cajan* are such that they may be complementary crops, with low levels of competition. In the trial plots they formed a robust vegetative cover for the soil. Given their success in the field trial, it is recommended that their use as colonisers in the rehabilitation project be assessed.

Cadmium

Buada soils contained the highest concentrations of cadmium. This may indicate that the soil poses a greater risk than either Black soil or Topsoil when used for agricultural purposes. Agriculture is currently practiced in the Buada area, in kitchen gardens and at the Taiwanese agricultural trial facility. It would be prudent to test for cadmium concentrations in agricultural products grown in Buada soil for comparison with equivalent products grown in other Nauruan soils to determine whether those agricultural products pose an unnecessary risk.

Measured variations in cadmium concentration in plant tissues allow us to make both general and specific statements. Generally, root tissues contain significantly higher concentrations of cadmium than above ground tissues. This can be understood as a consequence of the effect of the Casperian bands which significantly reduce cadmium transport out of the root system. More specifically, we can state that, within the context of comparison between the analysed species, the root tissues of *Cajanaus cajan* accumulate particularly high concentrations of cadmium; and that *Sida acuta* accumulates comparably high levels of cadmium in all tissues. These are important considerations when harvesting plant biomass where cadmium phytoaccumulation is an objective. It is likely that for soils intended for agriculture, increasing soil organic matter (SOM) and reducing the cadmium burden will be desired outcomes. Accordingly, as adding woodchip mulch is a relatively easy method for increasing SOM, selectively adding low cadmium biomass would be advised. For species containing relatively low concentrations of cadmium in leaf and stem tissues low cadmium biomass could be produced on soils containing significant levels of cadmium. Coppicing of suitable species may be a useful technique for harvesting biomass; however, due to the low levels of cadmium in leaf and stem tissue, it is unlikely that this technique will be useful for the phytoremediation of soils with the test species. Harvesting root tissues will be necessary for the phytoextraction of cadmium from soils to occur at a maximal rate. Harvesting the root tissue is a considerably more involved process than harvesting above ground tissues as it involves mechanical removal of root tissue from the soil medium. It cannot be expected that all root tissue will be removed and in doing so the structure of the soil will inevitably be disturbed. Due to this it is likely that efforts to phytoremediate cadmium by removing cadmium contaminated root tissue will be most effective in highly managed areas, for the purposes of generating a low cadmium soil for use in agricultural areas, rather than *in situ* phytoremediation.

Scheid *et al*. described how cadmium in leaf litter became relatively fixed in the leaf material of alder (*Alnus glutinosa*) and poplar (*Populus tremula*). Cadmium in leaf material was largely bound two years after leaf fall and thus was not returned to the soil (Scheid *et al.* 2009). This may also be the case for species grown in Nauru. If cadmium fixation in leaf litter does occur, we would expect that as a greater proportion of exchangeable cadmium is phytoaccumulated the dynamics of exchangeable cadmium will alter. While it is unlikely to be a priority at this stage in the rehabilitation process, assessing the degree to which cadmium is fixated in the tissues of species in Nauru may provide valuable insights into the future dynamics of cadmium in the Nauruan landscape, as affected by increasing proportions of organic material.

Germination

While soil cadmium had no effect on germination success, soil type did. Currently the nursery staff use Topsoil for raising seedlings as its presence in the nursery site makes it convenient to do so. Given that the highest rates of germination success were consistently found in the Topsoil, it makes sense for this practice to continue to ensure that the return on effort invested in seedlings is high. The reduced rates of germination success in Black soil may not be cause for concern assuming that, when used for land rehabilitation, the availability of seed in the rehabilitation areas is sufficiently high to ensure that recruitment rates allow for continued development of the vegetated ecosystems. In contrast to this, an overabundance of seed of some species may lead to them outcompeting other plants in such a way as to lead to low levels of plant biodiversity, as can be seen occurring with Red Bean in parts of the Buada district. Germination rates of Red Bean were very low at around nine per cent. The addition of dolomite to the Black soil resulted in reduced rates of germination for all experimental species. This result raises questions about the consequences of using dolomite gravel in the rehabilitation process. The mechanisms by which seed germination rates were affected by the trialled soil types are currently unclear. Possible mechanisms include soil pH and soil moisture. To ensure that germination success rates in the nursery can be optimised to produce large numbers of vigorous plants suitable for landscape restoration further experimentation and analysis is necessary.

