Indicators of Ecosystem Rehabilitation Success.

Stage Two – Verification of EFA Indicators.

Final Report

For the Australian Centre for Mining Environmental Research

Produced by David Tongway and Norman Hindley

CSIRO Sustainable Ecosystems

In association with Ben Seaborn
CMLR, University of Queensland

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Centre for Mined Land Rehabilitation

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EXECUTIVE SUMMARY

Field and laboratory investigations were undertaken at eight mines in Australia and one in East Kalimantan, Indonesia, covering bauxite, mineral sands, hard rock and coal. The principal objective was to verify that previously suggested indicators of minesite rehabilitation success produced by the Ecosystem Function Analysis (EFA) monitoring procedure properly represented soil properties measured by conventional field and laboratory procedures. Overall, the EFA indicators were shown to have a very high degree of correspondence with these measured soil properties.

Mined lands present unique and difficult places in which to do conventional soil measurements, most of which were developed for agricultural field application. Where verification was not fully met, the reasons behind this have been explained in the context of the specific locations.

An original design objective was for the field procedure to be generically applicable, this was reviewed at each mine and no changes were necessary. As the minesite locations varied from sandy deserts with 200 mm yr^{-1} rainfall to tropical rain forests with about 4000 mm yr^{-1} rainfall the method has shown very broad potential application. Many relationships are strong enough to use EFA indices in modelling soil stability, infiltration and nutrient cycling at hillslope and beyond scale. EFA has the potential to provide a spatially extensive data set over time at a fraction of the cost of biophysical measurements.

We developed a new way of representing the functional role of vegetation to overall ecosystem function at the hillslope scale by presenting vegetation cover on a layer-by-layer basis. Thus, we can show the value of the ground layer in ameliorating overland flow, soil erosion and the transport of organic matter as well as examining the role of the developing canopy in terms of wind interception, causing turbulence and thus reducing the capacity to retain resources in suspension. The sites where competent foliage is present may well become “sinks” for mobile airborne resources such as dust, organic matter and propagules.

The Stage 1 Final Report proposed that an analysis of the curve shape formed by the index values obtained by time series monitoring of rehabilitating lands should be the tool by which rehabilitation success is analysed. EFA has up to five landscape organisation indices and three soil surface indices, which can be used to delineate the ecosystem “trajectory”. Between them, these indices cover the range of scales and the complexity of issues that make up ecosystem function. Only one study site in Stage 2 permitted the full demonstration of this proposition, the Alcan bauxite mine at Gove. This was the only site to have a history of very similar rehabilitation technique used over a long time period. This enabled us to trace the full shape of the trajectory curve that denoted functional rehabilitation success. The “trajectory” proposal was demonstrated well enough to recommend implementing, as evidence of ecosystem rehabilitation success.

We supplied each major Sponsor with Site Reports soon after our initial field visit, followed up at half term by a Sponsors meeting at which we presented interim results. Final Site Reports have recently been prepared and this overall Project Final Report completes the reporting process. A revised technical manual is also being prepared as a final communication. This manual will replace the existing field manual and training course notes and will include the Excel templates and a greatly expanded image library. We expect to make this available as a CD and on the CSIRO, Sustainable Ecosystems and ACMER websites.

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For the Australian Centre for Minesite Environmental Research

ACKNOWLEDGEMENTS

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1. INTRODUCTION

This project is the second stage of a process to evaluate Indicators of Ecosystem Rehabilitation Success. The first stage evaluated the potential of a CSIRO developed approach called "Ecosystem Function Analysis" (EFA). The initial study was initiated by the ACMER (then ACMRR) and funded through the Australian Minerals Industry Association Ltd (AMIRA). That project commenced in March 1996 and concluded in September 1997.

The first study (Tongway *et al* 1997) showed that the EFA evaluation procedure could potentially be used for a wide range of mine types distributed across the continent without modification between sites. The EFA approach uses simple, rapidly assessed, visual indicators of surface processes mediated by both physical and biological components of the system, so repeated assessment is a cost-effective design feature. Overall, the indicators developed from the approach were shown to provide a wide range of information about the biogeochemical functioning of developing ecosystems on mined lands. The outputs appeared to agree with both measured attributes of ecosystems and also intuitive assessment of success. In addition, a procedure enabling the evaluation of "relative rehabilitation success" at different stages was proposed as a framework for future implementation (Tongway *et al* 1997). However, at the final Sponsors' meeting, it was decided that although considerable progress had been made towards project goals, the relationship between the EFA indicators and measured ecosystem variables had not been demonstrated in a sufficiently rigorous scientific fashion to create a strong case for Regulatory acceptance of the approach.

Accordingly CSIRO, through ACMER, was invited to submit a new proposal for a research project that would provide this level of evidence to the Industry. At length, the funding, the project and the personnel came together for a project commencement in April 2001 as ACMER Project No. 31.

2. PROJECT OBJECTIVES

There were four agreed objectives in the approved proposal for Indicators of Ecosystem Rehabilitation Success; Stage 2- Verification of Indicators and Transfer of Monitoring Technology project.

1. Conduct a program of scientific verification of the informing capacity of EFA indicators on a range of mine types (coal, bauxite, mineral sands, base metals and uranium) using conventional field and laboratory measurements.
2. Develop further links between existing methods of vegetation assessment and ecosystem function.
3. Report the results of testing the hypothesis by preparing papers for peer review and publication in the appropriate scientific literature.
4. Communicate the EFA techniques and the results of the Stage 2 study to minesite rehabilitators, regulatory agency personnel and community groups through the use of demonstration workshops, and prepare a new EFA manual for the Mining Industry.

These objectives were to be met by a coordinated study involving CSIRO and the Universities of Queensland and Western Australia. An MSc student from each University was included in the research team, with co-supervision by CSIRO and the relevant University. Towards the end of the first year of the project, the UWA student, Ms Vicki McAlister withdrew from the project and her work was taken over by the CSIRO team members, placing some strain on meeting time objectives and maintaining the budget outlays.

3. METHODOLOGY

3.2. What is EFA?

EFA is a monitoring procedure that establishes how well an ecosystem works as a biophysical system. It uses simple, visual, rapidly assessed indicators that focus on soil surface processes. As such it differs from conventional monitoring that typically records the presence and/or abundance of selected biota. EFA is comprised of four modules: a conceptual framework, a field methodology, a data reduction package and an interpretational framework. The conceptual framework was published in Ludwig *et al (*1997). The procedure uses a number of simple indicators easily assessable in the field. A full description of the EFA field methodology, including worked examples of real data, the data reduction software template and interpretational framework is available on the CSIRO Sustainable Ecosystems web page at:

www.cse.csiro.au/research/program3/efa/

Other relevant publications are Tongway and Smith (1989), Ludwig and Tongway (1992), Ludwig and Tongway (1995), Tongway (1995), Tongway and Ludwig (1996), Ludwig and Tongway (1996), Tongway and Murphy (1999).

The data are collected on line transects oriented in the direction of resource movement, which is usually down slope. There are two scales of data collection. At the coarser or hillslope scale, the line transect is differentiated into zones where resources tend to accumulate (patches) and zones where resources tend to be transported (interpatches). The width of the patches on the contour is also measured. These data produce a set of indicators of "landscape organisation" that can be used for time series monitoring, to see if the patches are growing larger or becoming more numerous, or the reverse, over time. At a finer scale, five replicates of each zone type are selected at random and the status of eleven indicators related to surface processes assessed. These individual indicators are assigned, by an Excel spreadsheet, to generate three emergent soil surface properties reflecting stability or resistance to erosion, water infiltration rate and nutrient cycling. The template is freely available on the web page above and contains some weighting factors so that the indices are well related to measured variables (from empirical evidence). With practice, each indicator takes about 5 seconds to assess. A manual provides illustrations of each indicator (Tongway and Hindley 1995). This process assesses the biophysical "quality" of the patches and interpatches, which is expected to improve over the course of rehabilitation.

EFA is designed for repeated use so that the development, or degradation, of a site can be assessed over time. The interpretation module proposes an analytical process that enables the user to examine the "trajectory" of the ecosystem being monitored and to use this information to decide if the site is converging on a "target" functional state, or needs further work to ensure ultimate success. Target values signifying rehabilitation success can be obtained by assessing "analogue" sites that represent the desired end point of rehabilitation. With EFA, a site may be deemed to be highly functional from a biogeochemical perspective, but have an inappropriate species composition, for example, weeds. This information might suggest that weed control is all that is necessary, and not major rehabilitation works.

An analogue site is one that is self-sustaining and has many of the attributes of the final landscape, particularly in respect to function. Note that the term "homologue" would be used to specify a landscape that would be replicated in every respect. Analogue sites would have similar slope, soil texture, resource regulation and many of the vegetation species required on the mature rehabilitation. Data from analogue sites forms part of the monitoring procedure through time, so that varying seasonal conditions result in a "band" of values to act as targets for rehabilitation.

3.2. Field and Laboratory measurements

Published procedures for physical, chemical and biological soil measurements were selected from the soil science literature for the verification process. As many measurements as possible were done in the field, so that data analysis and repeat measurements could be done on site. The budget did not allow for multiple site visits.

1. **Soil Stability**. To measure soil stability, intact cores of soil 75 mm in diameter and 50 mm in depth were sampled in metal rings from sites where the EFA assessment was made. These were returned to the laboratory, the soil was expressed from the ring in layers of 0 to10 mm and 10 to 30 mm. Wet-sieving a weighed sample through a nest of sieves assessed the stability of the soil fragments. A stability value was calculated by the procedure of Chaney and Swift (1984). At the Gove site only, a field-going water drop applicator was used to wet the soil with simulated rain directly in the field before sampling and sieving.

2. **Infiltration**. We used a disk permeameter (Perroux and White 1988) to assess saturated flow infiltration directly in the field. We initially attempted to also measure unsaturated flow infiltration, but technical difficulties in setting up this type of infiltrometer on minesites lead to the abandoning of this procedure. We recorded until a steady state of infiltration had occurred for some minutes.

3. **Nutrient cycling**. We used two procedures; soil respiration measured as evolved CO_2 in the field over a 24-hr period, which reflects biological activity in the soil and the pool size of biologically acquired soil nutrients. The latter included total nitrogen and carbon, plant available phosphorus and mineraliseable nitrogen. The underlying assumption being that as an ecosystem develop all these nutrients would tend to accumulate in the surface layers of soil due to plant growth, litter fall and decomposition, as has been shown in the general soil fertility literature of natural ecosystems.

There is a huge potential range of possible measurements, but those selected optimised the informing capacity within the limitations of the budget.

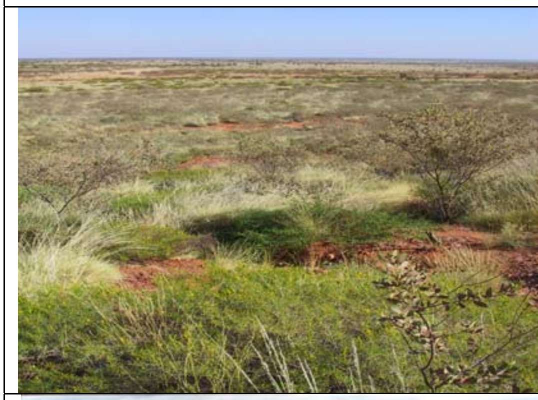
3.3. Verification Procedure

The EFA monitoring procedure generates three principal index values that represent respectively, soil stability or resistance to erosion, infiltration of rainfall and nutrient cycling. We tested those indices by regressing them against the field and laboratory measurements. The following criteria were proposed as comprising successful verification.

1. The regression relationship between the EFA index and relevant measured variables should have a high statistical relationship over a wide range of indicator values, with few outliers.
2. The relationship should preferably be linear, implying that the indicator sensitivity to environmental change was similar throughout the indicator range.
3. Data acquired from rehabilitation sites and relevant analogue sites should occupy the same data space (a sausage-shaped cloud of points), thus providing assurance that EFA index numerical values can be taken to have the same meaning throughout a given mine.

3.4. Sites Descriptions

	1. Brocks Creek gold mine (Anglo Gold) is located near Pine Creek, 150 km south of Darwin. Mining is now concluded and rehabilitation is well under way. The Faded Lily WRD in the background of the image is the location of our work. The rehabilitation methods for the lower, middle and top lift were all different, making the verification of EFA values difficult. *Eucalypt* savanna woodland (foreground) would be an appropriate vegetation structure, so couch grass established on lift 2 is incongruous.
	Carnilya Hill (WMC) is a former nickel mine located 30 km to the east of Kambalda in WA. Mining here is complete and rehabilitation has taken place in just two discrete time steps. There has been some erosion of the ripped WRD surface, but *Atriplex numularia* plants have established well. Decomposition of plant litter is stabilising the surface soil, which was initially dispersive. Feral goat grazing is having an affect on seedlings and needs to be controlled.
	Eneabba mineral sand mine (Iluka) is located 150 km south of Geraldton, WA, in a heath landscape. It remains an active mine but sections have been rehabilitated since the early 1970s, using a variety of techniques. Early rehabilitation has not progressed to the degree expected in 25 years, with bare soil areas remaining prominent, but more recent methods using an initial mulch comprised of slashed heath seem to have an improved the initial response rate.
	Gove bauxite mine (Alcan) is located on the eastern side of Arnhem Land, NT. It remains an active mine, but sections have been promptly and progressively rehabilitated since the early years with notable success. A successful technique was used right from the start and this is the only mine in the group where the trajectory of ecosystem development can be demonstrated. Topsoil management is the most benign of all mining procedures. Fire has been largely excluded from the rehabilitation, whereas fire is an annual occurrence outside the mine. This makes selection of an off-mine analogue site very difficult.

	Kelian is a gold mine (Rio Tinto) approaching closure, located near the equator in East Kalimantan, Indonesia. The reliable high rainfall, and availability and good management of high quality topsoil have resulted in spectacular growth. Full ground cover is achieved in just weeks, thus protecting the soil surface from rainsplash. The rehabilitation in the image is just 14 months old. "Horticultural" introduction of key species is a feature of the ongoing management of the rehabilitation. At about 4000 mm, this site has the highest rainfall of the study group.
	The Granites gold mine (Newmont) is about 600 km NW of Alice Springs, NT. There are a number of ore bodies. The image is of the Triumph WRD, looking out onto the Tanami Desert plain. This rehabilitation, comprised mainly of Spinifex is just a few years old, but the East Callie site also studied is dense *Acacia* shrubland. Erosion and deposition are active processes here despite having the lowest mean annual rainfall of the all the study sites at about 200 mm. Rocky surfaces prevented a full range of verifying data from being collected here.
	Gregory coal mine is located in the Bowen Basin, 200 km west of Rockhampton in Qld (BHP Billiton). It remains an active mine, but many areas mined in the past have been rehabilitated as rolling pasture grasslands intended for grazing by beef cattle. Dragline spoil is one of the more difficult media to rehabilitate because of the random mixture of soil materials from anywhere in the top 50 m of the regolith. The soils can be quite dispersive and rills may form early in the life of the rehabilitation. The available analogue site was a savanna woodland, and so not properly functionally comparable to the grassland in the rehabilitation.
	Nabarlek is a former uranium mine (*eriss*), located in west Arnhem Land, NT. There were two rehabilitation types examined here, the filled evaporation ponds (in image) and the former pit area. The EP area has subsided since being filled, creating a "perched depression" landform at the headwaters of 3 creeks. The area is substantially a grassland, but with areas of *Melaleucas*. The grass biomass creates a massive fire risk for young trees. The site is stable to erosion. The pit has mainly fire-prone *Acacias*, so also has some vulnerability to fire and erosion on its domed landform.

New Celebration gold mine (Newcrest) is 30 km SE of Kalgoorlie in WA. There are many ore bodies involved in the mining process, but we looked at the Pernatty WRD (image), which has been rehabilitated as a chenopod shrubland, though there are *Eucalypts* saplings present. Success has been patchy: good where water outflow from the top of the WRP is controlled and poor where runoff water concentrated from a large area is discharged down the batter slope. Soils are initially dispersive, but stabilize with plant litter decomposition. Second generation chenopods have established. A newly rehabilitated site at Mt Marion, about 30 km distant was also studied.

4. RESULTS

4.1. Summary of verification tasks

Table 4.1 summarises all the EFA soil surface index verification analyses from all the mines studied. The degree of verification is in table 4.2. The EFA indices were verified to a large degree: of the 9 mines x 4 indices matrix = 36 verification tests, 16 were strongly verified, 9 were moderately, 1 weakly verified, 9 not verified and for 2 it was not technically possible to be verify. Each of these circumstances is discussed in succeeding sections. “Strong verification” means that the points plotted in the correlation between the rehabilitation and relevant analogue site form a single “cloud”, so that the EFA index numerical value has the same biophysical meaning across all sites on the mine. “ Partial verification” means that whilst the rehabilitation sites and analogue sites each have EFA indices and measured properties that are internally well correlated, the respective regression equations are different, so that cross-calibration is needed to arrive at EFA index values to act as targets for rehabilitation. This cross-calibration would only need to be done once at each mine.

