Developing water quality closure criteria for Ranger billabongs using macroinvertebrate community data

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Background

The approach to deriving water quality criteria from local biological response data outlined in the Australian and New Zealand Water Quality Guidelines (ANZECC & ARMCANZ 2000) is being applied to the derivation of water quality closure criteria for waterbodies such as Georgetown Billabong, located immediately adjacent to the minesite (see maps 2 & 3). Specifically, if the post-closure condition in Georgetown Billabong is to be consistent with similar undisturbed (reference) billabong environments of Kakadu, then the range of water quality data from the billabong over time that supports such an ecological condition in Georgetown Billabong (as measured by suitable surrogate biological indicators) may be used for this purpose.

For shallow lowland billabongs such as Georgetown Billabong, distinctive wet season and dry season water quality regimes can be recognised. This is a consequence of flushing of the billabongs during the wet season, followed by contraction in surface area and substantial evaporative concentration of solutes during the six months of the subsequent dry season. If water quality closure criteria were derived from the annual-average water quality record, then the resultant values would be too conservative for the dry season and too lenient for the wet season. For this reason, two sets of water quality criteria are required – one for the wet season and one for the dry season.

Macroinvertebrates have enhanced sensitivity to water quality generally so can provide a good basis for the setting of water quality criteria for the protection of aquatic ecosystems. Hence monitoring of macroinvertebrate communities through time is being used to provide the data needed to develop closure criteria for relevant water quality indicators in the local Ranger billabongs.

Macroinvertebrates collected from aquatic plants (ie macrophytes) that are usually abundant along the waterbody edges, predominantly represent animals exposed to the water column while those collected from the benthic habitat represent those organisms exposed to sediment. It is possible that while mine-derived contaminants in the water column may be transient, reflecting short-term (wet season) changes to water quality, contaminants may accumulate in the sediment over much longer time periods, and thus present a legacy well after water quality has improved. Thus, sediment-dwelling organisms could potentially have a longer duration contact and perhaps higher effective concentration exposure to contaminants than those inhabiting the water column.

Before closure criteria for water quality indicators can be derived for Georgetown Billabong, it is important to establish whether or not the macroinvertebrate communities from each of benthic and macrophyte habitat do indeed resemble those of reference waterbodies. For example, if this were not the case for benthic macroinvertebrates and these assemblages resembled those from mine-disturbed waterbodies, it could suggest that the ecological health of this billabong was already impaired and a different approach to setting of water quality objectives would be required.

Detailed sampling for macroinvertebrates in most of the Ranger and relevant reference waterbodies was conducted previously in 1995 and 1996 and provides the starting point for time series comparison. For the 1995 and 1996 surveys (O’Connor et al 1996, 1997 respectively), the macroinvertebrate communities of Georgetown Billabong resembled those of reference waterbodies in the Alligator Rivers Region (ARR). However, for these surveys the macrophyte and benthic samples at each location were combined prior to compiling sample statistics. Thus the data arising from the composited samples represents a habitat ‘averaged’ condition for the macroinvertebrate communities in these billabongs.

Given the changes that have occurred on the minesite since 1996 – in particular the increased wet season loads of solutes entering Georgetown Billabong – a contemporary survey was needed to determine if the macroinvertebrate communities in the billabong were still comparable to reference waterbodies in the region. This survey was conducted in May 2006.

Previous reporting

The 2006 billabong survey results were last reported by Humphrey et al (2008) when Georgetown Billabong macroinvertebrate communities from macrophyte and benthic habitats were compared with corresponding communities collected from other ARR waterbodies, both mine-exposed and reference. For the first time, the samples from the macrophyte and benthic zones were not combined, and were processed separately prior to analysis of the data. The key findings from Humphrey et al (2008) are summarised below:

Combined habitats

- Simulating the approach adopted in previous years (1995 and 1996) where benthic and macrophyte samples were composited before sample processing, the separate datasets for the two habitats sampled in 2006 were combined for analysis. The resulting multivariate ordination showed a separation of macroinvertebrate communities from waterbodies most influenced by minesite inputs (RP1 and Coonjimba Billabong) from communities of reference waterbodies and those with minimal mine site influence (including Georgetown Billabong). This result was similar to that observed in 1995 and 1996, ie the composite habitat dataset for Georgetown Billabong indicated that the billabong had not been significantly impacted by mine inputs.
- The mean total abundance and mean taxa number for the combined habitat did not vary markedly amongst the waterbodies.

Macrophyte habitat

- When the macrophyte habitat data were analysed separately, the same ordination pattern arose as was observed for the combined habitat ordination described above (ie no evidence of mine-related effects upon Georgetown Billabong).
- The mean total abundance and mean taxa number for the macrophyte habitat also did not vary markedly amongst the waterbodies.

Benthic habitat

- When the benthic habitat data were analysed separately, the communities from Georgetown Billabong clustered among those sampled from the benthic habitat from more impacted waterbodies, most notably Coonjimba Billabong.
- The mean total abundance and mean taxa number for Georgetown benthic communities were also among the lowest recorded from the waterbodies.

In summary, the data indicated that macroinvertebrate communities from macrophyte (or combined) habitat in Georgetown Billabong are unaffected by inputs of mine-derived solutes (by nature of their similarity to those from the same habitat in reference waterbodies). However, the benthic communities from this billabong are relatively impoverished and resemble those from waterbodies receiving higher concentrations of mine water solutes.

Results to date

In August 2007, an extensive sampling program was conducted in which sediments were collected from the same waterbodies and littoral zones that macroinvertebrates were sampled from in 2006. Metals, including uranium, were analysed for in the fine (< 63 µm) sediment fraction and the results used to assess whether or not poor sediment quality was a possible cause of the lower diversity of benthic fauna in Georgetown Billabong compared to reference billabongs.

Uranium concentrations in the sediments of the waterbodies sampled in 2007 are shown in Figure 1 with a comparison, where available, to data from samples collected prior to mining in 1978 (Noller & Hart 1993).

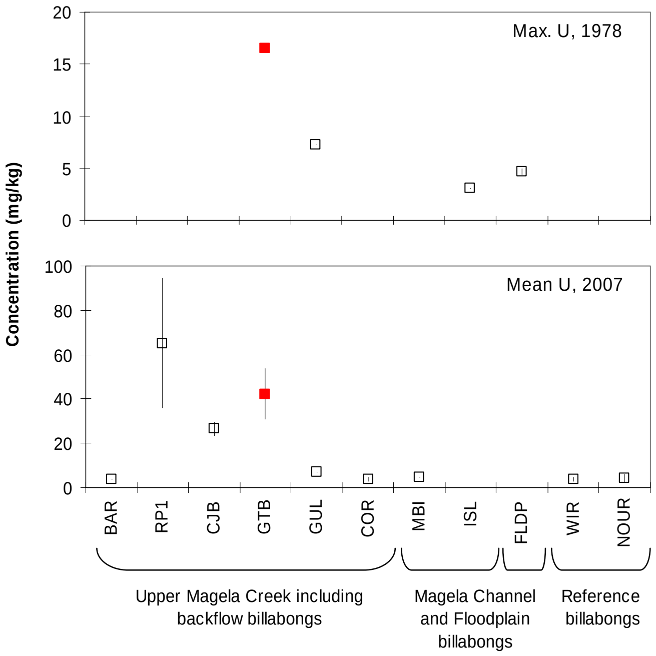

Figure 1 Maximum or mean (± SD) uranium concentration measured in sediments of a number of ARR waterbodies collected in 1978 and 2007. Uranium extracted using a nitric/perchloric digest of the fine (< 63 µm) sediment fraction. Site codes are Ranger Retention Pond 1 (RP1), Coonjimba (CJB), Georgetown (GTB), Gulungul (GUL), Baralil (BAR), Corndorl (COR), Wirnmuyurr (WIR), Mudginberri (MBI), Island (ISL), Magela floodplain (Leichhardt, Jabiluka: FLDP) and Nourlangie (Malabanjbanjdju, Anbangbang, Buba and Sandy: NOUR) Billabongs.

It is evident that U concentrations in the sediments of Georgetown Billabong have been systematically higher than those of other natural billabongs of the region since before the start of mining. This same pattern is observed for uranium concentrations found in freshwater mussels in or just downstream of Georgetown Billabong. The higher pre-mining uranium concentrations in both sediment and mussels from the billabong are attributed to natural erosional contributions from the surface expression of ore body number 1 located in the Georgetown Creek catchment (see 'A longitudinal study of radionuclide and metal uptake in mussels from Magela Creek and Mudginberri Billabong', this volume, 91–97).

The available time series of U data for Georgetown Billabong were reviewed carefully since methods of sample preparation (eg using size fractionated or total sediment) and chemical digestion (different acids and mixtures of acids) can confound the interpretation of such historical datasets. The most internally consistent set of data were selected and these have been plotted in Figure 2.

The most important observation from Figure 2 is that there appears to have been little change in sediment U concentration from before the start of mining until about 2002. Unfortunately, no directly comparable data are available between 2002 and 2007. Further and as noted above, the 2007 data were obtained from the edge of the billabong (matching sampling locations for macroinvertebrate collection) rather than from its centre. Since most of the data points in Figure 1 are for sediment from closer to the centre of the billabong, then this raises the question of whether the more organic-rich sediment from the edges contains higher U concentrations than the billabong centre. This aspect needs to be specifically addressed by obtaining contemporary samples from the centre.