Soil stockpiles

Of central importance to the rehabilitation programme are the soil stockpiles. Managing them in their current state so as to maximise their productive potential and limit the negative effects of stockpiling will pay significant dividends for subsequent land rehabilitation. Ideally, prior to use in rehabilitation areas, stockpiled Black soil will have been managed to increase organic content and microbial life to help ensure that the subsequently planted vegetation has a good chance of becoming established. Given the cyclical relationship between vegetation and soil, failure to quickly establish vegetation on Black soil in the rehabilitation areas is likely to result in further losses in soil fertility. It is recommended that a programme is established which attends to this concern as soon as possible, in order to ensure the availability of higher quality soils for rehabilitation and so provide a better chance of rehabilitation success.

Also of potential concern are the species present in the Black soil seedbank. Stockpile A is currently covered by a monoculture of *Leucaena leucocephala*. It is highly likely that the seed in the seedbank of stockpile A are almost exclusively wild tamarind seed. The field trial employed Black soil sourced from Stockpile B, which supports a wide range of species, as reflected in the species which successfully germinated and grew from the Black soil seedbank (Table 2.1). *Leucaena leucocephala* was one of the species which successfully germinated from the Black soil seedbank, and successfully developed into mature plants. *Leucaena leucocephala* was one of three species which successfully grew from the seedbanks of all four trialled soils. In all soils it was a high biomass producer. These factors indicate that it is well suited to the environmental conditions found in Topside. Given that *Leucaena leucocephala* has successfully established itself as a monoculture on Stockpile A, it is prudent to develop a plan for managing the species to ensure that it does not become a problem in the rehabilitation areas.

Leucaena leucocephala has a reputation in many other parts of the world for its uses in intercropped tree mulching systems. *Leucaena leucocephala* handles repeated prunings and regenerates vigorously, is deep rooted which reduces competition with other less deeply rooted plants, and produces large amounts of useful wood, has well balanced N composition in pruned biomass (Kang *et al.* 1981). Biannual lopping of seedless *Leucaena leucocephala* clones on Balinese coffee plantations resulted in nitrogen fertilisation of 30-80kg/ha (Brewbaker 1990). Cultivating seedless cloned *Leucaena leucocephala* may provide a method by which the species can be employed in rehabilitation efforts without the risk of it becoming a pest species.

Cadmium waste

The dramatically lower measured concentrations of total cadmium in the cadmium waste in this study compared with Blake (1992) and Baines (1994) require reconciliation (Table 5.1). It is recommended that additional, and ongoing assays of cadmium concentrations in the cadmium waste be performed to determine whether this study, Blake's, and/or Baines' present inaccurate measurements, whether methods of analysis of cadmium differed significantly between studies, and/or whether cadmium concentrations in the cadmium waste are dropping as rapidly as these studies suggest. If cadmium levels in the cadmium waste are dropping, as suggested by the measured data, determining the transport mechanisms and destinations of the cadmium is strongly recommended. To protect the health and safety of the people of Nauru it is necessary to ensure that vectors for exposure to dangerous levels of cadmium are understood and mitigated.