Table 4.1. Summary of the degree of verification for each mine, correlating the assessed indices against the measured variables. The meaning of the symbols is in Table 4.2.

Mine	Stability	Infiltration	Soil Respiration.	Nutrient Pool Size
Brocks Creek (Gold)	nv	nv	√√√	nv
Carnilya Hill (Nickel)	√√√	√√	√√√	√√√
Eneabba (Min. sands)	np	√√	√√√	√√√
Gove (Bauxite)	√√√	√√	√√√	√√√
The Granites (Gold)	√√	nv	√√√	√√√
Gregory (Coal)	√√√	nv	√√√	√√
Kelian (Gold)	√√	√√√	nv	√√√
Nabarlek (Uranium)	√√	nv	nv	nv
New Celebration (Gold)	np	√√	√√	√

Table 4.2. The verification classes used in table 4.1.

Class	Abbrev.	R^2	P
Strongly Verified	√√√	>0.60	< 0.01
Moderately Verified	√√	0.40 to <0.60	< 0.01
Weakly Verified	√	0.20 to <0.40	< 0.01
Not verified	nv	>0.20	< 0.01
Verification not Possible	np	-	-

4.2. Examples of successful verification of EFA indices.

Due to the large number of relationships deemed to have fully verified the EFA indices, only a sub-set will be discussed here. All the verification analyses are presented in the Appendix. The degree of verification between a measured variable and the EFA index is defined in Table 4.2. For a strong verification, the plotted data from both rehabilitation and analogue sites form a single “cloud” or “sausage”. Typically, this means that there is a linear regression, but sometimes in tropical ecosystems, there is an exponential relationship with an upper asymptote. EFA was deliberately designed to be more sensitive at the less functional end of the spectrum so that early rehabilitation could be assessed accurately in case a problem needing early attention was present.

4.2.1. Stability.

Data from the Carnilya Hill nickel mine site near Kambalda (Fig. 4.2.1a..) in the semi-arid lands of Western Australia and the Gove Bauxite mine (Fig. 4.2.1b.) in the seasonally humid tropics in the Northern Territory represent successful verification of the stability index. These mines have contrasting soil types, very different climates and differing rehabilitation techniques. The data represent a wide dynamic range of values of both the index and the measured variable.

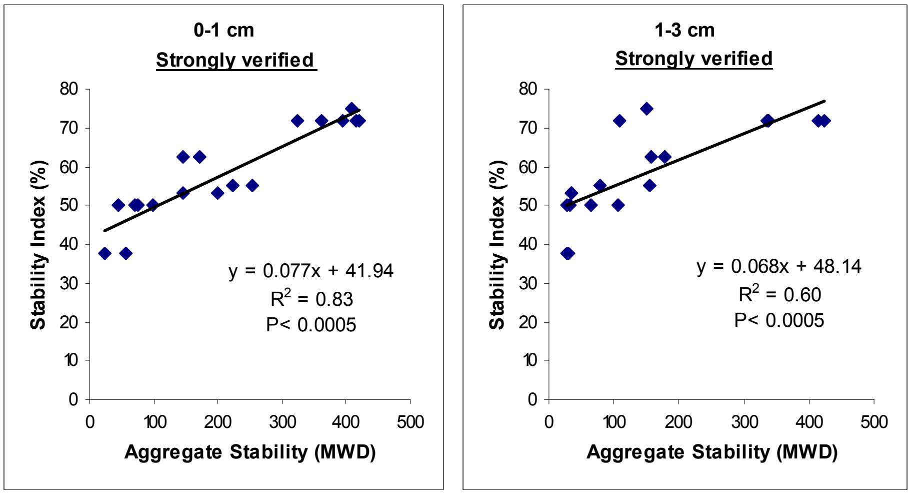


Figure 4.2.1.a.. Carnilya Hill site. The relationship between the laboratory measurement of stability (mean weight diameter) of the 0-1 and 1-3 cm layers of soil and the EFA stability index. The data show a good linear fit with high statistical significance across all rehabilitation and analogue sites. This verifies that the EFA stability index can be used to assess ecological development in the Kambalda district landscapes.

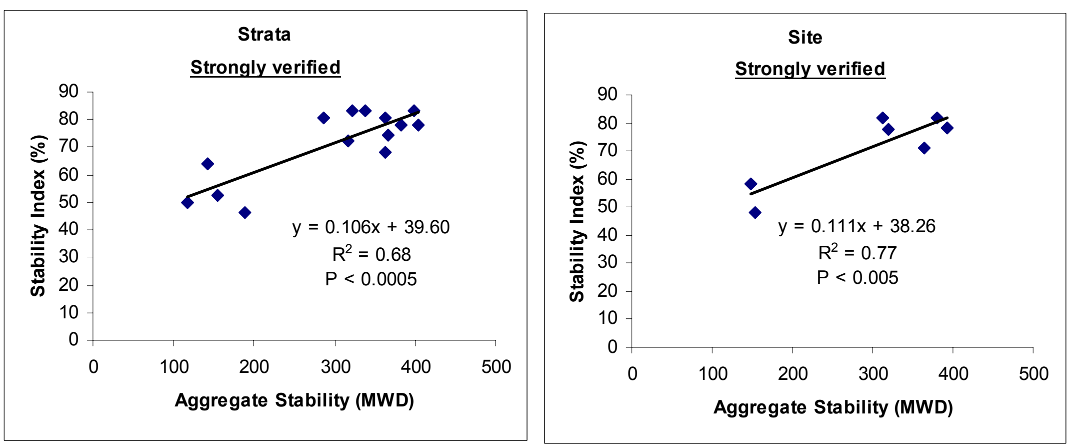


Figure 4.2.1.b. Gove site. The relationship between the EFA stability index and water stable aggregation measured in the field. The left hand graph represents the mean values of individual landscape zones and the right hand graph the mean site values.

4.2.2. Infiltration

Data from the Gove bauxite mine (Fig. 4.2.2.a.), a tropical woodland and from New Celebration (Fig. 4.2.2.b.) a gold mine near Kalgoorlie are presented as representing successful verification of the EFA infiltration index. These sites also differ in mining techniques, rehabilitation procedures, soil types and climate.

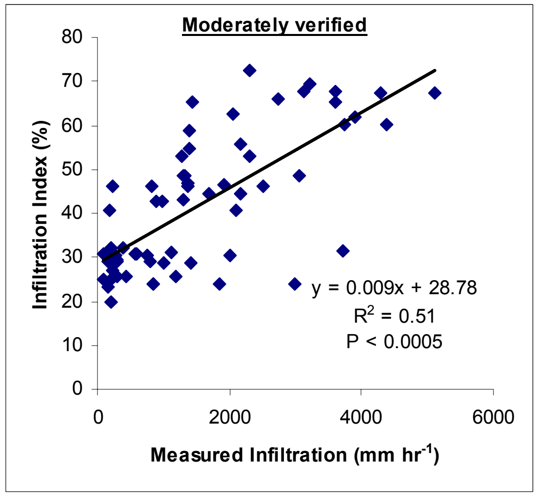


Figure 4.2.2.a. Gove. The relationship between the EFA infiltration index and the field measurement of saturated flow infiltration. All data for all sites are included and although there is a scattered in the data the large number of observations make the relationship significant.

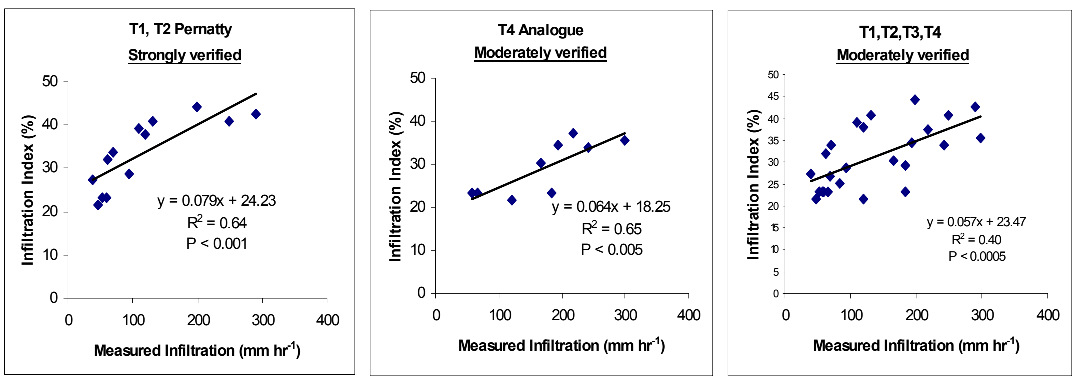


Figure 4.2.2.b. New Celebration. Relationships between the EFA infiltration index and the field measurement of saturated flow infiltration presented as linear regressions. The left hand plot contains the 2 rehabilitation sites on Pernatty, the middle plot the analogue site alone and the right hand plot the above 3 plus Mt Marion combined. Although there is more scatter in the combined graph, the relationship is statistically significant.

4.2.3. Soil Respiration

Data from the Gove bauxite mine, (Fig. 4.2.3.a.) and the Granites gold mine (Fig 4.2.3.b.) are presented as representing strong verification of the EFA nutrient cycling index using soil respiration as the measured property. Soil respiration represents the biological activity due to soil microbes and roots. It is an integrating measure, depending on the size of the microbial population and the quality of the organic substrate for them to process. In both cases the data from all rehabilitation and analogue sites studied at the mine are included in the analysis.

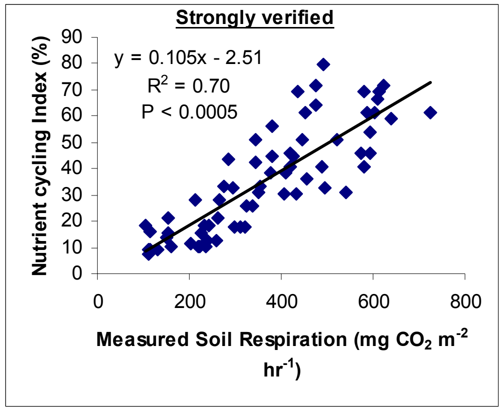


Figure 4.2.3.a. Gove Mine. The relationship between the EFA nutrient cycling index and soil respiration, using data from all studied rehabilitation, and the analogue sites. The good relationship verifies that the EFA nutrient cycling index can be used as a surrogate for costly and time-consuming measurements in monitoring rehabilitation progress.

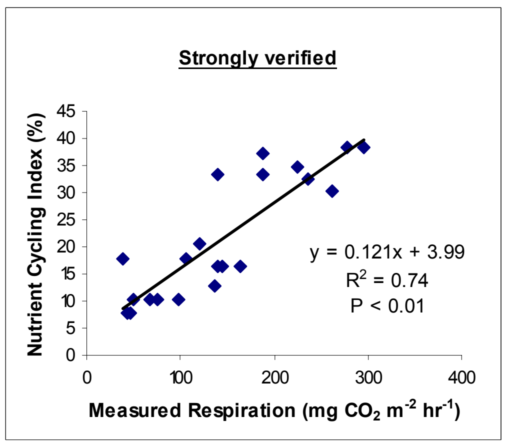


Figure 4.2.3.b. The Granites Mine. The relationship between soil respiration rate and the EFA nutrient cycling index. Data from all sites are represented.

4.2.4. Nutrient pool size.

Data from the Granites gold mine (Fig. 4.2.4.a.), the Nabarlek uranium mine (Fig. 4.2.4.b.) and the Gove bauxite mine are presented as representing successful verification of the EFA nutrient cycling index by examination of the soil nutrient pool size. This is not as simple a verification as the soil respiration procedure as there can be “old, recalcitrant” carbon and nitrogen present in the soil, especially that which comes from deep within the regolith and not “recent” nitrogen and carbon fixed by contemporary biological processes. In some mines, there was clearly a complex and heterogeneous mix of soil materials that militates against the use of C and N measurements as representing cycling nutrients.

Soil phosphorus estimated by dissolution in 0.5M sodium bicarbonate generally gave results not related to the nutrient cycling index. This is due to applications of superphosphate often provided at the outset of rehabilitation. That is, the P measured was a mixture cycling P and applied P.

Total soil sulphur was measured with C & N in an analyser but S chemistry on minesites is not well-enough understood to make use of the data in this study.

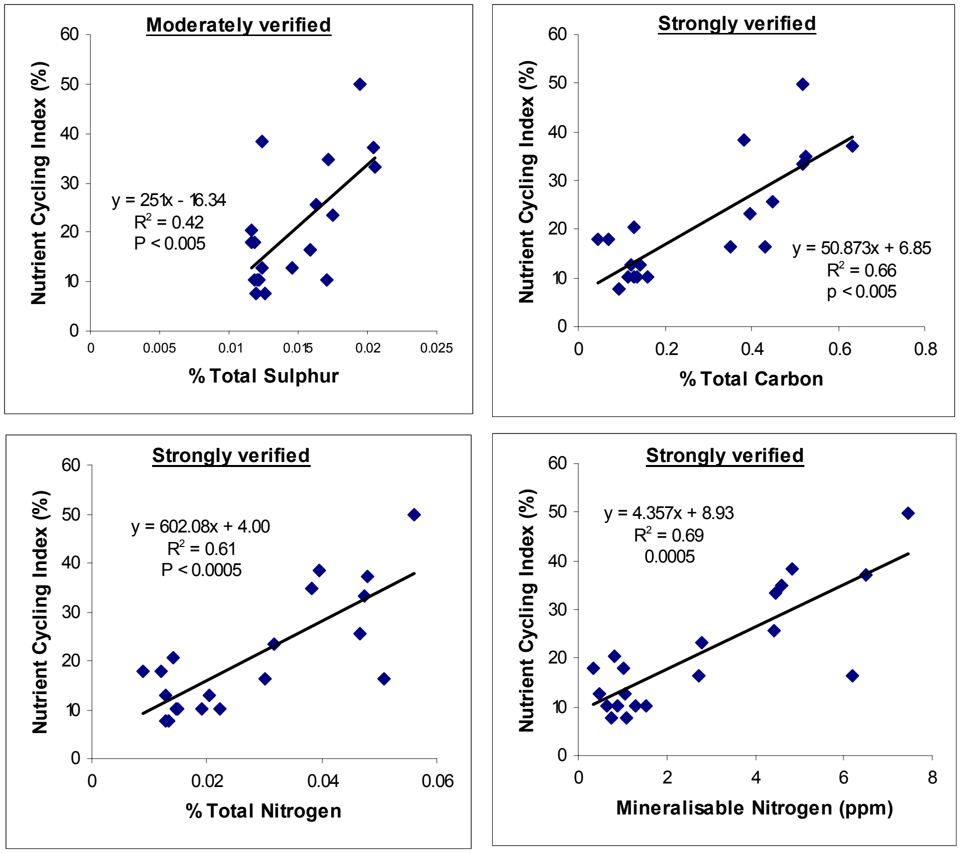


Figure 4.2.4.a. The Granites Mine. The relationship between the EFA nutrient cycling index and the concentrations of soil organic nitrogen and carbon, total sulphur and mineraliseable nitrogen from all sampling sites on the mine.

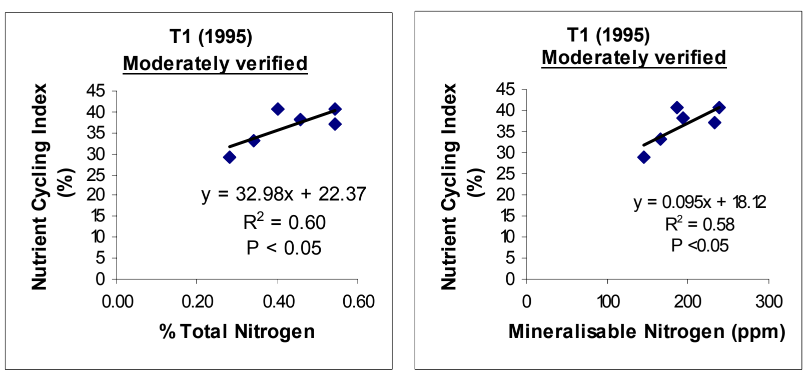


Figure 4.2.4.b. Nabarlek Mine. The relationship between EFA nutrient cycling indices with organic nitrogen concentration and mineralisable nitrogen pool size in the surface soil.