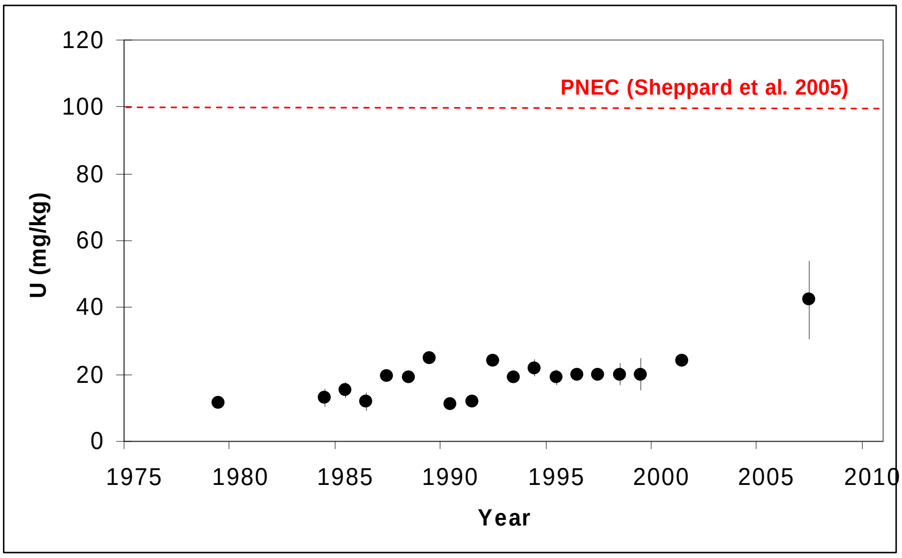

Figure 2 Mean (± SD) uranium concentration measured in sediments of Georgetown Billabong over time. Uranium extracted using a nitric/perchloric digest of the fine (< 63 µm) sediment fraction.

A similar trend for concentrations of U in sediment is evident in Coonjimba Billabong (data not shown here) with the increases in both billabongs likely due to an overall rise in U loads passing through both the Corridor Creek (Georgetown) and RP1 (Coonjimba) systems.

Despite the increase in U concentrations in Georgetown Billabong, the concentrations may not yet be sufficiently high to be toxic to benthic biota. Sheppard et al (2005), for example, derived a 'predicted no-effect concentration' (PNEC) for U in sediment based upon field-effects observed for freshwater benthic invertebrates. The PNEC (100 mg/kg, marked as a reference line in Figure 2) is well above the highest concentration observed in Georgetown sediments. This PNEC may be a reasonable ‘no effects’ threshold for ARR waterbodies given that sediments from locations within RP1 approached the PNEC (Figure 1) yet benthic communities from this waterbody were adjudged as similar-to-reference condition in macroinvertebrate diversity (Humphrey et al 2008). Nevertheless, possible confounding by effects of other metals present in the sediments from the field studies reported by Sheppard et al (2005), together with wide ranging toxicities reported in the limited number of laboratory studies completed and published to date (varying by at least three orders of magnitude, references not provided here) highlight the significant knowledge gap in sediment toxicity information for both the operational and closure phases of the Ranger mine.

Apart from lack of relevant sediment toxicity data and as previously reported (Humphrey et al 2008), a number of confounding effects diminish the ability to infer mining-related change to the benthic communities of waterbodies sampled in this study, including lack of comparable historical macroinvertebrate data for this habitat and the nature of this habitat itself. In particular, the size distribution of sediments can strongly influence macroinvertebrate communities; fine-grained, cracking-clay sediments that characterise the littoral benthos of Georgetown and Coonjimba Billabongs in particular, provide less habitat and less suitable dry season refugia for organisms compared with coarser-grained, sandy sediments such as those from Ranger RP1 and Jabiru Lake where higher abundances and taxa number were observed (Humphrey et al 2008).

At the time of sampling, field staff also made note of the particularly high amounts of leaf litter present in the Georgetown littoral substrate, arising from Melaleuca trees that closely abut the water’s edge in this billabong (ie more so than for the other waterbodies). Whether production of tannins or other compounds from recent leaf-fall had an inhibitory effect upon the benthos is an aspect that requires further study.

Future investigations will focus on:

1 Better quantifying and describing the physical nature of sediments from the various waterbodies by way of particle size distribution and possibly mineralogy (to confirm the fine-grained nature of sediments in Georgetown Billabong in particular).

2 Collecting a limited number of littoral and corresponding deeper-water sediment samples from Georgetown for chemical analysis. (The littoral samples collected in 2007 may be unrepresentative of the more central billabong samples collected by other agencies in the past.).

3 Examining the extent of metal extraction from sediments using different digest techniques on different size fractions. The results would be used assess the degree to which historical sediment quality data, often derived using different digest methods and size fractions, may be validly compared.

4 Using data from (i) and (ii), re-analyse and model environmental and biological data to better assess the degree and extent, if any, of possible mine-related change to benthic communities of Georgetown Billabong.

The outcome from this more detailed assessment will indicate if billabong closure criteria may be needed for sediments as well as water. The issue of the derivation of a site-specific sediment quality criterion for uranium at least, will be progressed with the development by ***eriss*** and collaborators of a manipulative, field toxicity experiment proposed for 2010–11. This will redress the general issue referred to above of the lack of relevant (site-specific) sediment toxicity data for the region.

Should the collective sediment quality studies proposed above show that sediment U concentrations have been increasing in Georgetown Billabong in recent years, and implicate sediment U toxicity as a factor in the low diversity of benthos, this could suggest that water quality criteria in Georgetown have already exceeded limits that protect the resident biota if it assumed that such recent sediment quality trends are a consequence of the declining overlying water quality. However, should the collective studies implicate other non-mining related factors as responsible for the observations of low benthic diversity in Georgetown, then the water quality record in the billabong associated with the periods of biological sampling (1995, 1996 and 2006) may be used to derive closure criteria. Jones et al (2008) derived interim criteria for Georgetown based on the assumption of the latter (non-mining-related) interpretation of results for benthic diversity in the billabong. Should this assumption be confirmed, then macroinvertebrate sampling may be repeated several more times between now and projected mine closure, and the guideline values adjusted, if required, to incorporate this new information. Whichever of these outcomes is confirmed, knowledge of the dynamic interaction between sediment and water quality, and interdependence of sediment quality on overlying water quality, will be required to be certain that final criteria derived for water quality in Georgetown Billabong are such as to be also sufficently protective of sediment quality.

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Use of vegetation analogues to guide planning for rehabilitation of the Ranger minesite

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Background

Characterisation of plant communities from appropriate natural analogue sites is being used to assist in selection of species for revegetation of the Ranger mine landform following rehabilitation of the site. The characteristics of these communities will also assist in developing performance measure targets (closure criteria) against which the success of revegetation can be tracked by the post-rehabilitation programme. For the range of key vegetation community types that represent the spectrum of environments likely to be found across the rehabilitated footprint, relationships with key geomorphic features (parent material, slope, effective soil depth etc) also need to be identified. By identifying the key environmental features that are associated with particular vegetation community types, either (i) the conditions required to support these communities or, alternatively, (ii) the community types that best suit particular environmental conditions, may then be specified for the rehabilitated landform at Ranger. Additional background and rationale for this study can be found in Humphrey et al (2006, 2007).

EWLS and ***eriss*** have collaborated on this project, combining and analysing vegetation and environmental data that both groups have been collecting in the Alligator Rivers Region since the early 1990s.

All EWLS vegetation analogue sites are located on the ancient weathered Koolpinyah landscape surface, with differences in vegetation assemblages determined by topography, depth of soil profile and availability of water (Hollingsworth et al 2003). In particular, EWLS focused its vegetation surveys on the so-called ‘Georgetown analogue area’ – a relatively confined area located a short distance to the south-east of the Ranger mine. A deliberately broad range of vegetation environments was covered by the EWLS work, encompassing rocky outcrops, slopes and crests, stream alluvium and poorly-drained flats. The philosophy behind this approach was that all of these types of environments, in greater or smaller measure, would be present across the rehabilitated footprint of the area disturbed by mining.

The ***eriss*** program also included areas adjacent to the Ranger mine (on the Koolpinyah surface). However, the study sites were deliberately focused on low, broad ridge environments, perceived at the time (early 1990s) to be more similar to conditions expected to prevail across the bulk of the rehabilitated Ranger waste rock dumps (Brennan 2005). The ***eriss*** work also covered a range of hill sites elsewhere in the ARR where, again, the topography and/or substrates were considered to resemble likely final landform conditions (based on the landform design concept at that time) at Ranger (Needham et al 1973, Uren 1992). The underlying geology of these hill sites encompassed quartzite, sandstone and schist mineralogies (Brennan 2005).

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Progress to date

At ARRTC 20 (October 2007), progress was reported on (1) classification of analogue vegetation communities (trees and shrubs) to seek pattern and groupings in the plant community data, (2) collection or collation of additional plant and environmental data for analysis, and (3) data analysis to seek relationships between plant, environmental and fire history data.