Table 5.1 – Comparison of measured concentrations of cadmium in cadmium waste

Study	Year	Cd conc. in Cd waste
Recorded in Baines (1994)	1990	~ 2000ppm
Blake	1992	169.7ppm – 781.9ppm
Current study	2008	18.9ppm – 21.4ppm

Ecological Restoration

Typically an ecological restoration project might involve one of the following

- restoring a highly degraded site such as a mine to ensure the return of vegetation
- improving the productive capabilities of soils for agriculture
- enhancing and protecting the conservation values of landscapes

The situation in Nauru involves all three, as well as complex social, historical, cultural, technical, aesthetic, economic, and political contexts (Hobbs & Norton 1996; Harris & van Diggelen 2006). It must be emphasised that the rehabilitation project is unlike any before attempted.

In the introduction to this thesis (Chapter 1) I posited that the goals of ecological restoration in Nauru might be – rehabilitating the mined landscape to a state which is safe for human habitation, increasing vegetative cover, increasing soil organic matter (SOM), the preservation and cultivation of culturally significant species, the preservation and cultivation of ecologically significant and endangered species, and the development of fertile soils for agriculture. This research provides a preliminary assessment of the relationship between soils and vegetation in the environmental conditions found in Topside, Nauru. Environmental cadmium was directly assessed and the general effects of the environmental conditions were assessed indirectly through measures of plant productivity and survival.

It is unclear what role environmental cadmium will have on ecological restoration. Germination rates were unaffected, and while cadmium did have a deleterious effect on plant productivity, the effect was very small. Assessments involving a larger range of species, specific life cycle stages such as seed set, and/or community effects, especially those involving trophic interactions, may reveal specific challenges posed by cadmium for the rehabilitation process.

This research has been limited to determining the impacts of specific environmental stressors which pose physiological challenges to the ecological restoration of rehabilitation land. A large number of ecological factors other than physiological challenges are relevant to the land rehabilitation process (Table 5.1). Attending to these factors will aid in ensuring the successful rehabilitation of Topside.

Generally, abiotic factors play a more significant role in the early phases of land restoration, while biotic factors become more pronounced as communities become established (Sänger & Jetschke 2004). In these circumstances we would expect ruderal and stress tolerant species to be successful as colonizers, although other studies have indicated that this is not always the case (Sänger & Jetschke 2004).

Table 5.2 lists a range of information targets which are valuable for ecological restoration. This report does not attempt to resolve the majority of these information targets and instead recognises that they are information ideals which may be resolved through the process of land rehabilitation in Nauru. This report emphasises aspects of the physiological challenges of land rehabilitation in Nauru, employing analytical research design. This report has touched on many of the other ecological restoration knowledge targets; however, they were not of central importance to this analysis. Part of the reasoning for the approach employed in this report is that the abiotic conditions found in Nauru are particularly severe and require initial attention. The relationship between soils and vegetation in the environmental conditions found in Nauru are assessed herein. Environmental cadmium is directly assessed and the general effects of the environmental conditions are assessed indirectly through measures of plant productivity and survival.

Table5.2 - Knowledge targets for ecological restoration (adapted from Palmer, Falk *et al*. 2006)

Propagule sources	• Locally adapted phenotypes • Bottlenecks and founder effects
Physiological challenges	• Stress tolerance • Physiological limits with regard to survival and reproduction • Site specific phenotypes

Community ecology	• Community composition • Trophic structure • Dispersal • Environmental filters • Disturbance regimes • Mutualisms
Ecological dynamics	• Resilience • Ecological thresholds • Linear and non-linear dynamics
Biodiversity and ecosystems	• Functional diversity • Redundancy
Invasive species	• Community invisibility • Alteration of ecosystem processes • Resistance and resilience • Competition • Disturbance theory
Research design	• Replication • Sample size • Statistical framework • Repeated measures through time
Climate	• Climate and relationship with vegetation • Natural variability

In order for the rehabilitation programme to benefit from ecological restoration principles it is recommended that rehabilitation management develop a clear understanding of how the knowledge targets proposed in Table 5.2 relate to the ecology of Nauru.