4.3 Examples where verification was partially achieved.

The extent to which verification was partially achieved is shown in the ensuing notes and graphs. Not all graphical relationships for all relevant sites are shown, but are available in the respective site reports and in the Appendix to this report.

a. Soil respiration at Brock's Creek. The nutrient cycling index was well related to soil respiration on the analogue site and also to the two rehabilitation sites where it was technically possible to make measurements. However, the two regression equations were quite different (Fig 4.3a). Combining all available data produced a non-significant and noisy relationship. We concluded that the soil differences between the analogue and the rehabilitation sites were such that the EFA values could not be reliably used across all the sites as representing the same measured property value. It is possible to calibrate the analogue site against the rehabilitation sites to rescale the Index appropriately.

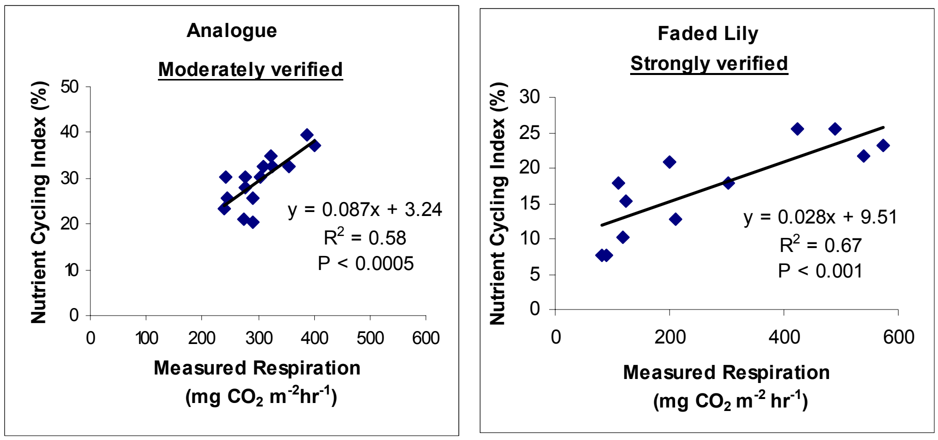


Figure 4.3.a. The regressions between measured soil respiration and the nutrient cycling index at Brocks Creek, showing that the analogue site and the rehabilitation sites have different response shapes, though both have acceptable correlations, taken singly. There is higher biological activity in the rehabilitation sites than in the analogue for a given EFA index value. Neither graph covers the full index range by itself.

b. Nutrient pool size at Brock's Creek. As with the soil respiration, there were some good within-site relationships (Fig.4.3.b.). Combining the data from all sites produced a very noisy graph. Cross-calibration of the analogue with the rehabilitation sites was not fully possible in this case, suggesting that soil materials used in different stages of rehabilitation were quite diverse to begin with.

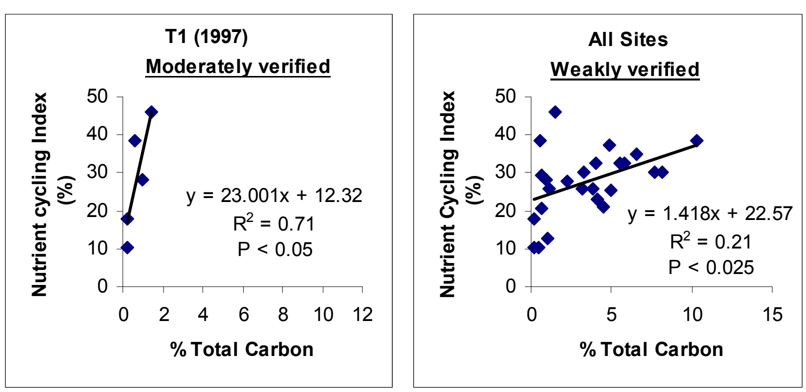


Figure 4.3.b. Illustrates that the correlation between measured % Total Carbon (0-1 cm) and EFA Nutrient Cycling Index. The lower lift on Faded Lily had a different slope compared with sites combined.

c. Soil infiltration at Eneabba. Within-site correlations (Fig. 4.3.c.) were quite acceptable but each site had a different regression equation (slope and intercept) (Fig 8.2), so that EFA index values could not be directly used to assess the degree of rehabilitation success or set target values. Cross-calibration would provide an appropriate link. When the infiltration rate rises above about 600 mm hr^{-1} on the rehabilitation sites, the EFA index is a poor predictor of actual infiltration. The individual indicators making up the infiltration index have been selected to discriminate soils with low to moderate infiltration. This capacity can be seen on the graph for infiltration rates below 600 mm hr^{-1}. At Eneabba, deep non-cohesive sands with no trace of a physical surface crust can have very high infiltration rates, as shown. A similar situation occurs at Nabarlek with highly structured clay soils when infiltration was measured in the dry season.

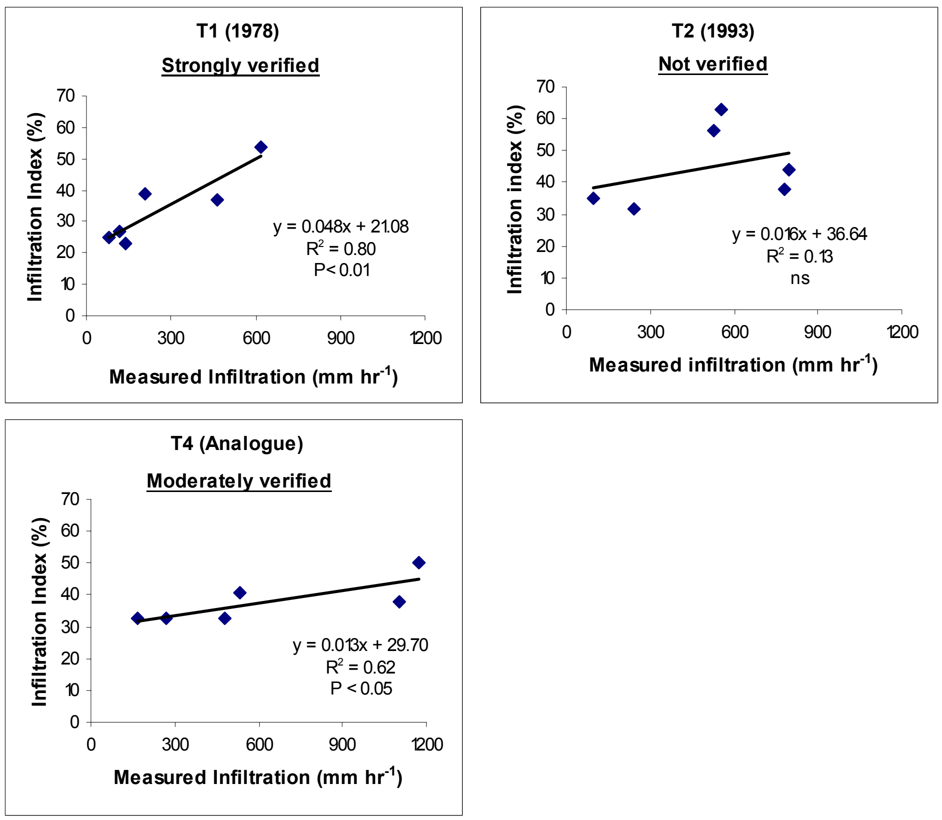


Figure 4.3.c. The relationship between the EFA infiltration index and measured infiltration on rehabilitated and the analogue sites at Eneabba. The within-site relationships are good, but the gradients of the relationships differ significantly.

d. Soil respiration at Eneabba. Within-site correlations showed good relationships but combining sites together produced a noisy plot (Fig. 4.3d). There were differences in the rehabilitation procedure at each of the rehabilitation sites, so the differences are not surprising. A very recently established site had high respiration, implying that current procedures, using a substantial application of shrub mulch give a biological kick-start to the system whereas former procedures did not. Cross-calibration is possible, however.

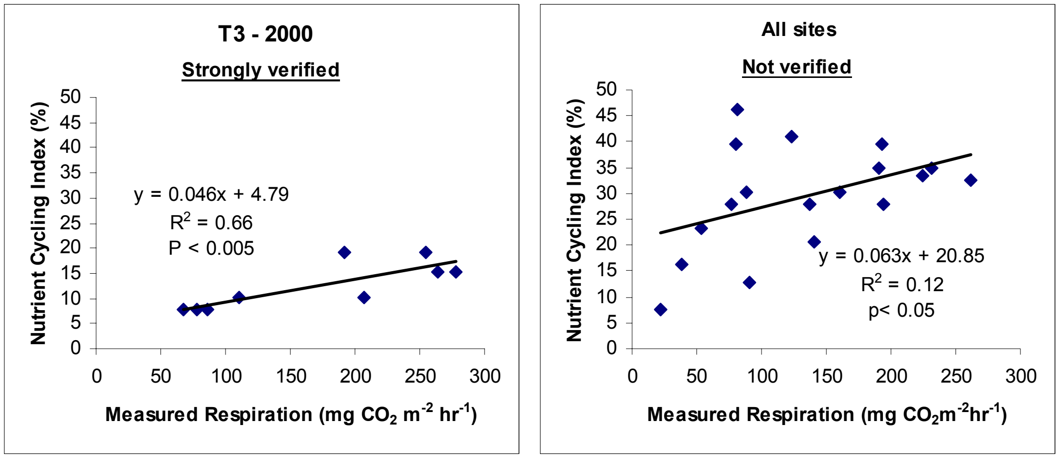


Figure 4.3.d. The within site correlations for T3 (2000 rehabilitation) were whereas combining all sites produced a very noisy and un-useable relationship.

e. Soil respiration at Nabarlek. Again, there were good within-site correlations, but between-site comparisons were incompatible to the extent, with existing data, that cross-correlation is probably not possible (Fig. 4.3.e.). A new grassy analogue site should be selected, that will be well away from the mine area, probably a small flood plain.

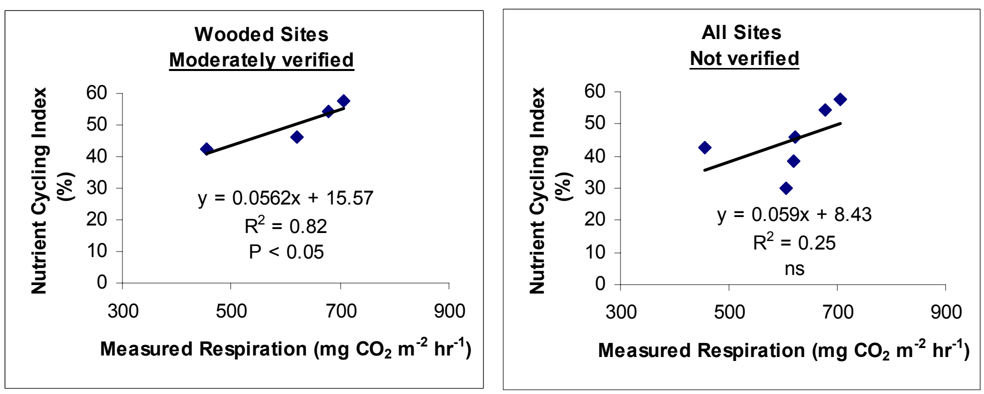


Figure 4.3.e.The relationships between measured soil respiration for the wooded sites (left) and all sites (right), and the nutrient cycling index.

The wooded sites were consistent across the range of analogue and rehabilitation but the grassy rehabilitation sites had a different response (lower points added in fig 4.3.e. right). This implies that grasslands and woodlands are not likely to be comparable. Calibration with the nearby analogue site would not be appropriate in this case and a new analogue site (off the mine area) should be selected.

f. Soil respiration at New Celebration. The rehabilitation sites had a combined data set that showed a good correlation, but which had a different regression equation to the analogue, which was also internally consistent (Fig. 4.3.f). Cross-calibration to reconcile this difference is possible.

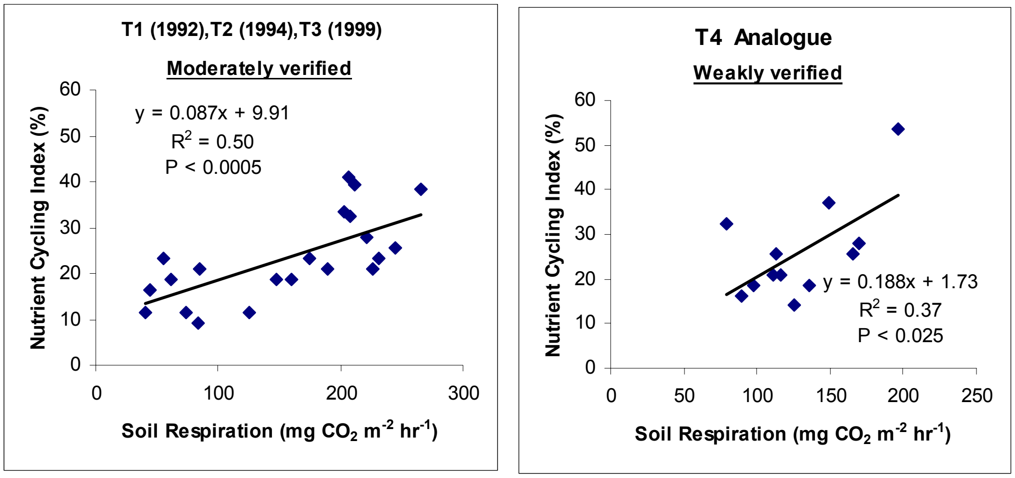


Figure 4.3.f. Combined Pernatty sites and Mt Marion rehabilitation sites (T1, T2 and T3), and the Analogue site (T4) showing the relationship between the nutrient cycling index and soil respiration rate. The slope of the relationship between the rehabilitated sites and the analogue were different, although individually significant, so could not be combined into a single graph.

4.4. Examples where verification was not possible.

At some sites, the soil surface conditions were such that some verification measurements were not technically possible within the financial resources and instruments at hand. Each of these circumstances will now be discussed in turn. Obviously, there are no data available for these sites

a. Stability at Eneabba. The soil here comprised non-cohesive sands that had no natural soil aggregation or "clumping" as such, and in our laboratory test no data was generated that properly reflected soil stability on wetting. Using a rainfall simulator and measuring sediment yield would better assess stability.

b. Infiltration at The Granites. Soil rockiness at the analogue site and one of the rehabilitation sites prevented a correlation being developed (Plate 4.4.c). Portable rainfall simulation equipment might be able to generate useful data.

Plate 4.4. This stony surface at The Granites prevented infiltration measurements with the instrument available.

c. Microbial respiration at Kelian. A minimum 24 hr. respiration period is necessary to obtain reliable values and we were not able to do this at Kelian as the respiration rates were very high, saturating the KOH solution too quickly. A return to the site with new field equipment is not now possible.

d. Stability at New Celebration. These samples were taken with the expectation that they would be processed at the UWA laboratory. With the withdrawal of Ms. Vicki McAlister from the project, the samples were ultimately sent on to Canberra for analysis, but arrived in such a disturbed state (powder!) that a soil stability test was not possible. However, a re-sampling, now not possible within the budget would most likely produce useful data as the soil has an aggregate structure suitable for water stable aggregation analysis.

4.5. Where verification failed.

Nabarlek infiltration. The soils on the evaporation ponds at Nabarlek were well-structured clays and we were present in the field in the mid dry season by which time the soil was dry to 50 cm (Plate 4.5). We measured extremely high infiltration rates on these soils, of the order of 2000 mm h^{-1}, with no relation whatever to the EFA index. Gillman and Bristow (1990) have also recorded similar values in well-structured clay soils on the Atherton Table-land when they were initially dry. The EFA index does not take account of the soil fabric within the profile, so no cross-correlation is possible. Advice from *eriss* personnel who visit Nabarlek during the wet season tell of water logging on the evaporation ponds. That might be a time to measure field infiltration, though it would be technically difficult to do so at those times. It is important to note that the index did not predict high infiltration when low infiltration was the reality. That is, no problem was overlooked. We found a similar problem at a newly developed site at Kelian that was comprised of paddock-dumped well-structured clay soil materials.

Plate 4.5. The clay soil from the grassy evaporation pond rehabilitation at Nabarlek, showing copious amounts of macro organic matter in the surface undergoing decomposition. Note the soil "darkening" and the open friable/fractured structure of the sub-surface clay when dry. These properties confer very high measured infiltration when as dry as this. In the wet season, the clay would swell and air voids would be eliminated: the infiltration would more closely resemble saturated hydraulic conductivity.

4.6. The functional role of vegetation: a new graphical index.

Typically, vegetation development assessment on mines looks at species composition and growth rates. These assessments use well-developed and time-honoured procedures that have been in the literature without substantive modification for decades, and with a history extending back well over a century (Bonham 1989). These methods remain important, but like many other monitoring procedures, represent past behaviour without a strongly developed predictive capacity. That is, if species X is missing from the rehabilitation, there is nothing in the basic data that can assist in deciding why this is so or what to do about it. Individual observers may use their experience and intuition to make practical suggestions, but these are not intrinsic to the data.