From the October 2007 meeting, a key information need that ARRTC sought from future analogue work was defining the characteristics of waste rock mixed with laterite material in the context of comparison with similar data from the analogue sites. Given that some combination mix of the waste rock and laterite will constitute the substrate for both the trial and final landforms, it was important to determine whether the vegetation selected for these landforms would thrive and be self-sustaining in these conditions. Thus, the analogue work would inform species selection for the landforms. Since ARRTC 20, staff changes at EWLS and within ***eriss***, together with delays by ERA in permitting access to the Ranger site to collect waste rock/laterite substrates, have led to the following issues with the project:

- Acquiring the full dataset of environmental variables for the analogue sites. While most of the data are now available, reconstructing the EWLS environmental dataset that was used in Hollingsworth et al's (2003, 2007) modelling has been a protracted exercise.
- Soil chemistry and physical characterisation data are not available for a small number of remote hill sites surveyed by Brennan (2005). For two other hill sites surveyed (see below), the surface substrate was so rocky that soil water retention properties could not be acquired. However, these missing data are not likely to affect future modelling proposed in this study. (Soil chemistry data were not included in the modelling conducted by Hollingsworth et al (2003, 2007).)
- Physical and chemical characterisation has not yet been conducted of the components that will comprise the proposed landform capping layer. Two types of substrate need to be characterised: (i) potential substrates or substrate mixes that will be used for the new trial landform, and (ii) existing, constructed (mine-derived) substrates that have provided a medium for growth of vegetation on various trial rehabilitation sites across the Ranger mine site over the past two decades. For (i), access to suitable sampling sites for the laterite material was only gained in early September (2008), after nearly 6 months of exchanges with ERA. Arrangements for physical and chemical analysis of substrates from (i) and (ii) above are now underway.

Notwithstanding the delays that have led to the slower than originally anticipated acquisition of data described above, some initial analyses have been conducted using the (mostly) original vegetation and recently-acquired soil description and chemistry data for 30 analogue sites. These sites include:

- 18 original sites from the Georgetown analogue area surveyed by Hollingsworth et al (2003)
- 2 additional Melaleuca-dominated sites from the Georgetown analogue area surveyed for vegetation and soils more recently (June 2007), and
- 10 of the original sites surveyed by Brennan (2005), including 4 lowland Koolpinyah sites adjacent to Ranger and the Georgetown analogue area, 4 sites from the hills at Tin Camp Creek, and 2 rocky hill sites (quartz and sandstone substrates respectively).

In previous meetings, ARRTC has sought physical and chemical data for components of the mine waste rock/laterite mix so that an assessment of the suitability of mine-derived substrates for plant sustenance on rehabilitated landforms could be made. While these data are not yet available (for the reasons given above), an indication of the importance of soil properties per se in determining the local vegetation classification groups may be gained by classifying and ordinating the soil data corresponding to the natural analogue vegetation sites. If the soil characteristics produce classifications similar to the vegetation groups, this might suggest that soil factors have some influence on the vegetation patterns. If a different pattern is observed, it would suggest that other environmental variables have greater influence over the vegetation patterns, including soil variables that have not been measured.

The classification and ordination of natural soil properties provides a useful tool for assessing suitability of mine-derived substrates as a medium for plant growth. Thus, once the latter substrates are characterised, the associated soils data may be combined with those from the natural sites and re-analysed. If the mine substrate data fall outside the space of the natural soils ordination (or 'envelope'), further investigation would be required. However, should the data fall within the ordination space of natural soils' properties, it would suggest the medium per se is not inhibitory to plant growth.

Group average cluster analysis and multi-dimensional scaling (MDS) ordination were conducted on tree and shrub data from 28 analogue sites for which there were complete, corresponding soil quality data, using the PRIMER (v6) multivariate software package (Clarke & Gorley 2006). Of the 28 sites, 26 of these had been used in the original 38-site classification derived by Humphrey et al (2006, 2007) and used in Hollingsworth et al's (2007) modelling. The new (re-)classification is shown in Figure 1A where site labels indicate the original vegetation classification class (C1-C5, described in Table 1). As shown in Figure 1A, all of the sites reclassify according to their original vegetation classes. Further, the two additional Melaleuca-dominated sites from the Georgetown analogue area surveyed more recently (June 2007, sites 33 and 41), classify together with the existing Melaleuca woodland sites (within classification class, C1, Table 1).

Table 1 Descriptions of the analogue communities identified in this study and, where available, the matching vegetation units according to Schodde et al (1987)

Broad vegetation community	**Dominant and/or distinguishing tree or shrub species**	**Classification unit from this study (Fig 1A)**	**Vegetation units used by Schodde et al (1987)**
Melaleuca woodland	*Melaleuca viridiflora*	C1	Myrtle–Pandanus savannah
Mixed Eucalypt woodland	*Eucalyptus miniata* *Eucalyptus tetrodonta* *Corymbia porrecta* *Xanthostemon paradoxus* *Acacia mimula*	C2	Open forest
Dry mixed Eucalypt woodland	*Corymbia foelscheana* *Xanthostemon paradoxus* *Erythrophleum chlorostachys* *Eucalyptus tectifica*	C3	Woodland
Low diversity schist hill	*Eucalyptus pruinosa* *Corymbia foelscheana* *Calytrix achaeta*	C4	(Not described)
Low diversity, *Corymbia foelscheana* dominated woodland	*Corymbia foelscheana* *Planchonia careya* *Syzygium suborbiculare*	C5	(Not described)

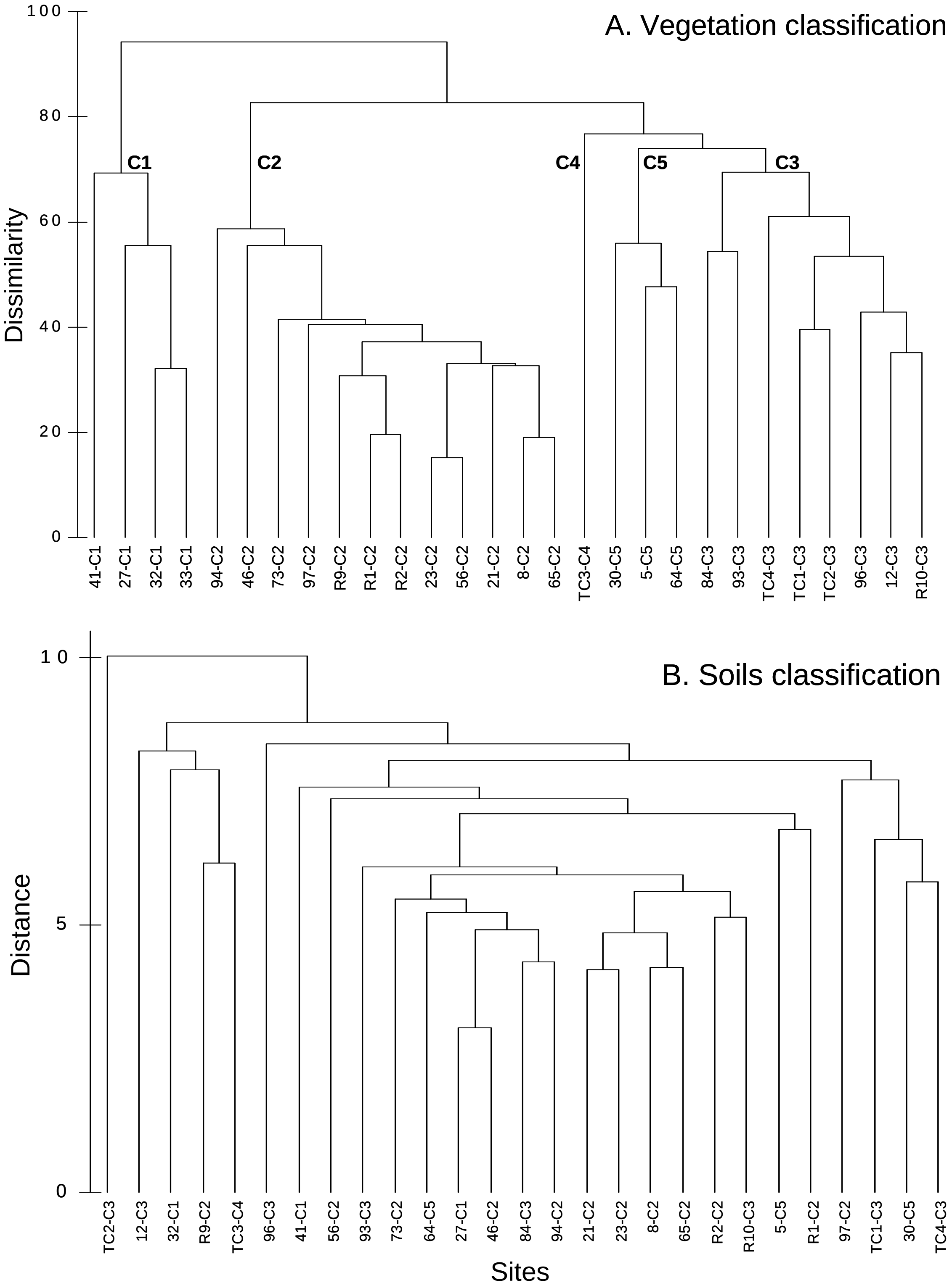

Figure 1 Cluster analysis (group average linkage) of A. vegetation (trees and shrubs) and B. corresponding soil description data for Alligator Rivers Region (ARR) vegetation analogue sites. (Vegetation data log transformed density/hectare units.) Key to site codes:
Site label suffix (C1-C5) = original classification class for the site (Humphrey et al 2006, 2007; see Table 1).
Numbered-only sites = EWLS Georgetown analogue area,
'R' sites = lowland Koolpinyah sites around Ranger,
'TC' sites = schist hill sites of Tin Camp Creek.