Adaptive Management

It is likely that even with comprehensive planning unexpected outcomes will occur. Rehabilitation management must be prepared to accept this, and contend with the information that such surprises provide. In accepting and preparing to contend with the inevitable uncertainty of how rehabilitation is to proceed, the NRC will enable itself to progress with land rehabilitation despite it.

Land rehabilitation in Nauru needs to progress to achieve Nauru's development goals. Progress may be measured in successful rehabilitation, but given the paucity of ecological information currently available to guide rehabilitation procedure a more valuable metric may be the acquisition of information about how to proceed. An adaptive management approach will allow for this progress to occur.

There is a need for explicit goals, a restoration design developed with an awareness of local ecology, ongoing monitoring to provide quantitative data of change and analysis of the results in order to adapt the design according to increasing knowledge of the ecology of the restoration landscape (Walters & Holling 1990; Gregory *et al.* 2006; Palmer *et al.* 2006).

In order to implement an adaptive management approach it will be necessary to ensure that there are stable institutions in place which will ensure that the program will persist long term. Particularly in the short term, there needs to be an understanding among high level managers that measures of success under an adaptive management framework should be found in acquisition of knowledge about restoration management based on hypothesis testing (Walters & Holling 1990; Gregory *et al.* 2006).

Two arenas exist in which adaptive management principles can be employed within the established rehabilitation framework, within the rehabilitation area and within the nursery supplying plants to the programme. The trial rehabilitation areas Pit 6 is an ideal setting in which to 'learn by doing'. It is part of the rehabilitation area, and the landscape has been resurfaced as per the rehabilitation plan. The current plan is to spread Black soil and plant a wide range of species cultivated in the nursery. Lists of species to be used in rehabilitation have been compiled, but there are no documents guiding the species composition of specific areas, planting densities and patterns, soil preparation, watering, or how planting will be temporally organised. The absence of these documents comes as no surprise given that there is so little known about how restoration should proceed. These knowledge gaps are all opportunities for the application of experimental assessment under an adaptive management framework. Other avenues for field trial experimentation include assessing the effects of different soil depths, use of different mulches, use of living ground covers, use of mycorrhizae, coppicing, pruning, and successional processes.

The other arena for adaptive management is the NRC nursery which provides a more laboratory like setting in which to explore aspects of the rehabilitation process which are relevant to the establishment of viable plant stock, and aspects of restoration requiring greater control over environmental conditions. The nursery conditions may be used to disentangle potentially relevant variables from environmental inconsistency, and test hypotheses which require more rigorously controlled conditions than are available in the field. Avenues for nursery based experimentation include variations in soil organic content, soil additives such as vermiculite, watering regimes, companion planting, mycorrhizal inoculations, seed treatments, and the effects of pruning on plant development.

Ideally, several management methods will be trialled at the same time within well defined land units. Management methods will need to be replicated several times in a randomised pattern to ensure the validity of statistical analysis. Establishing other trial areas employing the same, similar, contrasting, or different management approaches will allow for useful comparisons of management techniques between sites. The benefit of trialling the same group of management techniques in another area is that it increases the number of repetitions of any treatment to improve statistical power and stochastic difference can be better accounted for in the statistical model. An additional benefit may be the formation of an ecosystem chronosequence of rehabilitation areas, providing more information for comparison between rehabilitation areas as the ecosystems within them develop through time.

CONCLUDING REMARKS

Most restoration projects are not as complex as Topside, Nauru. There are a wide variety of uncertainties, and it is likely that there will be surprises. Accordingly, it is essential that the management of rehabilitation is prepared to learn and adapt. There is a need for experimentation with management techniques based on sound hypotheses, monitoring of the outcomes and adaptation of management to suit the developing knowledge of how rehabilitation management should proceed. The remainder of this section will introduce aspects of the restoration project which were not directly addressed in the body of this report but are relevant to its success.