In working towards addressing Objective 2, we have devised a vegetative index that has value at "site" or "hillslope" scale and refers specifically to the role of vegetation in ameliorating resource transfer by wind and water. This adds to the information collected in the "landscape organisation" (L/O) stage of EFA data collection. In L/O, both biotic and abiotic features that regulate the flow of resources are assessed on a line transect. This provides an assessment of the "mix" of resource regulation processes, but probably under-samples the role of the variety of vascular plant life forms.

The new vegetation index involves collecting data on plant cover and structure and differentiating the data in 0.5 m height classes, so that the role of vegetation in affecting surface flow can be distinguished from the role of canopy in affecting wind flow and turbulence. Typically, we collect data according to life form: grasses, low shrubs, tall shrubs and trees in separate assessments. The data are collected by "distance measuring, plot-less" procedures such as point-centred quarter (PCQ) for dense vegetation and wandering quarter (WQ) for sparse vegetation (Bonham 1989). At each plant, we measure the major and minor canopy dimensions, total height, height from the ground to the canopy base, and canopy density (McDonald et al 1990). These data are displayed as cover in square metres per hectare (x-axis) in 0.5 metre height classes (y-axis). This presentation provides a pictorial view of vegetation canopy distribution as a cross-section (Fig. 4.6.a). This presents data representing 3-dimensions on a 2-dimensional diagram. These data can be analysed by the "ecosystem trajectory" procedure described in section 4.7, below. An expectation for successful rehabilitation would be a high initial ground cover spread, followed by a vertical extension of canopy as shrubs or trees developed, heading towards values exhibited by the analogue site. Reaching analogue site values would not be expected in the time frame of deciding on rehabilitation success, as some life forms take many decades to fully develop. It is the shape of the trajectory as shown by regular monitoring that would comprise the evidence for success in rehabilitation.

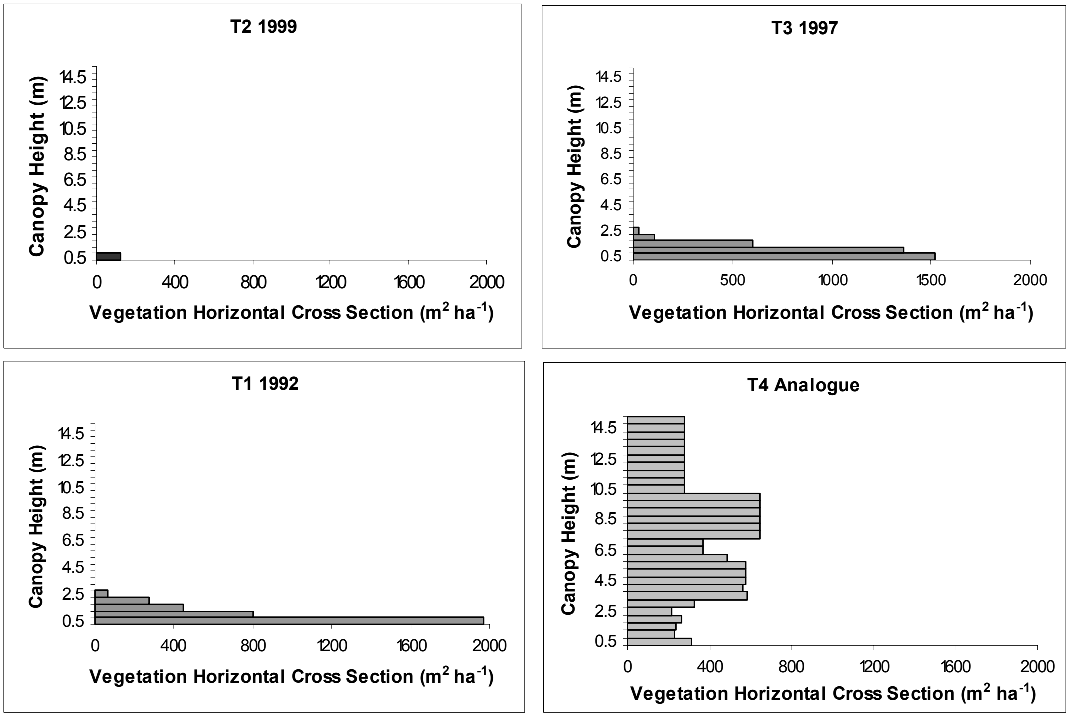


Figure 4.6.a. The vegetation horizontal cross sectional area for three rehabilitation sites and the analogue at Carnilya Hill, resolved into 0.5 metre vertical height intervals. There is still a considerable difference in the functional vegetation structure between the rehabilitation and the analogue. However, Eucalypt saplings growing on the rehabilitation sites are now 3 m high, so appropriate progress is being made.

Studies of non-mined lands subject to degradation by management have shown that good ground cover of vegetation and plant litter is a common feature in all highly functional landscapes. Conversely, on dysfunctional landscapes, lack of vegetation at ground level or lack of plant litter causes resources to be transported by wind or water too rapidly across the surface, resulting in too little water infiltrating or excessive loss of soil or plant litter by erosion. This is a concept that applies to mined lands as well. Initially of course, it is the geotechnical set-up of the mined lands that provides the initial site stability, but over time, biological development should dominate the ecosystem function. In Stage 1, this concept was presented as in Fig 4.6b. EFA data can be discriminated to show this transition from physically dominated to biologically dominated processes.

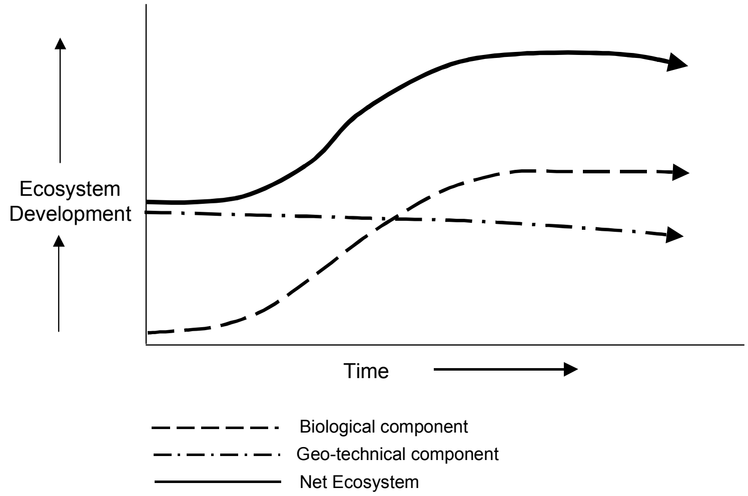


Figure 4.6.b. The change from Physical to Biological control on Rehabilitation over time and overall system response.

4.7. Assessment of rehabilitation success

4.7.1. The conceptual framework and practical application.

Most monitoring systems or procedures are focused solely upon showing that the proposed indicators suitably reflect the status of the system under examination. Many have been developed to assess degradation scenarios. EFA explicitly sets out to not only track the system status over time but also to specify a target region for EFA index values for self-sustaining ecosystems and assess the rate at which the system is approaching that target region. These design features are vital for full practical implementation. EFA data is well placed to achieve these design criteria because the emphasis is on ecosystem processes, rather than biota as such. Deficient or slowly changing process rates quickly indicate to rehabilitators the nature of the problem they face, whereas if, say, ants are the indictor, the nature of needed restitution is not clear and requires further investigation. It is the focus on processes that makes EFA a tool that can be used across a wide range of landscape/climate combinations and land use variation.

In Stage 1, the concept of "ecosystem trajectory" was proposed: the comparison of rehabilitation sites over time with appropriately selected analogue sites as the means of assessing rehabilitation success (Fig. 4.7.a). The curves would be generated by time series monitoring, plotting successive values of each index over time and examining the emerging curve shape. In the early stages of rehabilitation, assessment should be relatively frequent in order to observe the initial response rate. These data would give rise to a true time-series graph in normal practice. This concept arose from empirical observations of rehabilitation progress on a large number of mines: successful rehabilitation was characterised by a steep initial response, slowly flattening off over time, whereas less successful rehabilitation was characterised by either very slow response rate or a "saw-tooth" trajectory with no perceptible functional improvement. The data collected to develop this concept were from pseudo time series; sites assessed at a single time at different time intervals from the commencement of rehabilitation. This would never be as accurate as a true series where the same site is monitored over time. Nevertheless, a potentially useful concept emerged.

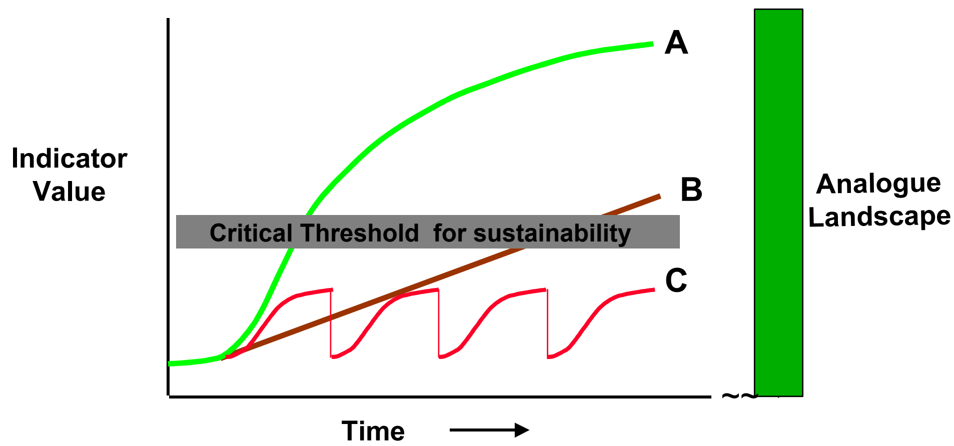


Figure 4.7.a. Three contrasting ecosystem function trajectories. Trajectory A shows a satisfactory response over time, passing rapidly through a critical functional threshold and continuing to improve. It is likely to be self-sustaining. Curve B represents a system that develops slowly and hence subject to stochastic events and possible failure. Curve C represents a system that frequently succumbs to external threats and fails to develop into a self-sustainable system.

In this project, we were able to provide a demonstration of this concept, but only at the Alcan Gove Bauxite Mine site. This site was the only one where a very similar rehabilitation technique had been regularly used for a continuous 26-year period. All other mines in the Stage 2 study had either changing techniques over time or had been operating for too short a period, or both for a proper demonstration of the concept. We had independently looked at the concept in a rangeland context for the National Land and Water Audit (Tongway & Hindley 2000), and found that a sigmoidal curve was particularly useful in describing the behaviour of the data. Previous practical and theoretical studies had already strongly suggested that this form of the curve was particularly appropriate and useful (Graetz & Ludwig 1978, Krebs 1972, Noy-Meir 1981). This curve shape indicates that, in the minesite context, after the initial rehabilitation landscape set-up, there was a brief plateau period followed by a rise in landscape function as the biota established and became active in ecosystem processes that gently flattened off after some years, eventually forming an upper plateau representing the biogeochemical potential of the site. This latter region is the “target” mentioned earlier and depends on the parent soil material and the climate. In practice, this value in mined lands, would come from a set of analogue sites similar to the final rehabilitation landscape phase in terms of slope, soil surface properties, vegetation composition and land use. Assessing the analogue sites would be an integral part of monitoring rehabilitation and in practice would generate a “band” of values depending on seasonal effects as well as stochastic events like storms, droughts and fire. Fig. 4.7.b shows the sigmoidal curve derived from a pseudo time series analysis of the Gove sites over a 26-year time span for the stability index. The sigmoidal shape conforms to the conceptual shape very neatly, with the exception of year 8.

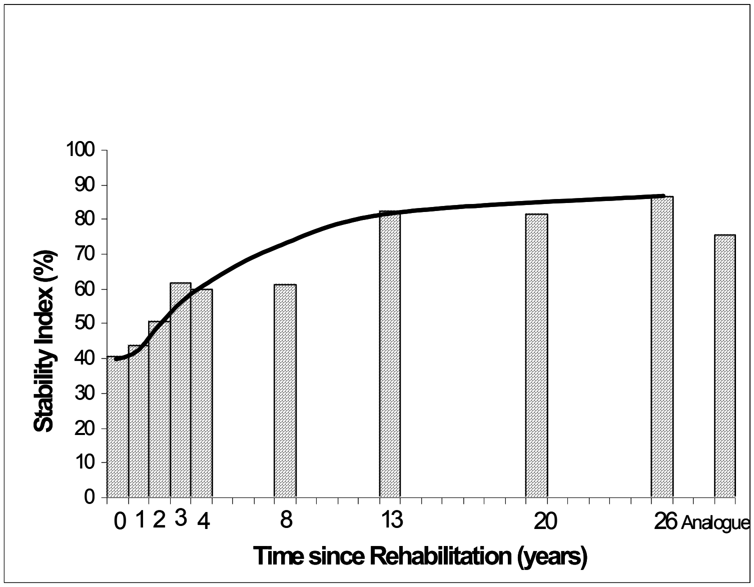


Figure 4.7.b. The sigmoidal curve reflecting the trajectory of stability development at Gove. Note that the analogue site value is lower than the older rehabilitation sites, due to effect of frequent burning of the analogue site.

This set of curves shows a considerable difference in the time to achieve plateau values. Both infiltration (Fig 4.7.c) and nutrient cycling (Fig. 4.7.d) rely on the long-term development of the vegetation and the increasing activity of soil "ecosystem engineer" fauna (Lavelle 1997). However, looking at the rate of increase of the indices at early times remains a powerful tool. At Gove, the utility of the analogue concept is affected by the unremitting fire regime in lands outside the mine.

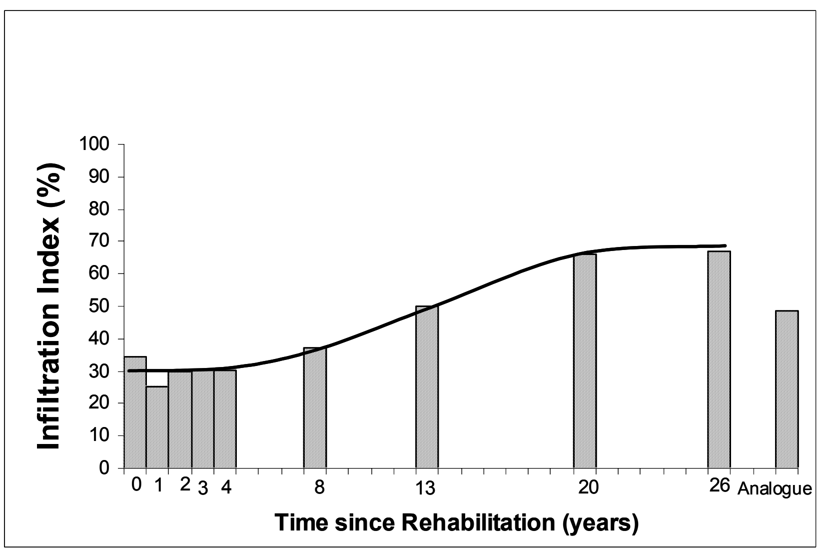


Figure 4.7.c. The sigmoidal curve reflecting the trajectory of infiltration development at Gove. Note that the development "lags" the stability curve (Fig 4.7b).

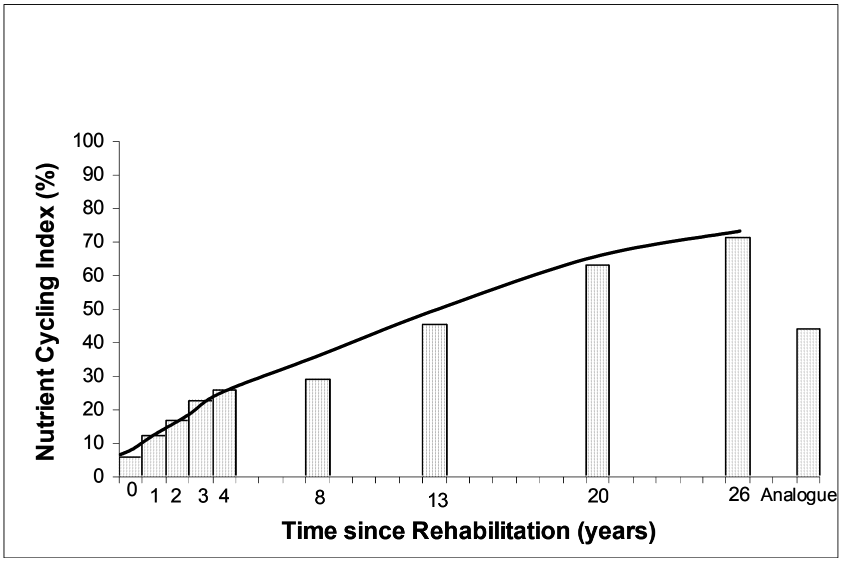


Figure 4.7.d. The trajectory of the nutrient cycling index at Gove. The full sigmoidal shape is not evident. The ecosystem has not yet reached a true plateau, even after 26 years, due to the growth of *Eucalyptus tetradonta*, which will continue for some time yet, with increasing canopy biomass and litter fall. However, the utility of the early steep rise of the sigmoidal curve remains as a useful tool in assessing ecosystem development.