A total of 39 soil variables were available for the analogue sites. These variables represented soil chemistry (major ions and nutrients, 18 variables), particle size distribution (4 classes), soil water retention properties (10 variables) and soil morphology and surface drainage classes from published classifications representing horizon thickness, gravel and texture, and soil permeability (total of 7 classes). Group average cluster analysis, together with Principal Components Analysis (PCA) and Multi-dimensional scaling (MDS) ordination, were conducted on normalised soil description data using Euclidean distance (using the PRIMER software). Data were available for different soil depths and for this study, analyses were conducted for both the 0-0.05 m depth interval and for data averaged over the two depth intervals, 0-0.05 and 0.05-0.2 m. For both depth intervals (0-0.05 m and averaged), data were analysed in their entirety, or for different subsets including soil chemistry only and/or with highly correlated variables (r >0.80) removed. The primary soils analyses reported below and depicted in the figures is for the entire dataset, using data for the 0-0.05 m depth interval.

The soils cluster analysis (based on Euclidean distance) is shown in Figure 1B, together with the corresponding vegetation cluster analysis (based on Bray-Curtis dissimilarity) described above (Figure 1A). Corresponding MDS ordinations for vegetation and soils data are also shown in Figure 2. Apart from some separation of the soils from *Melaleuca* woodland (C1 sites) and soils from the Tin Camp Creek schist hills, both the soils cluster analysis and corresponding ordination display generally weak groupings, unlike the well-defined major groups represented in the vegetation analysis (statistically verified using ANOSIM analysis from PRIMER). The soils PCA ordination (not shown here) showed a very similar pattern to that of the MDS ordination. Comparatively small amounts of the variability present in the original 39 soil variables were captured in the PCA, namely, 31, 16 and 9% for PC axes 1 to 3 respectively. Thus, soils from sites representing the three woodland classification groups (Table 1) are generally interspersed (Figure 2) indicating similar, average soil characteristics amongst the vegetation communities.

For cluster and ordination (MDS and PCA) analyses, the various permutations of data analysis (soil depth, data subsets, correlated variables removed) showed similar patterns to those shown for the entire dataset for the 0-0.05 m depth interval (results not shown).

The BIOENV routine in PRIMER was used to calculate the smallest subset of soil variables explaining the greatest percentage of variation in the vegetation ordination patterns. (The BIOENV procedure takes combinations of the environmental variables, k at a time, and derives the best matches of biological and environmental similarity matrices for each k, as measured by (in this case) Spearman rank correlation.) For the soils data in which highly co-correlated variables were removed, quite low Spearman rank correlations (rho) were observed amongst the best 10 solutions. Results may be summarised for the two depth intervals as follows:

- Data from the 0–0.05 m depth interval:
  - Rho values between 0.356 and 0.377. Influential variables included % sand and sulfur (all 10 solutions), potassium (8), soil permeability (7), cation exchange capacity (6), copper (3), zinc (2) and total organic carbon (1).
- Data from the 0–0.2 m depth interval:
  - Rho values between 0.337 and 0.356. Influential variables included % sand and sodium (all 10 solutions), soil permeability (9), pH (7), potassium (5), zinc and soil depth (2) and borehole infiltration, soil density and cation exchange capacity (1).

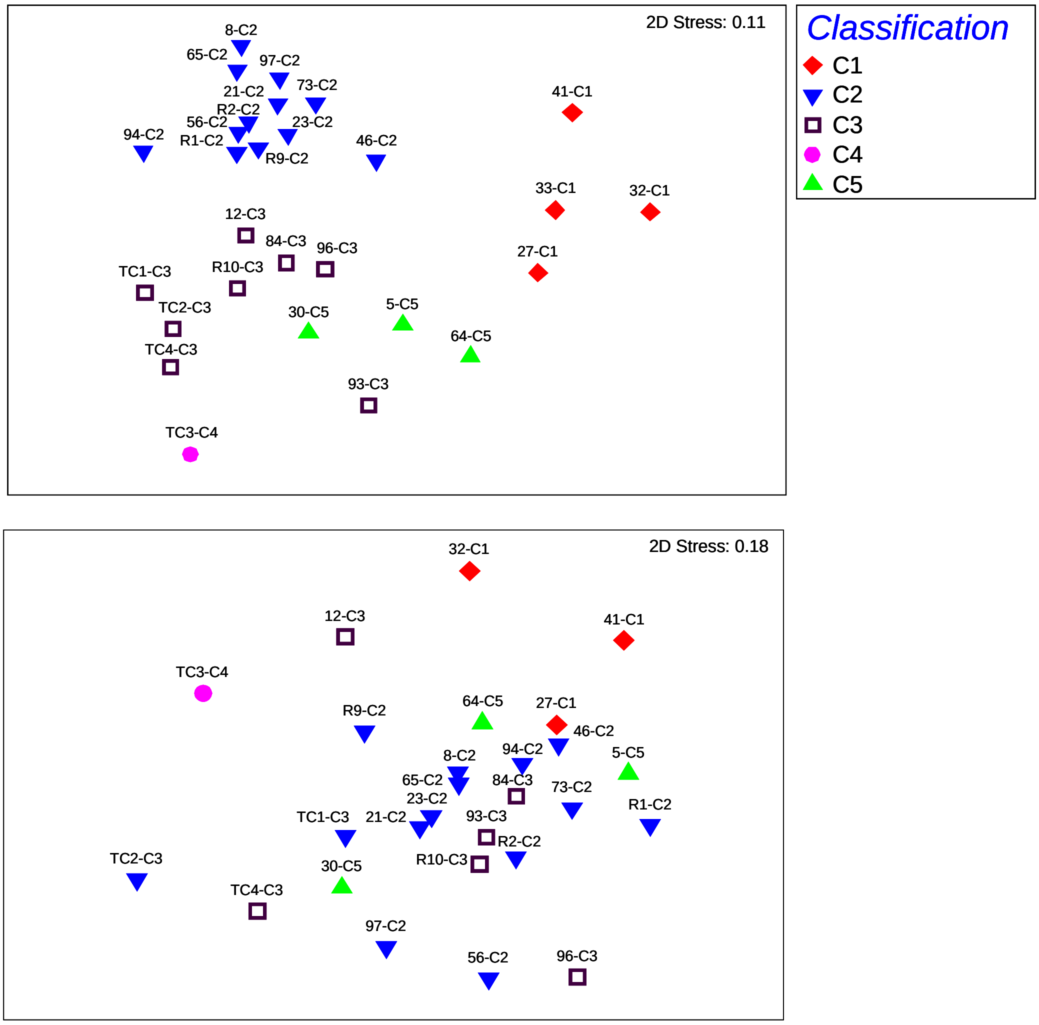

Figure 2 MDS ordinations of vegetation and corresponding soil description data for 28 ARR analogue sites. Site codes described in caption to Figure 1 while classification codes (C1–C5) are described in Table 1.

While several soil chemistry variables are correlated with the vegetation ordination space, cause and effect may be difficult to separate as similar correlations were also observed for key landscape parameters (results of the latter analysis not reported here). For example and from the BIOENV results reported above, soil pH averaged over the 0–0.05 and 0.05–0.2 m depth intervals was correlated with the vegetation ordination space, with lower pH soils associated with sites of poorer drainage and slower runoff – such as Melaleuca woodland sites (C1) sites) and low diversity, *Corymbia foelscheana* dominated woodland sites (C5), ie sites on the right hand side of Axis 1 of the vegetation ordination (Figure 2A). (Axis 1 of the vegetation ordination represents a gradient in slope from left to right, with hills sites located on the left hand side of the axis, merging to sites on flats on the right hand side.) When the numeric values of pH and runoff are superimposed on the vegetation ordination as symbols of differing size, reflecting variable magnitude (‘bubble plots’), the close correspondence between the variables can be seen (Figure 3).