Freshwater

The lack of availability of large amounts of fresh water in Nauru is likely to be one of the most limiting factors for land rehabilitation. Soil moisture deficits in the rehabilitation areas will restrict the diversity of species, and their growth rates. Field trials to determine optimum and minimum functional levels of soil moisture will help to determine the freshwater demands of the rehabilitation process. A management priority should be the collection and storage of rainfall to ensure that rehabilitation does not further reduce freshwater availability. Once vegetation is well established soils will be able to retain greater soil moisture, reducing the impact of drought conditions, and reducing the freshwater needs of the rehabilitation sites. An additional benefit of healthy soils will be the protection of the freshwater lenses beneath Nauru. Soils are valuable assets in protecting water quality, as they can be effective as repositories and biodegraders of toxins which might otherwise enter the freshwater lenses (Lal 2007). There are large water storage tanks on Nauru which are currently unused and have fallen into disrepair. It is recommended that the existing infrastructural assets be assessed to determine whether they could be used in a rainwater capture and storage system.

Community restoration

Nauru is not a large island. Human impacts are widespread and pervasive. For land rehabilitation on Nauru to be successful there is a need for strong Nauruan community dedicated to the sustainable management of Nauruan soils. Including community in mine rehabilitation may assist in this (Leigh 2005). Community based restoration can facilitate stronger relationships between land and culture by reconnecting communities with their landscapes, empowering citizens through participation, and promoting enduring awareness of the relationship between healthy environments and healthy communities (Harris & van Diggelen 2006). While it is uncertain how community based restoration may contribute to the rehabilitation effort, it is an avenue which may provide significant benefits and should be explored.

Tension between mining and rehabilitation

Mining in Nauru has resulted in extensive ecological degradation. The ethos which resulted in these losses cannot be expected to be appropriate for guiding the rehabilitation process. The Nauru Rehabilitation Corporation (NRC) has emerged from the Nauru Phosphate Corporation, utilising the same or similar staff, equipment, and management. This is to be expected due to convenience; however, there is the potential for management conflicts to emerge. A potential example of such a conflict is with the current status of mined lands. Currently, almost all mined lands are not classified as mined-out due to the significant volumes of phosphate remaining in the landscape post-mining. Global phosphate prices are trending upwards, making secondary mining increasingly attractive. Much of the mined land is thus in an interim state, neither mined-out nor un-mined. The current proposal is that land rehabilitation coincides with secondary phosphate mining, to generate revenue through phosphate exports and to mechanically resurface the landscape prior to soil deposition and planting. While secondary mining and rehabilitation will benefit from a combined effort, circumstances may rise where their interests do not perfectly coincide. In such a case compromises will need to be made. It is recommended that rehabilitation management policy contain provisions for deciding which objective is prioritised. The author of this report emphasises that to ensure that the rehabilitation of mined lands effectively progresses it will be necessary to ensure that the operational procedures of secondary phosphate mining do not supersede those of land rehabilitation.

Buada lagoon

Water quality in Buada lagoon is currently degraded due to feedbacks between high dissolved nutrients and algae. Eutrophication is a serious concern for the lagoon. The lagoon is a valuable resource, providing an environment which has traditionally been used for aquaculture. The lagoon is a potential source of nutrients for soil rehabilitation, both from aquatic plants and algae, and from dredged sediments. However, material removed from the lagoon may contain levels of cadmium contamination which are too high for use in areas where cadmium contamination is a concern.

Biochar

Biochar is a manufactured product which is used as a soils amendment to improve soil quality. It is produced from organic waste products by low-temperature pyrolysis which also produces volatile compounds such as bio-oil and synthesis gas which can be used as a source of energy. Biochar improves various properties of soils such as water retention, soil volume, microbial mass, soil structure, and nutrient retention.