5. CONCLUSIONS

5.1. EFA index verification.

The EFA indicators were shown to have a very high degree of verification with the measured properties in the surface soil. Mined lands present unique and difficult places in which to do conventional soil measurements, most of which were developed for agricultural field application. Where verification was not fully met, the reasons behind this have been explained in the context of the specific locations.
The EFA procedure was the same for all the minesites, which was an original design factor: generic procedure. As the sites varied from sandy deserts with 200 mm a^{-1} rain fall to tropical rain forests with about 4000 mm a^{-1} rainfall the method has shown very broad potential application. It may well be possible to refine the procedure for use at specific locations to give results with higher precision, or greater sensitivity, but this is not necessary for monitoring, especially if the ecosystem trajectory process is followed.
The quality of many of the relationships were sufficient to use to model soil stability, infiltration and nutrient cycling if hillslope and above scale studies were required. EFA could provide an extensive data set of adequate quality at a fraction of the cost of direct measurements.

5.2. Functional vegetation data.

We have proposed a new way of representing the contribution of vegetation to ecosystem function at the hillslope scale by representing the role of vegetation layer by layer. By this means, we can show the value of the ground layer in ameliorating overland flow and erosion of soil and transport of macro-organic matter at the same time as the role of developing canopy spread that will intercept wind, causing it to become turbulent and losing the capacity to hold resources in suspension. The sites where competent foliage is present may well become "sinks" for airborne resources such as dust organic matter and propagules.

5.3. Ecosystem trajectory: a tool to judge rehabilitation success.

The Stage 1 final report proposed that an analysis of the curve shape formed by the index values obtained by regular monitoring of rehabilitating lands should be the tool by which rehabilitation success should be judged. EFA has up to five landscape organisation indices and three soil surface indices with which to look at the ecosystem "trajectory". Between them, these indices cover the range of scales and the complexity of issues that make up ecosystem function. Only one study site in Stage 2 permitted the full demonstration of this proposition. This was because a very similar rehabilitation technique had been used over a long time period, which enabled us to trace the full shape of the trajectory curve. This was a useful demonstration in showing functional rehabilitation success. The Eneabba site had an example of 22-year-old rehabilitation that had made slow functional progress, but due to the "once-off" assessment, the shape of the trajectory was not possible to delineate. The "trajectory" proposal appears to be well enough demonstrated to recommend implementing as an overall indicator of ecosystem rehabilitation success.

5.4. Communication of the Project outcomes.

We supplied each major Sponsor with Site Reports soon after our initial field visit, followed up by a Sponsors meeting at about half term at which we presented data already processed. Draft Final Site Reports have recently been prepared and sent to the relevant Sponsor with this overall Project Final Report complete the reporting process. A revised technical manual is also being prepared as a final communication. This manual will replace the existing field manual, the training course notes and will include the Excel templates. We expect to make this available as a CD or on the CSIRO Sustainable Ecosystems and ACMER websites.

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7. APPENDICES

These appendices contain the processed data from the project. Each mine's data is presented in the same order.

7.1 Brocks Creek

7.1.A. Stability

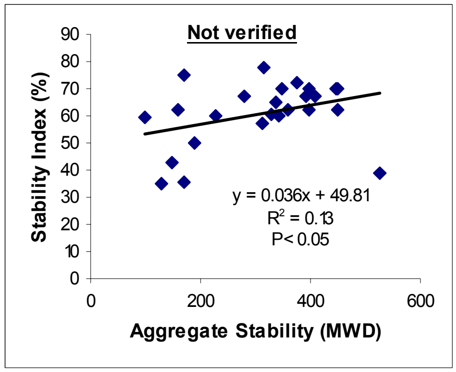
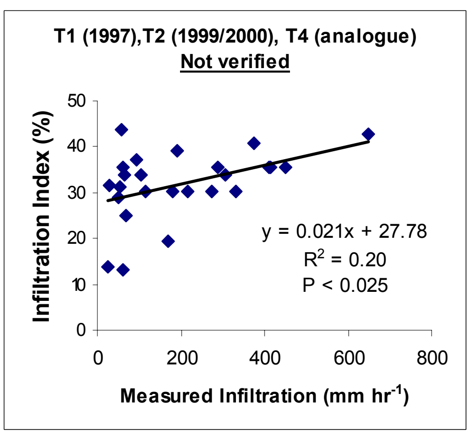


Figure 7.1.a. The relationship between measured aggregate stability and the EFA stability index. The relationships for individual sites were poor or non-existent and all sites lumped give a noisy plot.

7.1.B Infiltration



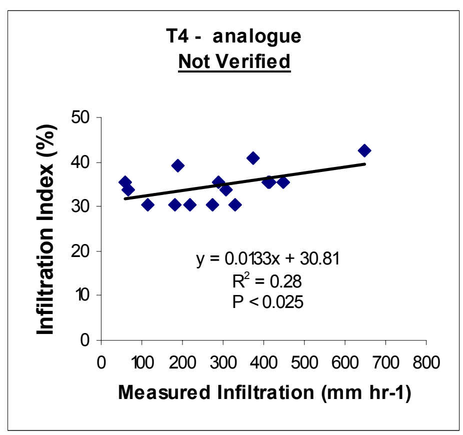


Figure 7.1.b. Due to the rocky nature of the surface, it was difficult to set up the infiltrometer without disturbing the soil and thus the relationships obtained were poor.

7.1.C. Soil Respiration

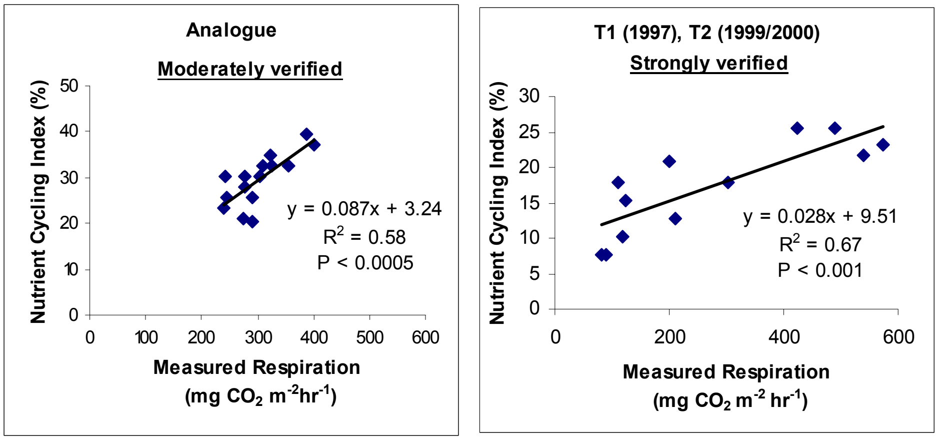


Figure 7.1.c. Soil respiration as a function of the EFA nutrient cycling index. The analogue site and the rehabilitation sites had good independent relationships, but different response functions.

7.1.D. Nutrient Pool size.

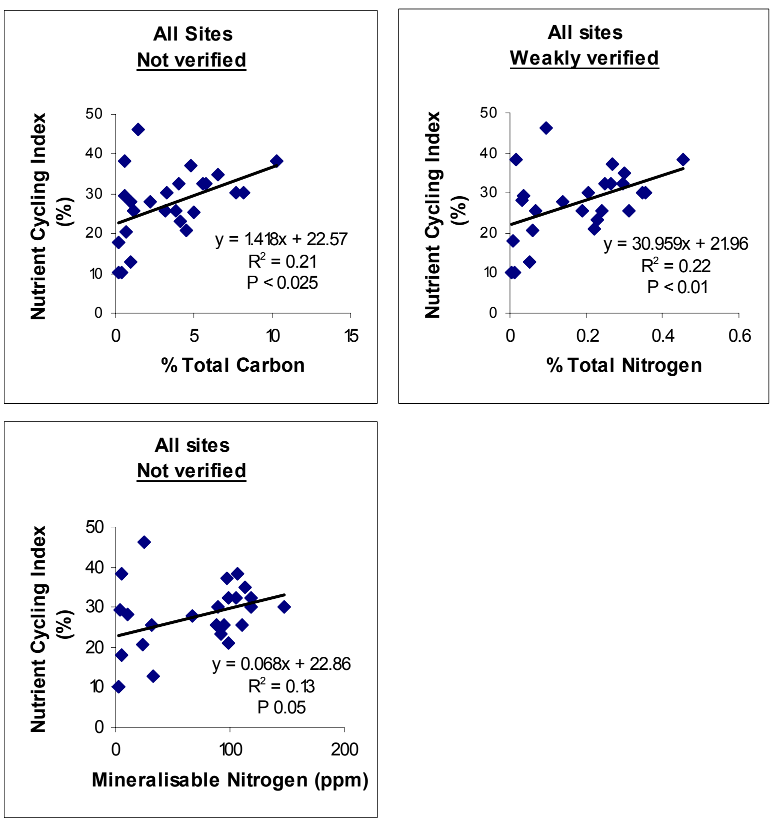


Figure 7.1.d. The relationships between total N, total C and mineralisable N verus the EFA nutrient cycling index.

7.1.E. Functional Vegetation

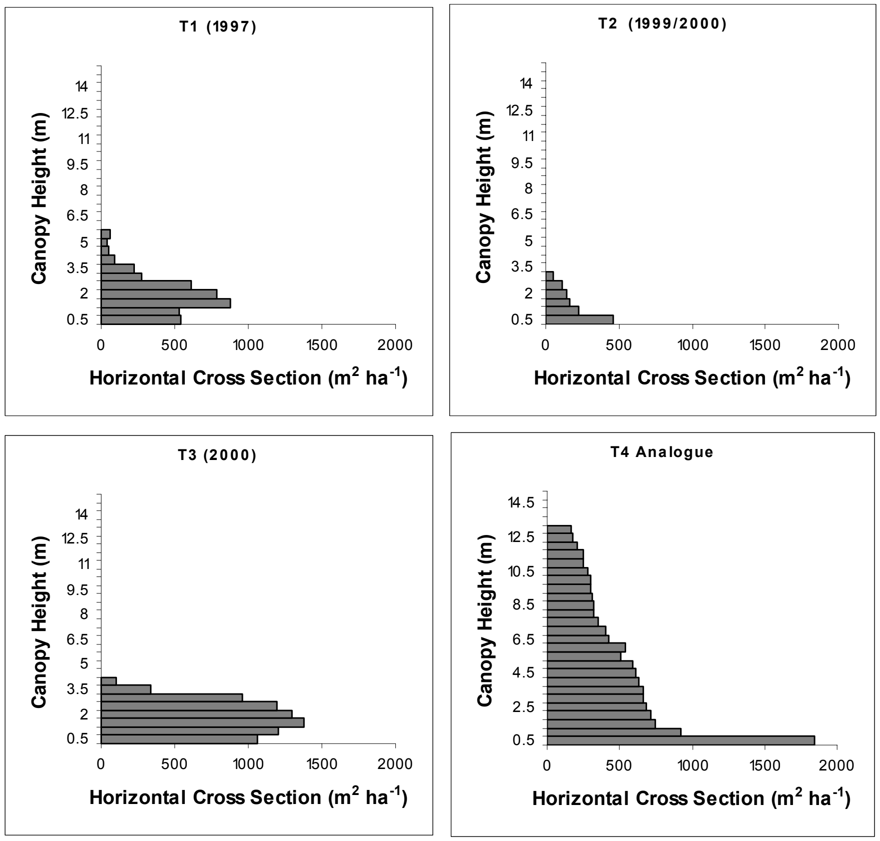
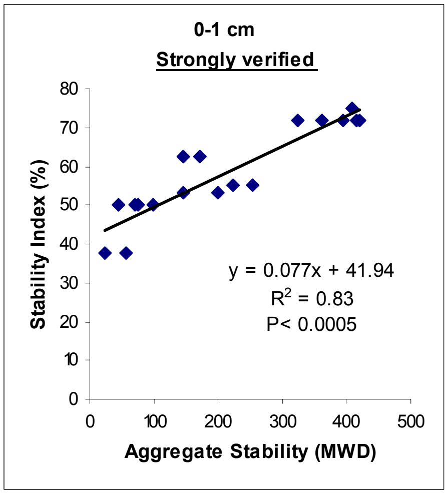


Figure 7.1.e. The horizontal cross sectional area of the foliage is plotted against the canopy height in 0.5 metre intervals to show the vegetation development over time. It would be anticipated that successful rehabilitation would reach the values of the analogue in a reasonable time.

7.2 Carnilya Hill

7.2A. Stability



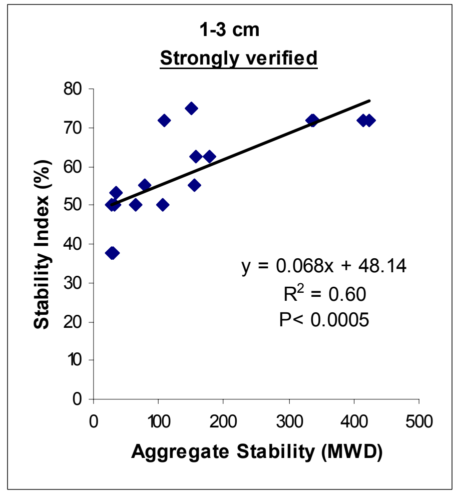


Figure 7.2.a. show the relationship between the laboratory measurement (MWD) of stability of the 0-1 and 1-3 cm layers of soil and the EFA stability index. These data show that a good linear fit with high statistical significance for the data across all rehabilitation and analogue sites. This verifies that the EFA stability index can be used to assess ecological development across all the Kambalda landscapes.

7.2.B. Infiltration

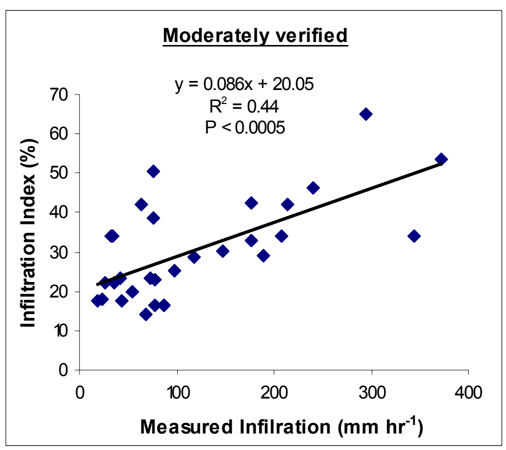


Figure 7.2.b. The relationship between saturated flow infiltration rate and the EFA infiltration index.

7.2.C. Soil Respiration

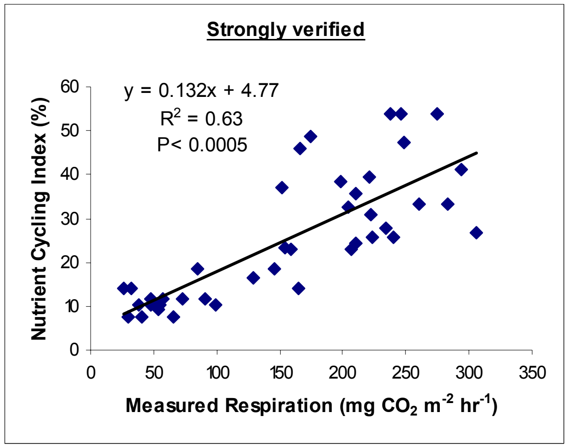
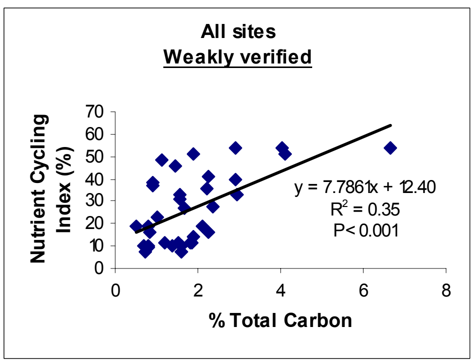


Figure 7.2.c. The relationship between soil respiration rate and the EFA nutrient cycling index for all sites combined at Carnilya Hill.

7.2.D. Nutrient pool sizes



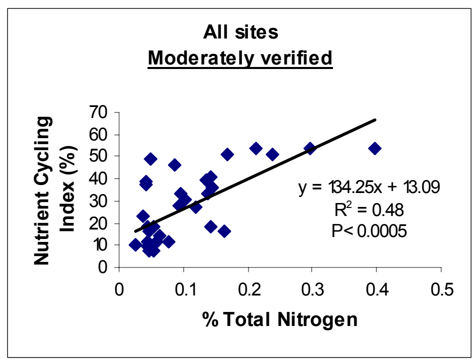


Figure 7.2.d.(i) The linear relationship between total organic carbon and total nitrogen and the EFA Nutrient Cycling Index across all sites at Carnilya Hill.