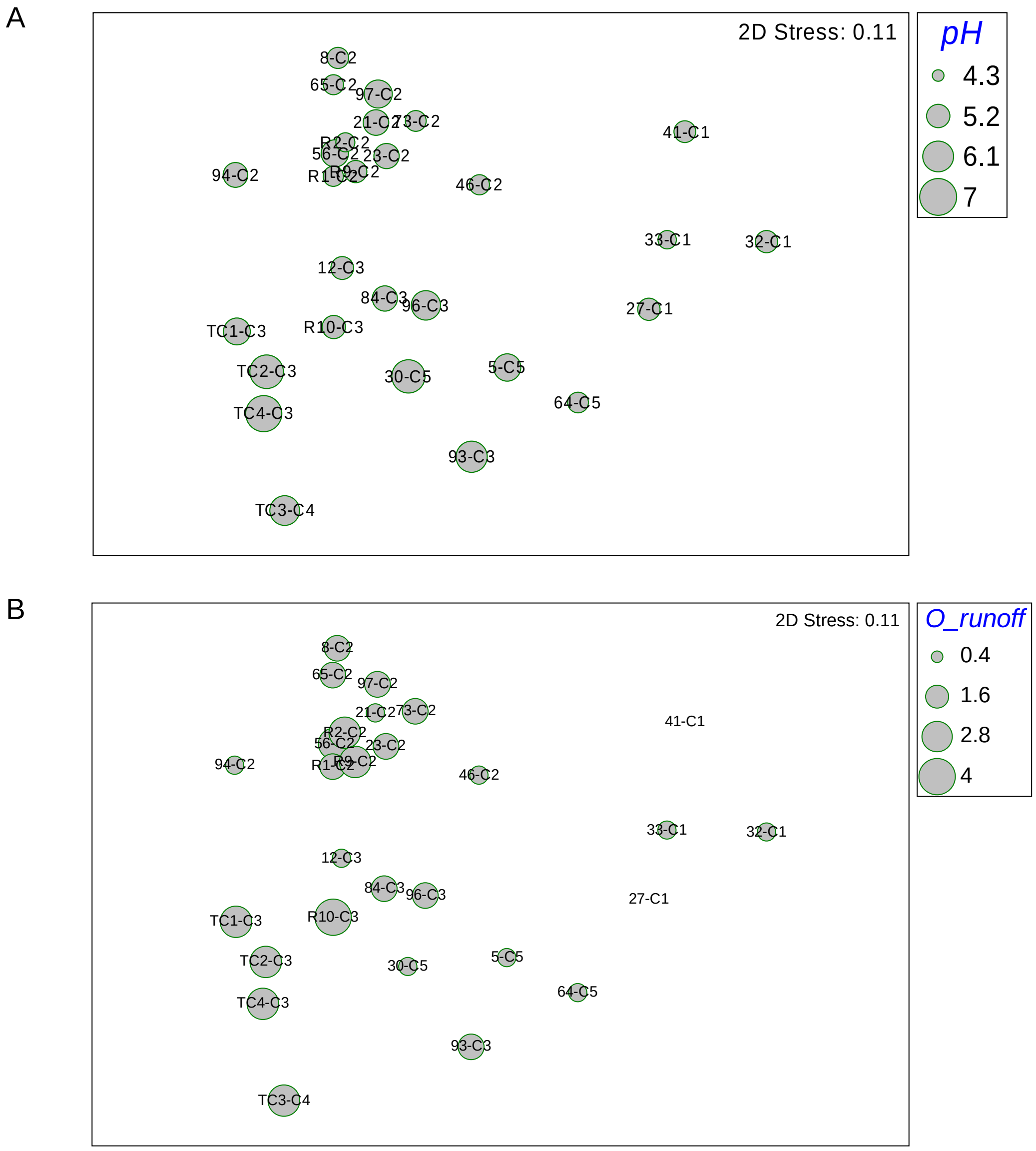

Figure 3 MDS ordination of shrub and trees data for 28 ARR analogue sites with superimposed (A) soil pH and (B) site runoff attributes overlain as bubble plots. Site codes described in caption to Figure 1 while Classification codes (C1–C5) are described in Table 1.

In general, the classification, ordination, ANOSIM and BIOENV results indicate a degree of independence of vegetation community composition and structure from the underlying soil properties that were measured and used in this analysis. These results and the demonstration by ERA and its consultants over the years of successful plant growth on harsh and stony mine-derived substrates (including neat waste rock), suggest that most of the soil descriptor variables used in the present analysis may not be fundamental to successful minesite revegetation at Ranger.

Only a limited number of soil descriptor variables (broad classes of parent material and soil morphology) were included in original plant-environment modelling conducted by Hollingsworth et al (2007), hence the need to undertake a more comprehensive assessment of the relationship between vegetation assesmblage type and soil physico-chemical parameters.

Other variables included in the analysis by Hollingsworth et al (2007) were relevant to climate and water balance, local topography, as well as fire disturbance. This work concluded that landform relief, slope and curvature were the highest correlates with important framework tree species. The results of the present analysis also strongly implicate landscape variables as being the most important determinants of vegetation communities, as drainage and runoff (correlates of topographic descriptors) were consistently correlated with the vegetation ordination space (eg Figure 3B).

The primary environmental factor to be tested for in the trial landform being established by ERA is the soil/substrate medium (three treatments – waste rock and two thicknesses of laterite/waste rock overlying waste rock). Landform features such as those identified by Hollingsworth et al (2007) (eg relief, slope, curvature) have been deliberately removed from the design in order to control just for substrate. In this conext the results presented here show that the relationship between soil characteristics and vegetation class are weak and suggest broad tolerances of plant communities to soil type. Thus, it is unlikely that potential plant-soil description modelling would greatly inform ERA of the species composition to plant out on the trial landform.

The only caveat to apply to the suggestion that soil quality may not be an important factor to revegetation at Ranger is the observations of Ashwath et al (1994) who noted elevated leachable $MgSO_4$ concentrations in some waste rock types at Ranger. Soils associated with this waste rock have the potential to become saline and therefore may be potentially toxic to some plant species (Ashwath et al 1994). Vegetation potting trials are required to elucidate these risks further.

For the trial landform, the key species representing the dominant vegetation communities that characterise the broader ARR analogue sites will be planted out and their progress monitored ('learning by doing'). In tandem with this approach, modelling of plant and environmental data using a more expanded data set than that used by Hollingsworth et al (2007) is proposed such that both approaches will inform the broader revegetation requirements for the final landform at Ranger. The expanded modelling will include the current soil description data as well as those from the newly-constructed trial landform and from existing, constructed (mine-derived) substrates that have provided a medium for successful vegetation growth on various trial rehabilitation sites on the Ranger minesite. A full suite of landscape variables will also be included.

At the time of writing this report and as reported above, the datasets for only a few of the landscape variables originally used by Hollingsworth et al (2007) had been located for re-analysis. In the documentation prepared for ARRTC 20 (October 2007), additional modelling requirements were also noted. In particular, future analyses were also needed to incorporate better (finer) resolution Landsat-derived fire history information to ensure that the long-term ecological effect of fire as a driving variable is accounted for at the required scale (see 'Undertake an ecological risk assessment of Magela floodplain to differentiate mining and non-mining impacts', this volume, 196–198).

It is worth noting, finally, that the trial landform is not likely to yield useful information on the role and importance of landform features such as relief, slope and curvature in determining vegetation outcomes (because these factors have been 'designed out' of the landform). These factors were identified from the analogue study of Hollingsworth et al (2007) as important in determining the occurrence of plant community types. Thus future analogue work will continue to be important in gaining an appreciation of how the final landform will need to be designed to facilitate establishment of the required vegetation types.

Tree root penetration study

For final landform design, the depth of soil/substrate cover that retains sufficient water-holding capacity for plant maintenance and growth, particularly during the dry season, is a key knowledge requirement. To this end, ERA/EWLS have incorporated two depth treatments (2 and 5 m) for the mixtures of laterite/waste rock overlying waste rock on the trial landform. The basis for the advice and decisions on these cover depths is from the published reports of Kelley et al (2002, 2007), as well as reports cited within these papers (not yet sighted). Tree root depth is either (i) inferred from the soil water store required to account for 100% of dry season transpiration of trees (eg Kelley et al 2002), or (ii) from cited observations of the maximum depth tree roots have been observed in the NT Top End's soils, which purportedly may reach maxima of 8 m (Kelley et al 2007). The water balance budget of Kelley et al (2002) indicated that 100% of transpiration of trees can be accounted for if rooting depth is set to 5 m.

Nevertheless, these findings appear to contradict the findings of Werner and Murphy (2001) who examined the roots of 47 trees (*Eucalyptus miniata*, *E. tetrodonta* and *E. papuana*) excavated from a site on Kapalga, on the lowlands of western Kakadu National Park. A root from only one of the 47 trees had penetrated the ferricrete layer located, on average, 0.5–0.6 m (or full range of 0.3–1.4 m) below the surface. Thus all the root mass was confined to the overlying sandy clay loam. Werner and Murphy (2001) concluded (along with other papers they cited) that trees in the NT's Top End could obtain all their water requirements during the dry season from water reserves present in the upper metre of soil.

To seek further information on this matter and thereby perhaps usefully inform decision making on this aspect with respect to minesite rehabilitation, local studies were initiated to examine root penetration of trees planted on trial rehabilitation sites on the Ranger mine site.

Some trial rehabilitation sites dating back to over a decade have been recently subsumed as a result of the recent lift of the tailings dam wall. This provided an opportunity to carefully excavate a selection of trees in the areas to be cleared. EWLS and ***eriss*** have used these occasions to opportunistically examine the depth of penetration of roots of excavated trees, growing in media that includes waste rock, waste rock and fines, or various laterite/waste rock mixes. In addition to the historic trial rehabilitation areas, the footprint area for the new trial landform has recently been cleared. This provided the opportunity to excavate trees from a woodland growing in a natural soil profile.

While the measurements made during the present investigations have not yet been analysed fully, some early findings include the observation that, while some roots can penetrate to depths of 2.1 and 2.5 m in mine-derived and natural soils, respectively, the main rootball of trees, comprising an estimated >95% of the root biomass, is invariably contained in the top 0.7 m of the soil profile (see Figure 4). What is unknown, however, is the extent to which the small percentage of roots which do penetrate to greater depths (in moist soil zones) play a critical role in meeting the tree's water requirements in the dry season. To this end, EWLS has recently completed installation of monitoring systems to measure soil moisture down to 6 m in four vegetation types in the Georgetown analogue site. Over the next two years, seasonal soil water extraction patterns, combined with whole-tree water use patterns, will be measured to assist in resolving this issue (Ping Lu, EWLS, pers obs). Such knowledge on the extent to which trees in the local region depend upon soil moisture at depth during the dry season is important. For example, if local trees, on natural or on trial rehabilitation sites are obtaining the vast majority of their dry season water requirements from the top metre or so of soil/substrate, then a 5 m thickness cap treatment for trial or final landforms would represent a substantial and costly overdesign.

Figure 4 Rootball of 7.7 m high *Eucalyptus glomericassis* excavated from a trial rehabilitation site on the eastern edge of the Ranger tailings dam (from the so-called, 'Heritage' site). While shallow lateral roots have been broken off, the main primary (tap) root is intact.