Biochar is produced from waste organic material. This characteristic can be especially useful in circumstances where disposal of organic wastes such as animal manures and human body waste may be problematic due to risks of contaminating the environment with pathogens. The pyrolysis process destroys pathogens, producing a biochemically useful substance without contamination risks. Biochar can also be produced using cultivated organic material. By converting organic material into black carbon through the pyrolysis process, carbon is stabilised in a form which has greater longevity within the soil system than organic material normally would. A significant issue with fertility in Nauru soils are the impermanence of soil organics, the high temperatures and humidity result in relatively rapid loss of soil organics through microbial processes. Stabilising carbon in the soil system through the use of biochars may provide long-term benefits for the fertility of Nauruan soils.

Biochar is known to absorb toxic heavy metals, substantially reducing their availability in soils. This quality, along with the other soil benefits listed, suggests that biochar may be an ideal soil amendment material for Nauru if sufficient biomass feedstock can be sourced.

Composting toilets

Composting toilets, while lacking the energy production possibilities of a centralised sewerage system, have a number of advantages making them a practical solution for managing Nauru's human waste. Functioning composting toilets remove or destroy pathogens in human excrement and produce soil organism rich humus as an end product much. They can be built from local materials according to local needs; have negligible freshwater inputs by comparison with sewerage systems; lack the need for expensive reticulation systems, which is particularly beneficial in facilitating waste management in isolated locales; and greatly reduces the risk of soil and groundwater contamination due to structural failures in reticulated pipe and subsurface storage and treatment infrastructure (Del Porto & Steinfeld 2000). Added plant material is an essential input to maintain the high Carbon:Nitrogen ratio needed for proper functioning of composting toilets (Crennan 1996).

Human resources

A wide range of skills will be required for the rehabilitation programme in Nauru. It will be important to identify required and useful skills, recognise which of these skills are available in the NRC staff, and methods for acquiring those skills currently lacking. It is likely that many of the skills required can be attained for the rehabilitation project by supporting skills development in NRC staff. The Nauruan branch of the University of the South Pacific (USP) is available to NRC for skills development. A mutually supportive relationship based in open communication between NRC and USP will foster both organisations to achieve their goals.

RECOMMENDATIONS

- Black soil seedbank species
    - It will be necessary to categorise the species according to their desirability in rehabilitation areas.

    - It will be necessary to identify which species pose risks as invasive species and establish appropriate management techniques
        - eg. - *Calopogonium mucunoides, Leucaena leucocephala,* and *Indigofera hirsuta*
- Biomass production
    - *Calopogonium mucunoides* and *Cajanus cajan* are promising biomass production crops which can be used to colonise, cover, protect and improve Black soils.
    - Black soil productivity was determined to be 34.8±9.2 tonnes of biomass per hectare per year.
- Cadmium
    - Management of biomass production should recognise that *Sida acuta* biomass and root tissues of *Cajanus cajan* may contain significant concentrations of cadmium where grown in cadmium contaminated soils.
    - Ongoing monitoring of cadmium concentrations in cadmium waste dump sites should be performed to determine whether the dramatic losses of cadmium suggested in the literature accurately reflect changes in cadmium concentration. If significant amounts of cadmium are being lost from the cadmium waste, it will be important to identify where the cadmium is going to ensure that the people of Nauru are not unnecessarily exposed to excess cadmium.
    - Monitoring of cadmium concentrations in groundwater is advised.

- It is recommended that adaptive management principles be adopted to allow rehabilitation to progress in the face of considerable uncertainty.
    - Management will need to proceed by testing clearly specified hypotheses.
    - Management should expect that successful rehabilitation is very unlikely in the short term. Rehabilitation success should be measured in the acquisition of information relevant to rehabilitation knowledge targets.
- Stockpiles
    - The vegetation on the stockpiles should be managed to reduce weed numbers, and increase soil organic matter in preparation for use in rehabilitation areas.
- Ecological restoration
    - Rehabilitation management should proceed in a manner that achieves ecological information targets (listed in Table 5.2).

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