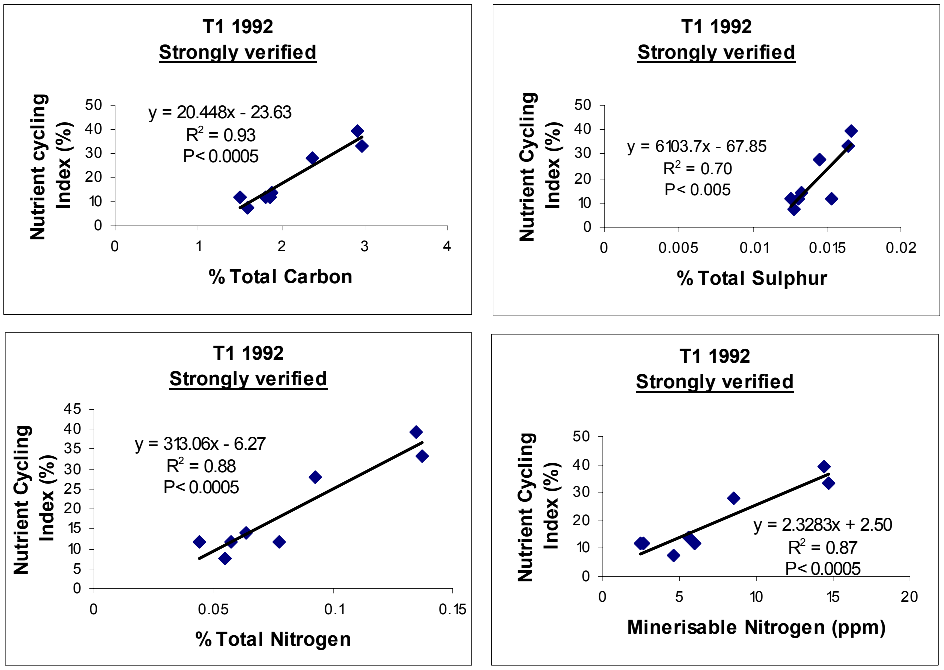


Figure 7.2.d.(ii). The relationship between laboratory measured values for total carbon, total sulphur, total nitrogen and mineralisable nitrogen and the EFA nutrient cycling indices for transect 1.

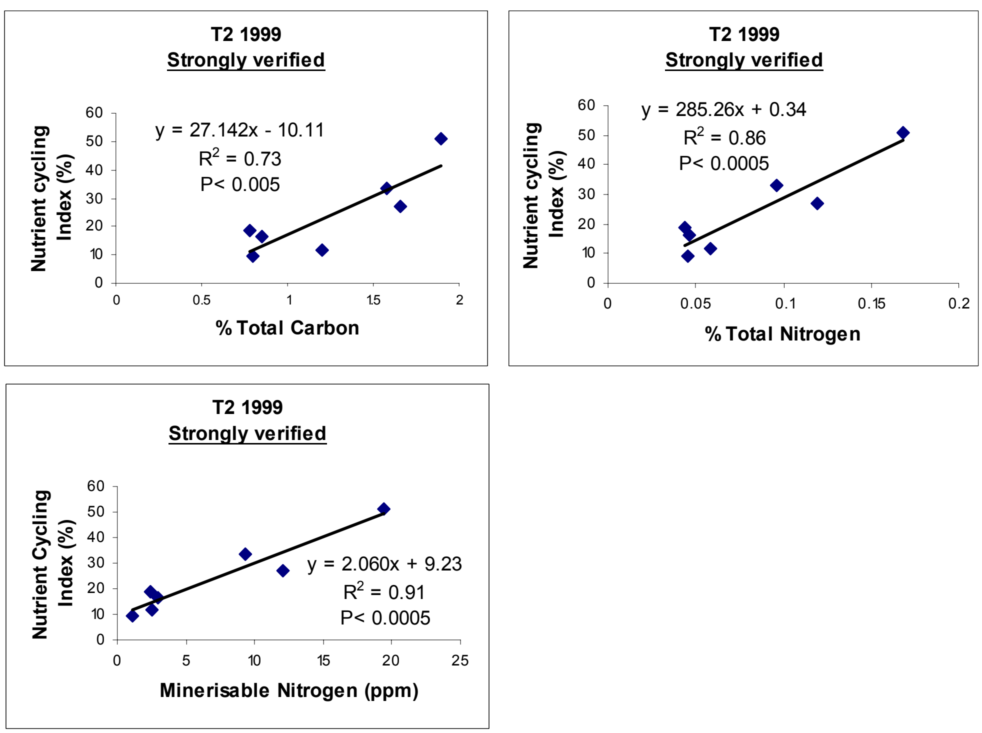


Figure 7.2.d.(iii). The relationship between laboratory measured values for total carbon, total nitrogen and mineralisable nitrogen and EFA nutrient cycling indices for transect 2, Carnilya Hill.

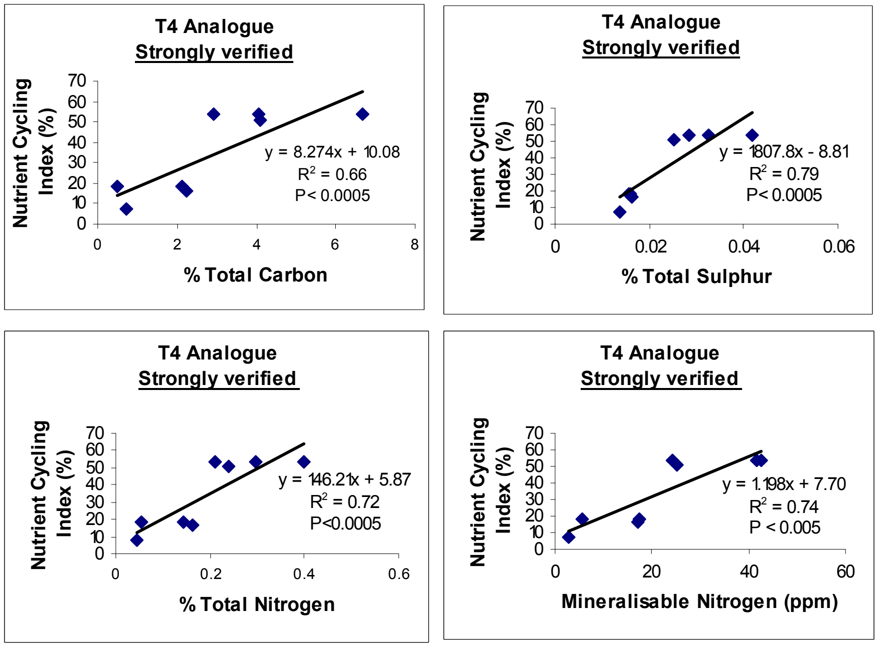


Figure 7.2.d.(iv). The relationship between laboratory measured values for total carbon, total sulphur, total nitrogen and mineralisable nitrogen and EFA nutrient cycling indices for the analogue site .

7.2.E. Functional Vegetation Index

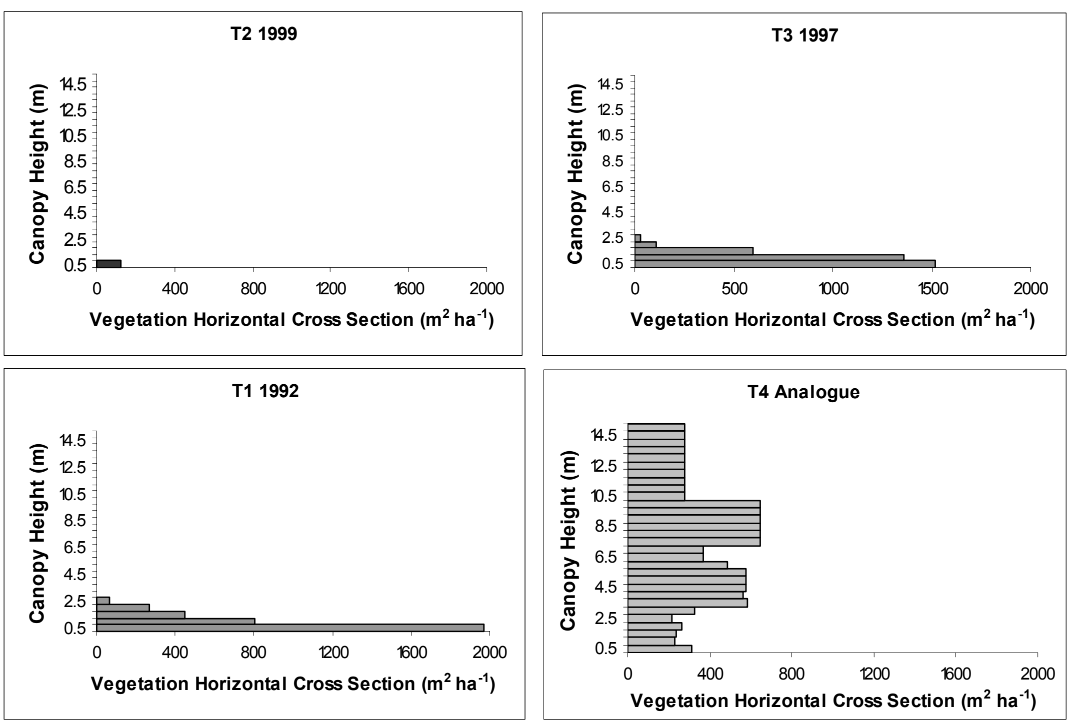


Figure 7.2.e. The vegetation horizontal cross sectional area for all four sites measured resolved into 0.5 metre vertical height intervals.

7.3. Eneabba

7.3.A. Stability

It was not possible to verify this index at Eneabba because the sandy soil at the site was non-coherent and the water stable aggregation procedure did not yield any interpretable results.

7.3.B. Infiltration

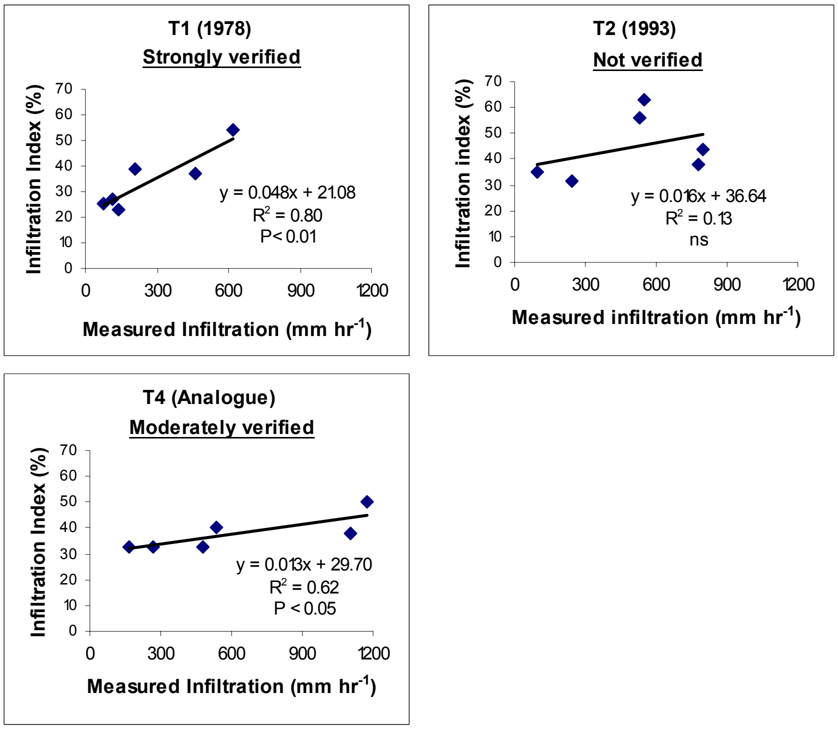


Figure 7.3.b. There were variable and only partially reconcilable relationships at Eneabba for infiltration. The analogue site and T1, the oldest site, both possessing surface crusts had useful, within-site relationships, but T2, with a mobile, non-cohesive sandy soil did not.

7.3.C. Soil Respiration

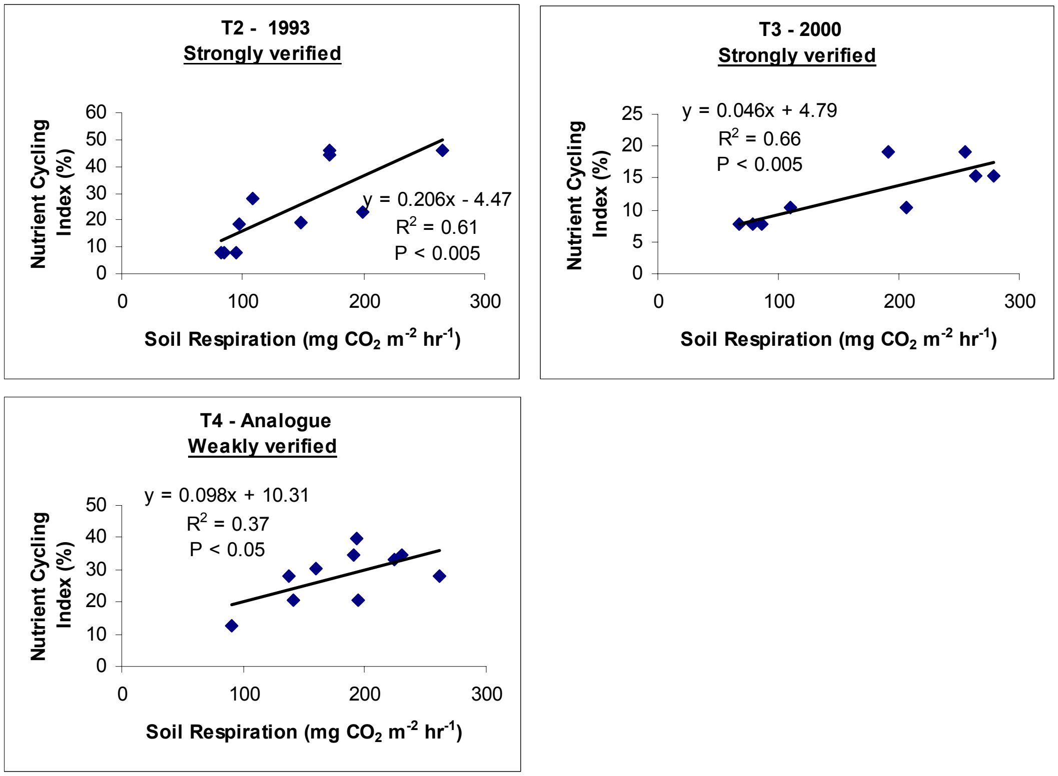


Figure 7.3.c. Soil respiration rate verus the EFA nutrient cycling index. These graphs reveal significant correlations between the index and measured respiration for the two 'younger' sites T2 (1993) and T3 (2000) and the analogue site, but the differing slope values militate against a single practical regression.

7.3.D. Nutrient Pool size

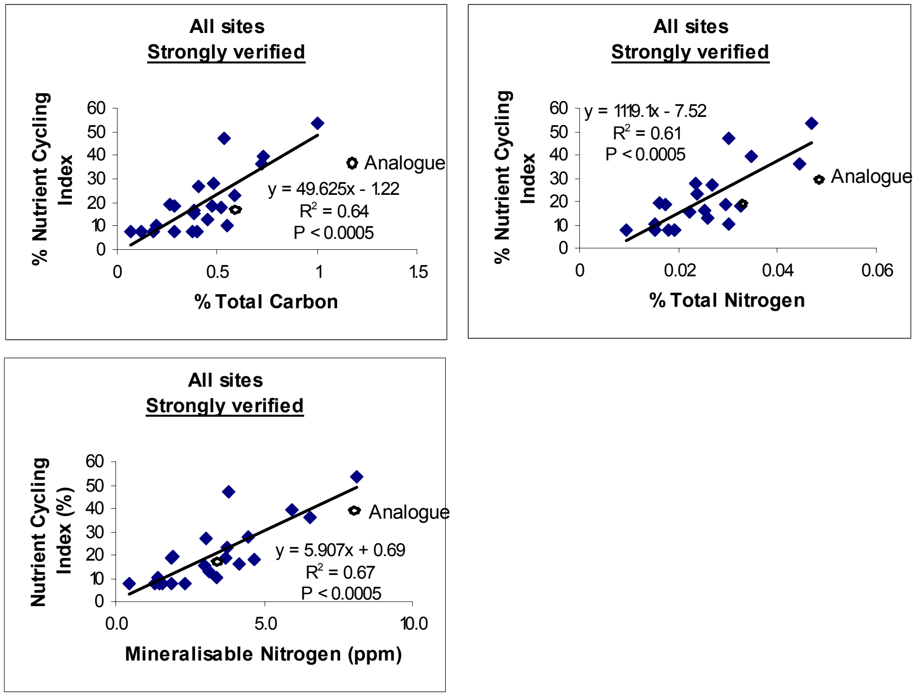


Figure7.3.d. The relationship between the EFA nutrient cycling index and soil total N, total C and mineraliseable N.