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Charles Darwin University seed biology research

S Bellairs[1]

Introduction

Charles Darwin University staff are undertaking seed biology research to optimise germination of local native species to support the rehabilitation of the Ranger mine site. The project involves collaboration between the CDU researchers and personnel from ***eriss***, ERA, Kakadu Native Plant Suppliers (KNPS), EWLS, Greening Australia and Top End Seeds.

Energy Resources of Australia are intending to establish a range of local native species on rehabilitation areas at the Ranger mine site when revegetation of the site commences. To rehabilitate these areas large numbers of plants of a range of species will be required. Therefore effective techniques will be required to germinate the seeds, whether for direct seeding or for propagation of tube stock. KNPS are producing tube stock for current rehabilitation areas using nursery facilities in Jabiru. They are collecting seeds from the local area to produce native plants that are adapted to local conditions.

Most Australian species have poor germination from seeds unless seed treatments are applied but treatment information is lacking for the vast majority of NT species. Australian plant species tend to have seed dormancy mechanisms that prevent or delay germination except in response to specific cues. Very little information is known about the seed biology of the local species including how to optimise viability of seeds during collection, how to store the seeds, or how to overcome dormancy and germinate the seeds (Bellairs 2007, Bellairs & Ashwath 2007). Tropical flora species are likely to differ in their seed biology responses to environmental cues from other Australian flora. Therefore, although southern Australian studies can be used as a guide, for most species results obtained for similar southern species are unlikely to be directly applicable. KNPS is also identifying species that are difficult to germinate in their nursery operations.

This project is investigating seed collection, viability, germination, dormancy and storage for 50 species that occur on the Ranger mine lease that have been identified as potentially important for rehabilitation of the Ranger mine site. The project aims to develop protocols for effective seed storage and germination.

A PhD student research project supervised by Dr Sean Bellairs commenced in May 2008 and is investigating seed germination of fleshy and woody fruited species on the priority species list. The student, Mr Jagmohan Singh Sidhu, gained a CDU research scholarships and operational costs are being supported by ERA.

Approach

Seed lots are being supplied by KNPS, or from Top End Seeds and Greening Australia when KNPS is unable to provide supplies of seed. While most seed lots have been obtained from KNPS, factors such as unusual rainfall patterns and cyclones have prevented KNPS from

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supplying seeds during some seasons and alternate supplies have been obtained. It also appears that seed collection of many of the species is more difficult that originally anticipated.

Testing of seeds is being carried out under standard conditions in laboratory incubators to control light and temperature conditions. Seed responses are highly susceptible to variation in temperature and moisture conditions, thus controlled conditions are necessary to standardise the many factors impacting on seed germination. Otherwise variability can make it difficult to determine which treatments are most effective, without using large quantities of seeds.

Testing is based on the International Seed Testing Association guidelines and methodologies, with modifications to enable fewer seeds to be utilised. The methodologies used by the Australian Millennium Seed Bank Projects and other published studies are also being used as a guide so that results can be compared with those groups and so that the results obtained by MSB projects can be used as a guide when choosing treatments.

Factors being tested include seed viability following collection, the types of dormancy mechanism(s) present, effective treatments to overcome dormancy and seed longevity under various storage conditions.

The frugivory project involved feeding captive figbirds (*Sphecotheres viridis*) and pied imperial pigeons (*Ducula bicolour*) with seeds of two *Ficus* species (*F. virens* Aiton and *F. benjamina* L) to determine if seed passage through frugivore digestive tracts results in higher seed germination success than untreated (control) seeds. Seeds were also treated with acid to ascertain if artificial procedures could mimic the action of gut passage on seeds. Seed retention time was recorded to determine the likely dispersal distance of consumed seeds.

Progress to date

The seed biology project commenced on 3 July 2006. The research associate position was advertised and strong local and interstate candidates were interviewed. Ms Julie Crawford accepted the position and commenced employment on 3 July 2006. Ms Crawford obtained another position and resigned in November 2007. The position was advertised and Ms Melina McDowell commenced full time employment on 3 March 2008. Previously Ms McDowell worked part time on this and other CDU seed biology projects.

A meeting was held at Jabiru with ERA, ***eriss***, EWLS, KNPS and project staff in 2006. Fifty priority species were chosen based on their abundance in the analogue sites (data provided by EWLS) and their difficulty in propagation (information provided by Peter Christophersen). Species were chosen that tended to be perennial and were likely not to create a fire risk when established on the rehabilitation areas.

Seed lots of twenty-five of the fifty priority species have been received at CDU (Table 1). KNPS supplied five seed lots in August 2006, two in October 2006, four in January 2007 and 14 in July 2007, including some additional seed lots of previously supplied species. Thirty two seed lots have been supplied by Top End Seeds or Greening Australia NT between November 2006 and September 2008. As well as the priority species some testing has occurred for 17 other species (Table 2). Where we have not been able to source seed lots of the priority species but have been able to obtain local seeds of other species in the same genus we have obtained seed lots and tested them. In some cases other species that also occur on the Ranger mine lease have been tested for student projects or to provide a more detailed assessment of germination and dormancy trends.

An annual report on the viability, germination and dormancy present in seventeen species was provided to project sponsors August 2007 (Bellairs & Crawford 2007). The species in the report included: *Alloteropsis semialata, Aristida inaequiglumis, Brachychiton diversifolius, Brachychiton megaphyllus, Buchanania obovata, Chrysopogon fallax, Denhamia obscura, Eriachne burkittii, Eriachne obtusa, Livistona humilis, Owenia vernicosa, Persoonia falcata, Setaria apiculata, Tephrosia rosea, Terminalia carpentariae, Terminalia ferdinandiana* and *Verticordia cunninghamii*. Test procedures have been developed for these species and initial viability, germination and dormancy testing has been conducted.

In 2008 summary reports in excel have been provided to sponsors and to Kakadu Native Plant Suppliers. The research work will continue to test new species and new seed lots of existing species. Considerable literature has been obtained on the taxa (although often on southern species of the genera in the priority list).

Student Ms Bela Shah has completed carrying out experimental work for the *Ficus* frugivory project and successfully completed her Masters of Tropical Environmental Management research thesis. Removing the flesh from the seeds of *Ficus benjamina* or *F. virens* resulted in substantial germination and similar germination to that achieved by passing through the gut of either bird species. Thus acid treatment was not necessary to simulate levels of germination achieved by having the fruit eaten by the birds.

Table 1 Summary of progress investigating seed biology of the 50 priority species

Species	***# Lots received***	***Weight / Number***	***Viability***	***Imbibition***	***Germination***
Alloteropsis semialata	2	C	C,N	C,N	C,N
Aristida inaequiglumis	2	C	C,N	C,N	C,N
Brachychiton diversifolius	1	C	C	C	C
Brachychiton megaphyllus	1	C	C	C	C
Buchanania obovata	2	C	C	I,C	C
Chrysopogon fallax	2	C,P	C,N	C,N	C,N
Denhamia obscura	2	C	C,N	C	C,N
Eragrostis sp TBI	1	C	C	C	P
Eriachne burkittii	1	C	C	C	C
Eriachne glauca	1	C	C	C	P
Eriachne obtuse	2	C	C,N	C,N	I,N
Gomphrena spp TBI	2	C	C	N	P
Haemodorum coccineum	1	C	C	I	C
Livistona humilis	2	C	C	C	I
Livistona inermis	2	C	C	C	I
Owenia vernicosa	3	C	I,N,N	I,N,N	I,N,N
Persoonia falcate	2	C	C	C	C
Schizachyrium fragile	1	C	C	N	P
Setaria apiculata	1	C	C	C	C
Setaria sp TBI	1	C	C	N	P
Spermacoce sp TBI	1	C	C	N	P
Terminalia carpentariae	3	C,C,N	C,C,N	C,I,N	C,C,N
Terminalia ferdinandiana	4	C	C,N,N,N	C,N,C,N	C,P,P,N
Terminalia pterocarya	1	N	N	N	N
Verticordia cunninghamii	1	C	C	C	C

C Completed; P In progress; N Not started, I insufficient seeds.

Table 2 Investigations of species that are related to the 50 priority species or other species that occur on the Ranger area, including student projects

Species	***# Lots received***	***Weight / Number***	***Viability***	***Imbibition***	***Germination***
Chrysopogon latifolius	1	C	N	N	N
Cymbopogon bombycinus	1	C	N	N	N
Cymbopogon sp TBI	2	C	C	C	C
Dichanthium sericeum	1	C	N	N	P
Ectrosia leporine	1	N	N	N	N
Ectrosia sp TBI	1	C	C	N	P
Eriachne schultziana	1	C	C	N	P
Eriachne triseta	1	C	C	N	P
Eulalia aurea	1	N	N	N	N
Eulalia sp TBI	1	C	C	C	C
Ficus benjamina	1	I	C	C	C
Ficus virens	1	I	C	C	C
Fimbristylis sp TBI	1	C	C	N	P
Heteropogon contortus	1	N	N	N	N
Heteropogon triticeus	2	C,N	C,N	C,N	C,N
Sarga intrans	1	N	N	N	N
Sarga plumosum	1	C	N	N	N
Tephrosia rosea	1	C	C	C	P
Themeda triandra	1	N	N	N	N
Triodia bitextura	1	N	N	N	N

C Completed; P In progress; N Not started, I insufficient seeds, TBI – identification to be confirmed.

In June 2008 Casuarina Secondary College student Ms Pritika Desai carried out germination trials on fresh Gomphrena seeds under the supervision of Sean Bellairs and Melina McDowell as part of the CSIRO Student Research Scheme. The results suggested that strong physiological dormancy was present in freshly collected seed batches.