7.3.E. Functional Vegetation Index.

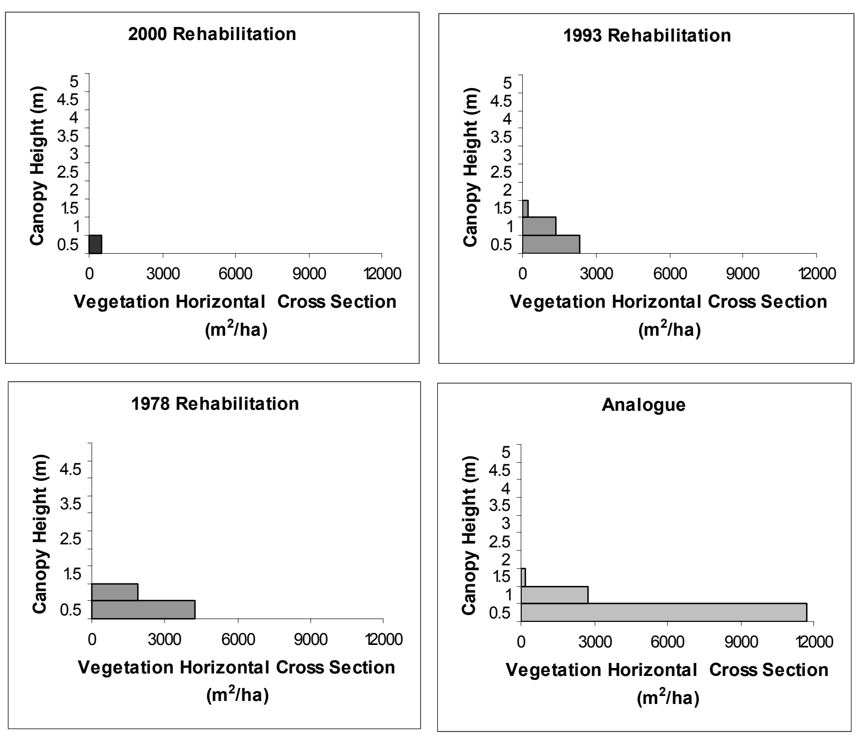
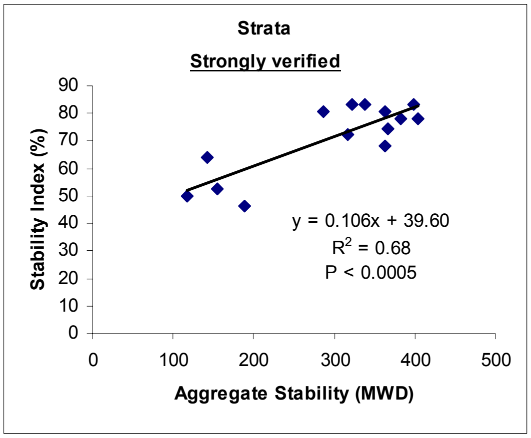


Figure 7.3.e. The vegetation horizontal cross sectional area for all four sites measured, resolved into 0.5 metre vertical height intervals.

7.4. Gove Bauxite Mine

7.4.A. Stability.



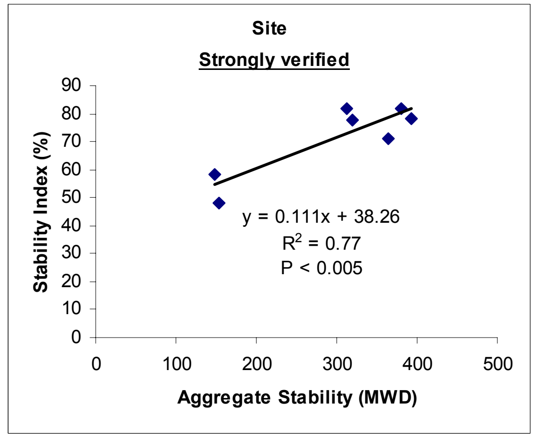


Figure 7.4.a. Shows the significant relationships between the EFA stability index and measured aggregate stability for all individual landscape strata (left hand) and the site means (right hand).

7.4.B. Infiltration.

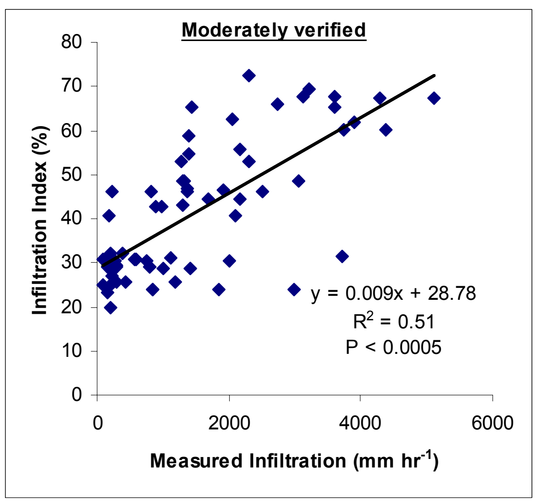


Figure7.4.b. Shows the relationship between the EFA infiltration index and measured infiltration. Data from all studied rehabilitation sites and the analogue site are included in this plot. Note that measured infiltration rates are very high at all locations and do not present a problem in rehabilitation.

7.4.C. Soil Respiration.

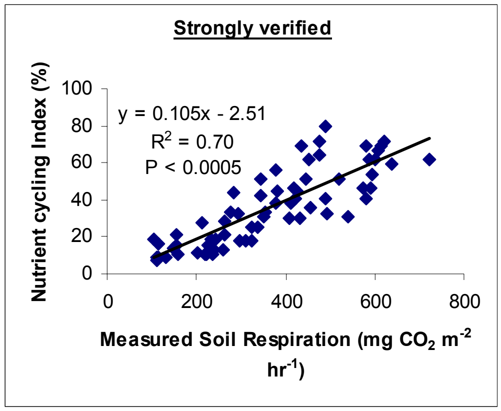
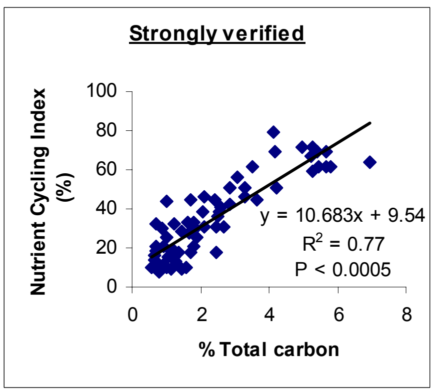
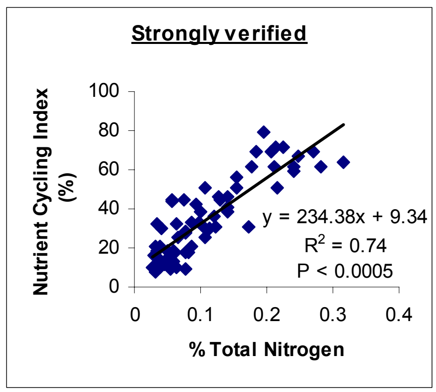


Figure 7.4.c. Shows the relationship between the EFA nutrient cycling index and measured soil respiration, using data from all the studied sites. The tight relationship verifies that the EFA nutrient cycling index can be used as a surrogate for costly and time-consuming measurements in monitoring rehabilitation progress.

7.4.D. Soil Nutrient Pool Size





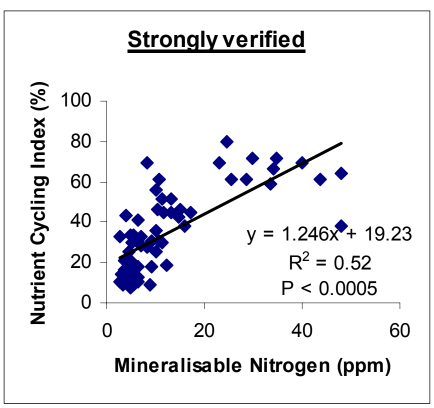


Figure7.4.d. The relationships between the EFA nutrient cycling index and measured levels of total carbon, total nitrogen and mineralisable nitrogen at Gove.

7.4.E. Functional Vegetation Index.

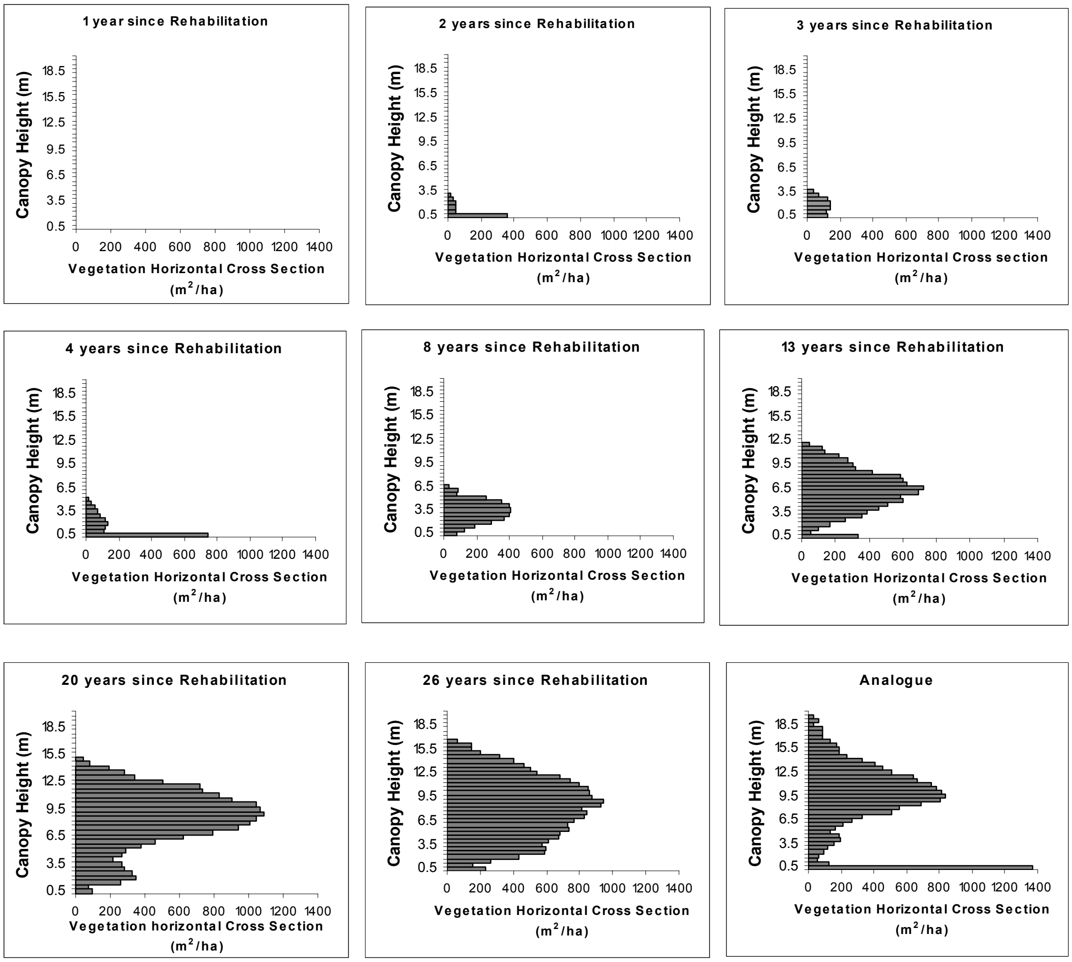


Figure 7.4.e. The vegetation horizontal cross section area for all nine sites measured, resolved into 0.5 metre vertical height intervals. Note that the rehabilitated lands develop a good canopy structure, but do not emulate the ground cover of the analogue site.

7.5 The Granites

7.5.A. Stability.

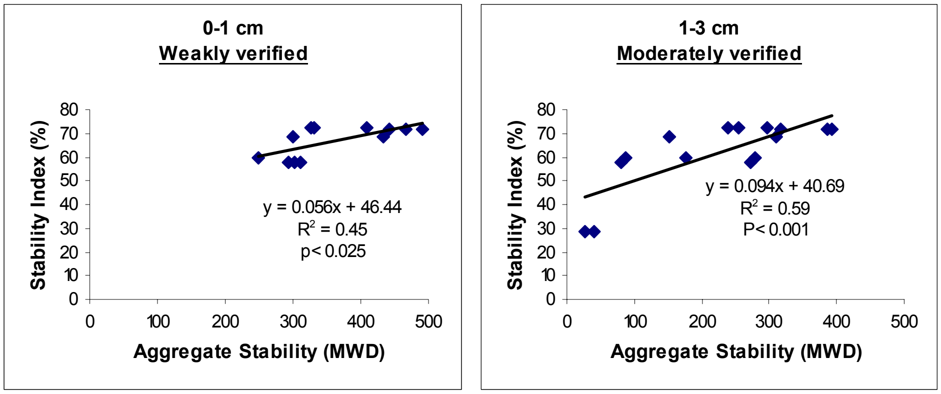


Figure 7.5.a. Two relationships are shown. The left hand graph represents the 0-1 cm layer, where data were available: a reasonable relationship but restricted in dynamic range, due to the loose, non-coherent nature of some samples. The right-hand side graph represents the 1-3 cm layer, where a full set of data was available.

7.5.B. Infiltration.

At The Granites the relationship between EFA infiltration index and measure infiltration was not verified, due to the rocky nature of many of the soils. Too few data were collected and over a very limited dynamic range.

7.5.C. Soil Respiration.

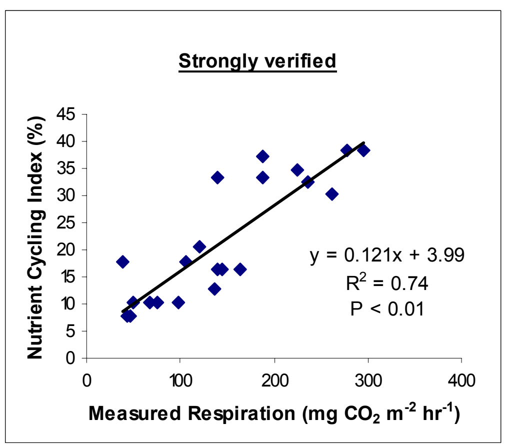


Figure 7.5.c. The relationship between soil respiration rate and the EFA nutrient cycling index. Data are combined from all sites.

7.5.D Soil Nutrient Pool size.

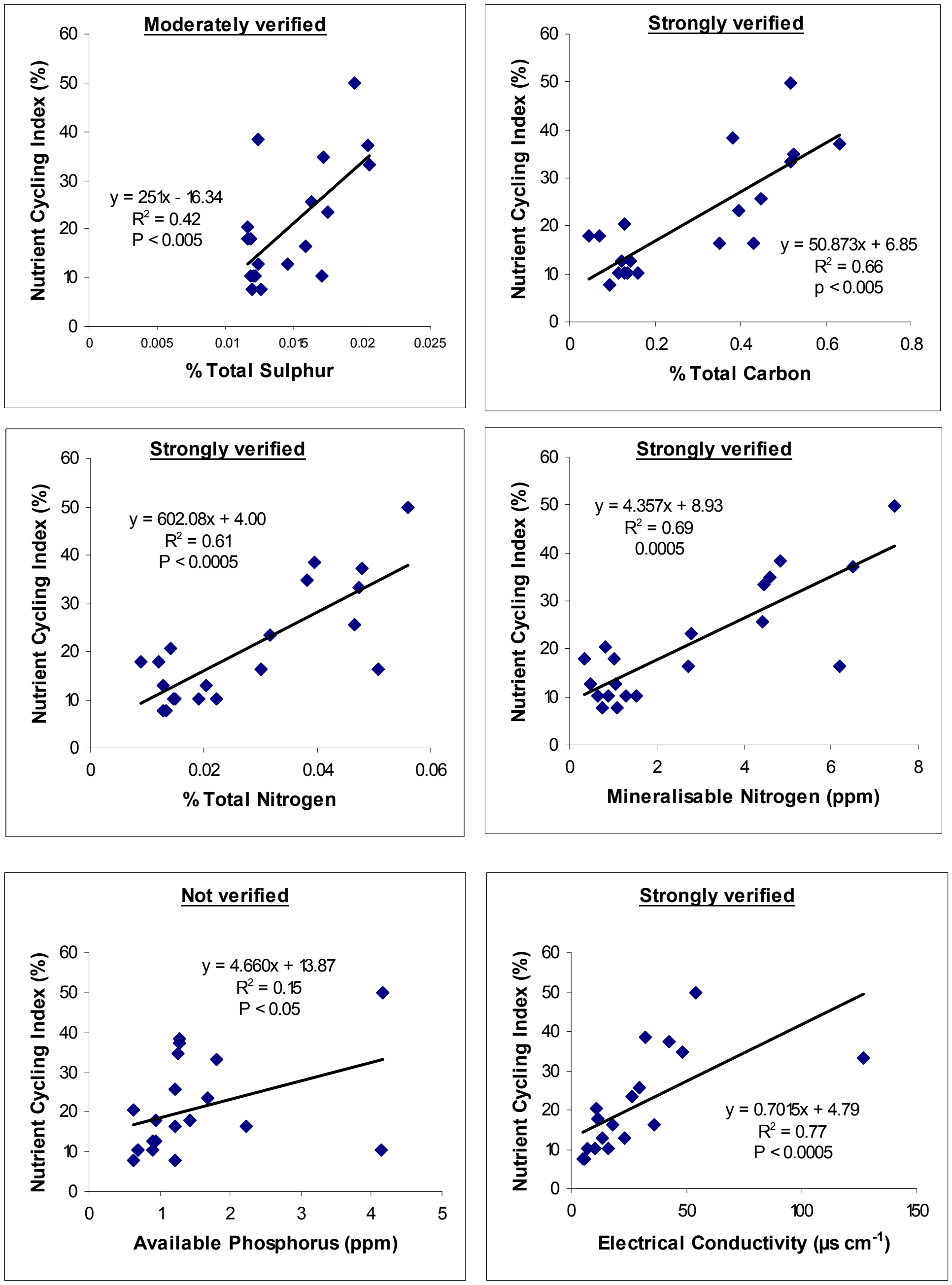


Figure 7.5.d. The relationships between the EFA nutrient cycling index and measured levels of total carbon, total sulphur, total nitrogen, available phosphorus, mineralisable nitrogen and electrical conductivity in the top 1 cm of the surface.