PhD student Mr Jagmohan Singh Sidhu will focus on the biology of the more difficult species with woody and fleshy fruits. Trials investigating germination of *Persoonia falcata* following various fruit treatments are currently underway.

Figure 1 Treatments applied to *Persoonia* seeds (Photo: Julie Crawford)

Acknowledgments

Ms Pritika Desai from Casuarina Secondary College established experiments investigating germination of *Gomphrena* as part of the CSIRO Student Research Scheme.

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Bioaccumulation of radionuclides in terrestrial plants on rehabilitated landforms

B Ryan, A Bollhöfer & P Medley

Introduction

The principal conduits identified for radiological exposure from current mining and milling operations at Ranger are the atmospheric and aquatic pathways. Martin et al (1998) when estimating the radiation dose received from the consumption of aquatic foodstuffs following a hypothetical release of Ranger Retention Pond 2 waters to Magela Creek, found that the mine related dose would be dominated by the intake of ^{226}Ra in freshwater mussels. This is due to the high radionuclide concentration factor for mussels and their strong representation in the local Aboriginal diet. The permanent Aboriginal settlement Mudginberri is located approximately 12 km NNW of Ranger and downstream and adjacent to Mudginberri Billabong on the Magela Creek. As of May 2008 there were approximately 30 residents of this community accommodated in permanent housing.

Customary harvesting of terrestrial bush foods may become more prevalent following the rehabilitation of the Ranger Mine with the land use expectations of local Aboriginal people changing. If this is the case the ingestion pathway has been identified as a major potential contributor to the post mining related radiological dose to humans of the area, and needs to be taken into account for the post rehabilitation dose assessment. During the development of the dose assessment models it has become apparent that these models need to be site specific and must include local dietary habits, land use and the land use expectations of the region and make use of concentration factors specific to the wet-dry tropics.

Results

Estimate of the dose to local Aboriginal people: concentration factors

Little work has been done on the uptake of radionuclides into traditional bushfoods across Australia. However, a relatively comprehensive knowledge base exists for aquatic bushfood items (Johnston 1987, Martin et al 1998) and some terrestrial foodstuffs (Martin & Ryan 2004, Ryan et al 2005) in the Alligator Rivers Region.

The aim of the current study is to bring together the radiological data collected from earlier studies which focussed more on the aquatic pathway, conducted by the Supervising Scientist Division over the last 25 years, and combine this information with the data that have been gathered more recently, particularly the terrestrial plant and animal data. This information will be used to create an up-to-date ingestion pathway model using locally derived values, replacing the IAEA default values previously used, for the group most at risk – the Aboriginal inhabitants living downstream of the Ranger mine at Mudginberri Billabong.

Dose estimate

A hypothetical diet has been developed by gleaning information from several sources which include:

- a questionnaire developed by ***eriss*** and distributed to local Aboriginal people in 2006,
- information supplied by a local supplier of meats to Aboriginal outstations and
- data gained from the ***eriss*** Kakadu bushfood project over the last 11 years.

The current status of the model diet has previously been reported (Ryan et al 2008). It must be noted that this is a work in progress and as more data become available the tables are updated with the latest results, and doses estimates are recalculated.

The model diet reported in Jones et al (2008) is somewhat different to the diet reported for Aboriginal people at Nabarlek in western Arnhem Land (see section 4). This is due mainly to the availability of shop bought food, as it is easier to access for people living in this region because of the proximity of the outstations to the mining town of Jabiru. ICRP Publication 23 states that the per capita estimate of food supplies for Reference Man from Oceania (Table 122, page 349) is 677 kg/yr. Through our research we have estimated that shop bought food makes an approximately 55% contribution to the total food intake. This would then give an annual bushfood intake of approximately 318 kg/yr. For a 10 year old child the intake is halved.

Activity concentrations for the various foodstuffs used in the dose calculations are presented in Table 1. Table 2 gives the concentration factors that have been determined for Aboriginal dietary items in northern Kakadu, and their sources are listed below.

ICRP Publication 23 gives a reference value for water intake at 1900ml per day for Reference Man (page 359). It is also stated in this publication that ‘at temperatures greater than 25°C, there is a sharp rise in water intake, largely to meet demands of an increased sweat rate’. To take into account the higher temperatures an consequent water consumption in Kakadu it has been assumed that an adult drinks four litres of water (two litres for a 10 year old) water per day. This gives a total of 1400 litres for the year.

Measured radionuclide activity concentrations in food items were used for the dose assessment calculations where possible. However, to determine radionuclide activity concentrations downstream of Ranger for some food items such as fish, turtle, crocodile and freshwater shrimp, concentration factors shown in Table 2 were used in conjunction with radionuclide activity concentrations measured in Mudginberri Billabong water.

Concentration factors will also be used to help estimate the pre mining contribution to terrestrial ingestion dose as the current Ranger Anomaly 2 project progresses (see Anomaly 2 paper in section 2) and results become available. Radioactive equilibrium of all progeny in the dietary items was assumed for dose assessment purposes, unless direct measurements of progeny were available.

To assess the terrestrial pathway it was assumed that all buffalo meat consumed by the Aboriginal inhabitants of north Kakadu was supplied from the buffalo farm situated in Kakadu. Since the BTEC buffalo eradication program, Parks Australia North have kept buffalo numbers down in the north of the park and this is especially true for the Magela wetland area, making it difficult to hunt wild buffalo.

Table 1 Activity concentrations [mBq·kg^{-1}] in food stuffs used in North Kakadu dose calculations

Food item	^{226}Ra	sd	^{210}Pb	sd	^{210}Po	sd	^{238}U	sd	^{234}U	sd	^{230}Th	sd	^{228}Ra
Buffalo – flesh	18	15	16	5	230	20	8	6	13	12	2	6	-
heart/tongue	20	16	97	31	525	42	15	6	11	11	13	7	-
kidney	188	16	140	20	19000	600	5	5	11	8	7	6	-
liver	43	15	320	20	3165	320	4	8	2	17	5	5	-
Mussels	705687	-	169829	-	534751	-	2027		2027		2027		233678
Pig	29	17	21	8	4967	267	14	4	12	5	12	4	-
Magpie goose	57	25	50	8	1199	121	26	2	8	5	7	4	-
Fish group 2	216	-	43	-	1280	-	5		10	-	8	-	56
Fish group 1	3500	-	198	-	882	-	85		160	-	15	-	910
Wallaby flesh	1889	64	700	72	700	72	25		25	-	25	-	491
liver	1565	103	4300	165	4300	165	420		420	-	420	-	407
kidney	4700	201	24033	933	24033	933	281		281	-	281	-	1222
heart	635	49	981	95	981	95	29		29	-	29	-	-
Yams	6	91	9	16	0	1	3	6	0.06	.01	0.08	0.	-
Turtle flesh	160	57	98	-	1210	-	7	7	8	8	7	4	-
liver	990	1146	890	-	45000	-	95	50	130	71	45	22	-
Water lily	5090	-	4310	-	4310	-	960		1440		1440	-	-
Fruit	7.4	8.5	0.7	0.4	2.5	1.4	0.3	0.3	0.3	0.3	0.6	0.5	-
Filesnake	31	10	37	16	1177	456	21	9	21	9	53	13	-
Crocodile	120	-	34	-	1200	-	8		1		0	-	-
F/W shrimp	530	-	40	-	800	-	30		40		2	-	-
Water	3	-	6	-	3	-	1		2		1	-	-

Table 2 Concentration factors used in North Kakadu

Food item	^{226}Ra	sd	^{210}Pb	sd	^{210}Po	sd	^{238}U	sd	^{234}U	sd	^{230}Th	sd
[a]Buffalo flesh (x10^3)	0.2	-	0.2	-	2.3	-	16	-	0.20	-	0.04	-
heart/tongue (x10^3)	0.3	-	0.3	-	3.4	-	0.2	-	0.3	-	0.2	-
kidney (x10^3)	2.6	-	1.4	-	78	-	0.1	-	0.1	-	0.1	-
liver (x10^3)	0.3	-	3.1	-	8.3	-	0.1	-	0.01	-	0.1	-
[a]Pig (x10^3)	0.28	-	0.14	-	45	-	0.15	-	0.10	-	0.20	-
Magpie goose	80	-	30	-	400	-	4.0	-	8.0	-	7.0	-
Fish group 2	190	-	35	-	180	-	15	-	-	-	22	-
Fish group 1	1200	-	160	-	1400	-	250	-	-	-	40	-
[a]Wallaby flesh (x10^3)	0.08	0.03	-	-	13	0.64	0.04	0.01	-	-	-	-
liver (x10^3)	0.20	0.05	-	-	79	20	0.76	1.1	-	-	-	-
kidney (x10^3)	1.4	0.18	-	-	504	146	0.39	0.37	-	-	-	-
heart (x10^3)	0.23	0.10	-	-	20	2.0	0.04	0.01	-	-	-	-
[a]Yams (x10^3)	93	62	19	16	19	17	2.9	1.6	2.9	1.6	8.2	9.6
Turtle flesh	250	71	120	-	1000	-	25	21	18	15	32	19
liver	1200	1131	1100	-	38000	-	420	325	380	311	120	28
[a]Water lily (x10^3)	27	22	16	4.0	28	6.0	11	8.0	11	7.0	17	11
[a]Fruit (x10^3)	18	1.2	4.5	0.7	11	4.4	1.6	0.6	-	-	5.0	0.7
Filesnake	93.0	-	20.0	-	490	-	38.0	-	-	-	150.0	-
Crocodile	200	-	23	-	2400	-	40	-	3.0	-	40	-
F/W shrimp	14	-	0.5	-	20	-	0.9	-	1.1	-	0.1	-

[a] concentration factors have been multiplied by 10^3, eg the buffalo flesh concentration factor for ^{226}Ra is 0.2·10^{-3}

Below is a list of the dietary items and the source of the information used for the dose calculations summarised in Table 3.

Buffalo and pig: Activity concentrations for buffalo and pig are from the Magela floodplain (Martin et al 1995, 1998).

Wallaby: Activity concentrations used in the dose calculations have been determined from samples taken from Ranger Mine and Maningrida in western Arnhem Land (Ryan & Bollhöfer 2008).

Fish: Concentration factors from Martin et al (1995, 1998) were used to calculate activity concentrations for most progeny. However, measured flesh activity concentrations for ^{226}Ra in both groups of fish and ^{210}Po in Group 2 fish were used from fish caught at Mudginberri Billabong in 2002 and 2003 (Ryan et al 2005) .

Magpie goose + waterfowl: Magpie Goose flesh activity concentrations from animals collected at Red Lily Billabong in the South Alligator district and from Maningrida in Western Arnhem Land (Ryan & Bollhöfer 2008) were used in the dose calculations.

Turtle: Concentration factors for turtle have been determined for animals collected at Bowerbird Billabong (Martin et al 1998). These have been used in conjunction with activity concentrations in water from Mudginberri Billabong to calculate doses.

File Snake: Concentration factors for file snake flesh are from Martin et al (1998) and flesh activity concentrations have been calculated using radionuclide activity concentrations in Mudginberri Billabong water .

Crocodile: Concentration factors for crocodile flesh are from Martin et al (1998) and activity concentrations have been calculated using radionuclide activity concentrations in Mudginberri Billabong water.

Shrimp: Freshwater shrimp activity concentrations were calculated from concentration factors in Martin et al (1998) and Mudginberri Billabong water activity concentrations.

Mussels: Average mussel flesh activity concentrations from mussels collected from Mudginberri Billabong from 2000–2007 were used in the dose calculations.

Yams/Fruit: Activity concentrations for specimen collected in the vicinity of Ranger, Magela Creek and from the South Alligator floodplain were used from Ryan et al (2005).

Table 3 Becquerels ingested per year from various bush foods and total annual ingestion dose in μSv for a person from North Kakadu using the model diet reported previously

Food item	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{230}Th	^{228}Ra	Dose μSv/yr
Buffalo flesh	0.59	0.52	7.42	0.26	0.41	0.06	0.15	10
Buffalo heart/tongue	0.06	0.11	1.49	0.05	0.04	0.04	0.02	2
Buffalo kidney	0.42	0.31	42.6	0.01	0.03	0.02	0.11	52
Buffalo liver	0.15	1.08	10.7	0.01	0.01	0.02	0.04	14
Mussels	356	85.7	270	1.02	1.02	1.02	118	564
Pig	0.20	0.14	34.7	0.10	0.08	0.09	0.05	42
Magpie goose	0.32	0.28	6.78	0.15	0.05	0.04	0.08	9
Fish group 2	0.83	0.17	4.95	0.02	0.04	0.03	0.22	6
Fish group 1	10.5	0.60	2.65	0.26	0.48	0.04	2.74	8
Wallaby flesh	9.25	9.25	3.43	0.12	0.12	0.12	2.40	15
Wallaby liver	0.53	0.53	1.45	0.14	0.14	0.14	0.14	2
Wallaby kidney	1.35	1.35	6.89	0.08	0.08	0.08	0.35	10
Wallaby heart	0.18	0.18	0.27	0.01	0.01	0.01	0.05	1
Yams	45.6	67.1	2.78	20.2	0.46	0.58	11.9	72
Turtle flesh	0.14	0.09	1.05	0.01	0.01	0.01	0.04	1
Turtle liver	0.18	0.16	8.17	0.02	0.02	0.01	0.05	10
Water lily	1.27	1.07	1.07	0.13	0.17	0.17	0.33	3
Fruit	7.00	0.66	2.31	0.25	0.25	0.53	1.82	7
Filesnake	0.02	0.02	0.58	0.01	0.01	0.01	0.00	1
Crocodile flesh	0.40	0.06	3.02	0.03	0.00	0.03	0.10	4
F/W shrimp	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0
Water	3.88	8.32	4.10	1.96	2.48	1.78	1.36	13
Total dose [μSv/yr]								844

Using ingestion dose coefficients given in ICRP72 (1996) and the estimated annual consumption, total annual doses received via the ingestion of various bush foods for adults have been calculated and are shown in Table 3. It can be seen that in terms of terrestrial food items, buffalo, pig and yams are the biggest contributors to ingestion doses. As previously discussed an above background dose will be calculated and incorporated into the dose assessment when further data are collected and analysed for Anomaly 2.

Radium uptake in terrestrial plants

Concentration factors for passionfruit (*passiflora foetida*) have been determined relative to total soil and various soil leach fractions, respectively. These leach fractions are meant to represent a range of bioavailability from the easily available water leachable fraction (which can be mobilised by rainfall) through to the least available fraction (mainly $RaSO_4$) that can only be mobilised through the use of complexing agents .

The results of the study are shown in Table 4. A wide range of concentration factors for radium isotopes from varying environments has been reported in the literature (Simon & Ibrahim 1990, Ryan et al 2005, IAEA 1994). Fernandes et al (2006) suggest that a range of 10^{-3} to 10^{-1} should accommodate most currently known concentration factor values for soil/plant systems across different cultures, soils and natural radionuclides. This proposed range of concentration factors is similar to the range observed for radium uptake in passiflora at our study sites, relative to total soil activity concentrations of radium.

Table 4 Concentration factors for radium uptake in passionfruit (*passiflora foetida)* relative to different fractions produced by a sequential extraction process for soils from the Rockhole Residues (RR) site in the South Alligator Valley, Nabarlek and the Ranger mine

Sample ID	**Total Soil**	**Water**	**$CaCl_2/MgCl_2$**	**HCl**	**EDTA**	**$CaCl_2/MgCl_2$ + Water**
RR	0.030	213	31	0.20	0.70	27
Nabarlek	0.086	64	1.4	0.32	1.6	1.4
Magela LAA	0.018	29	0.44	0.08	0.16	0.43
Gulungul 1	0.005	8.5	0.35	0.01	0.04	0.33
Gulungul 2	0.007	11	0.32	0.007	0.03	0.31
Magela DS	0.238	4.9	2.8	1.1	1.4	1.8

The hypothesis developed from previous $^{226}Ra/^{228}Ra$ activity ratio measurements on passiflora samples and associated leaches (Medley 2007) was that the variability of concentration factors should reduce significantly when calculated relative to the water and $CaCl_2/MgCl_2$ fractions, respectively. However, a range of concentration factors still spanning almost two orders of magnitude for the water extractable fraction was observed, and the variation across all samples was similar to that when using the soil based concentration factor.

This variation is, however, biased by the concentration factor values determined for passiflora growing on an area that is contaminated by ^{226}Ra rich tailings from historic mining activities at the Rockhole Residues site in the South Alligator River Valley. In contrast, when considering natural soil profiles at Nabarlek and Ranger Uranium Mine only, concentration factors relative to the water extractable and the $CaCl_2/MgCl_2$ fractions, respectively, exhibit a much higher degree of uniformity. In particular, concentration factors relative to the water and $CaCl_2/MgCl_2$ fractions across four sites on the Ranger lease, covering 2 substantially different soil types (Chartres et al 1988), vary by a factor of only six compared with a variation spanning two orders of magnitude when using the total soil concentration (Figure 1).

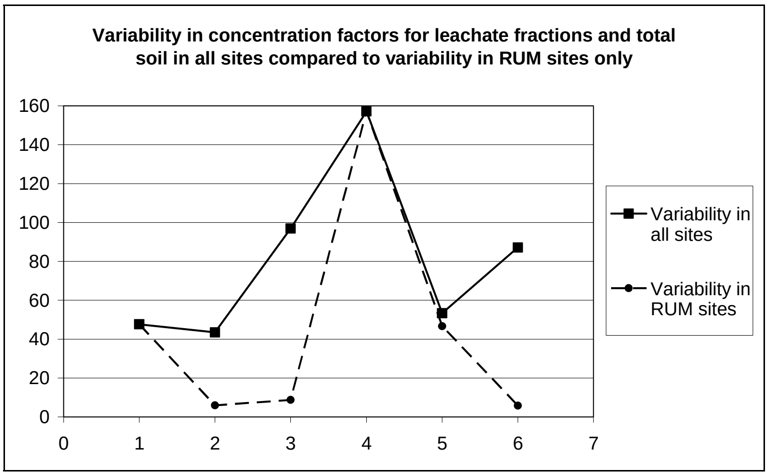

Figure 1 Variability in concentration factors (maximum:minimum) for each leach fraction at each site. Variability is shown considering all sites studied, compared to just RUM sites (from Medley 2007).

Future work

Final data analysis, in particular analysis of ^{226}Ra/^{228}Ra activity ratios in all samples and leachate fractions is underway to determine the fraction most suitable to use to (a) determine concentration factors for uptake of radium and (b) predict radionuclide activity concentrations in plants at the rehabilitated Ranger mine.

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