7.5.E. Functional Vegetation Index.

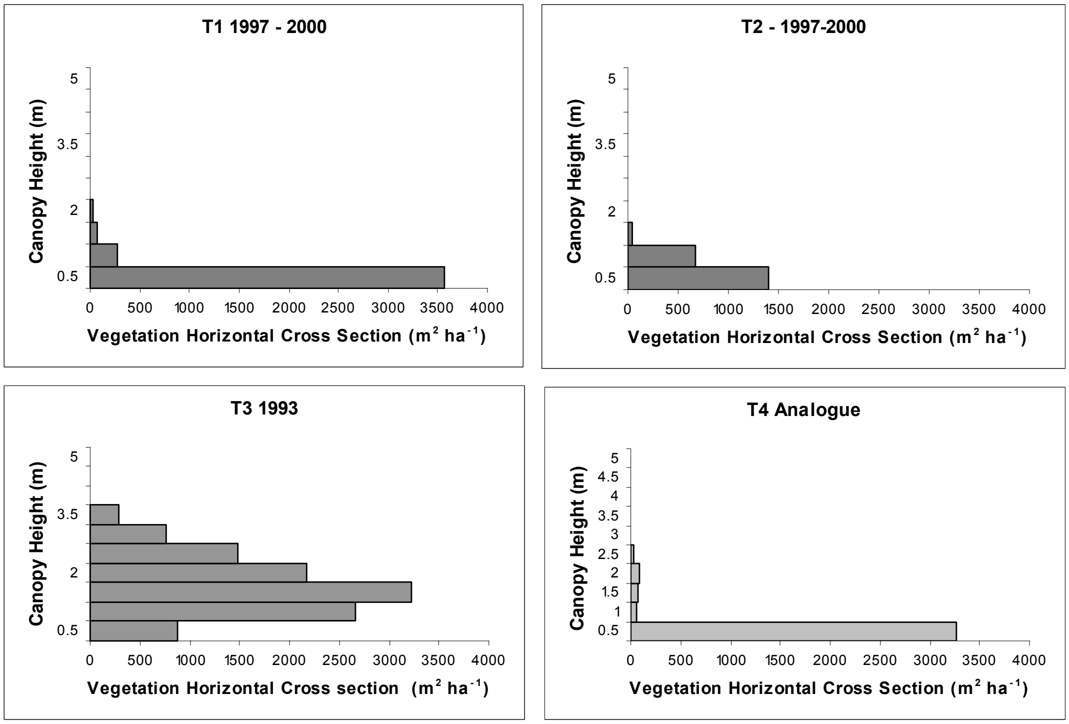


Figure 7.5.e. The vegetation horizontal cross-section area (m^2 ha^{-1}) expressed at 0.5 m height increments at each site.

7.6 Gregory Coal Mine

7.6.A. Stability

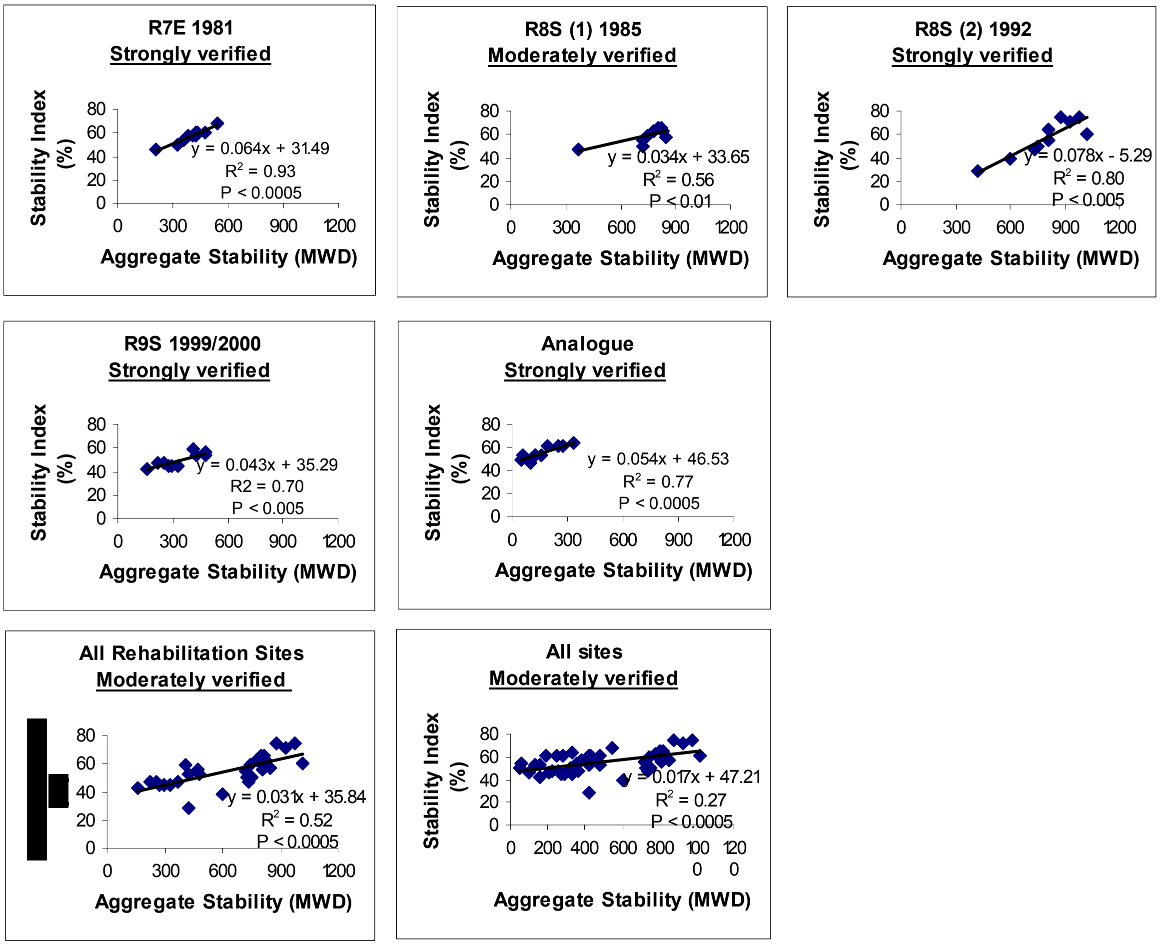


Figure 7.6.a. Showing the significance of relationships between the EFA stability index and measured aggregate stability for each of the individual sites, all rehabilitation sites and all sites. It be seen from the regression equations that the slope of the relationship is different for each site, and that the combined data set is noisy.

7.6.B. Infiltration

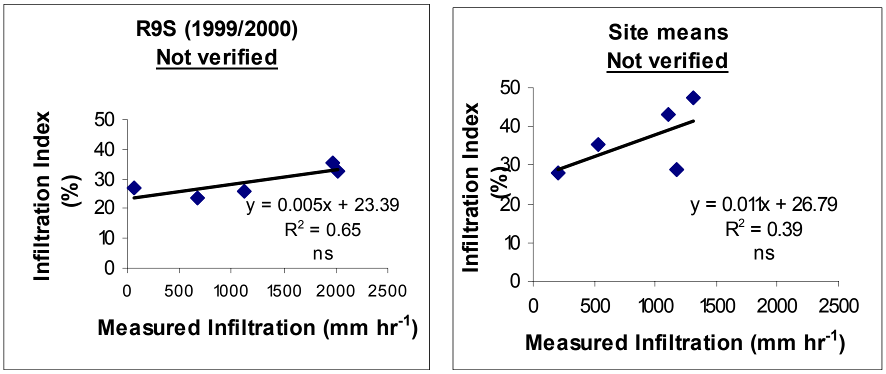


Figure 7.6.b. Showing the relationship between the infiltration index and measured saturated for R9S (left) and site means (right). It was technically difficult to set the infiltrometer up due the nature of the soil surface and the prevalence of root masses under the grasses present on some sites.

7.6.C. Soil Respiration

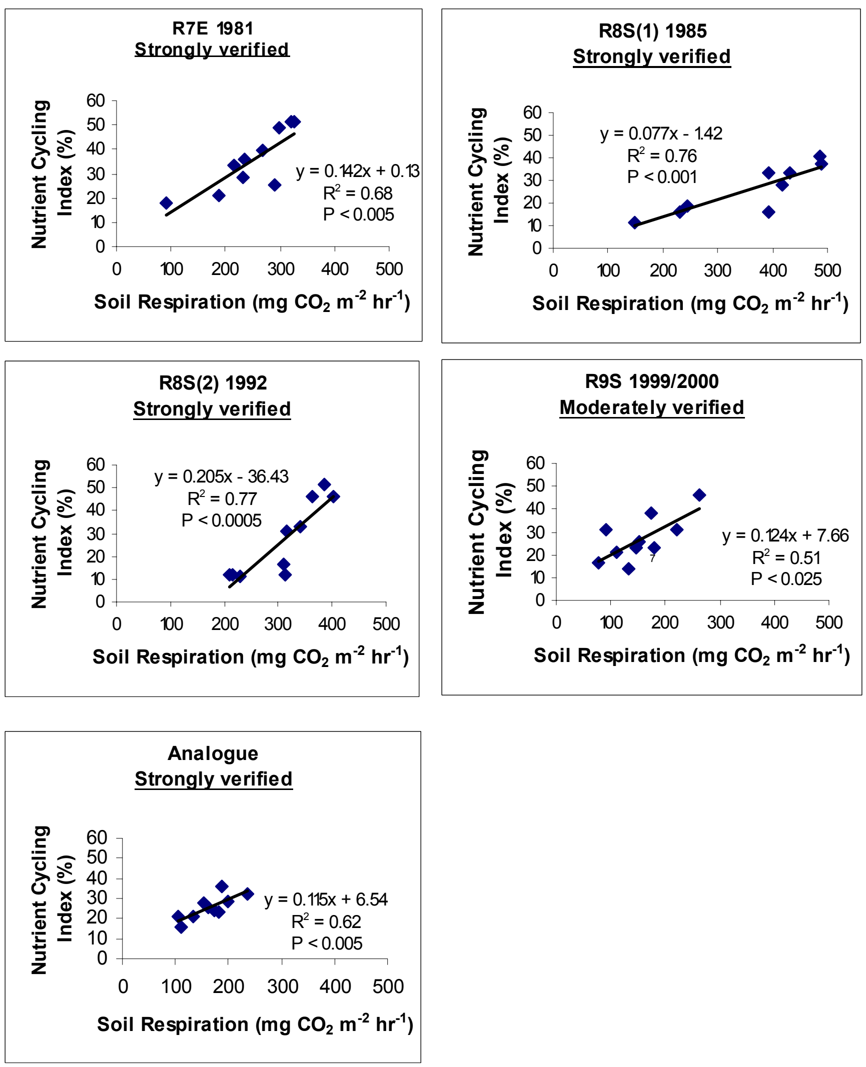


Figure 7.6.c. The relationships between the EFA nutrient cycling index and the measured soil respiration.

7.6.D. Soil Nutrient Pool Size.

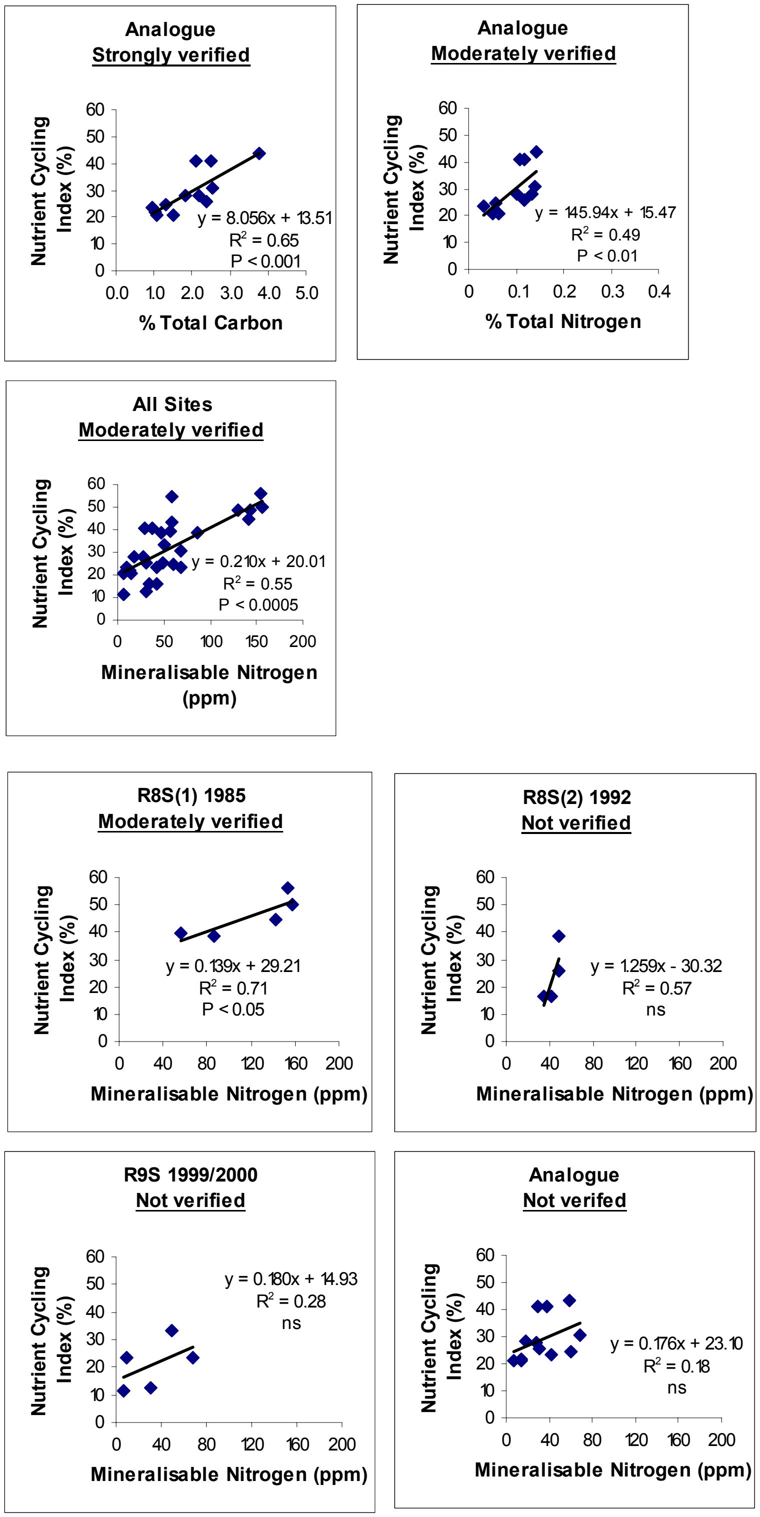


Figure 7.6.d. Showing the relationship between the EFA nutrient cycling index and total nitrogen, total carbon for the analogue and mineralisable nitrogen.

7.6.E Functional Vegetation index

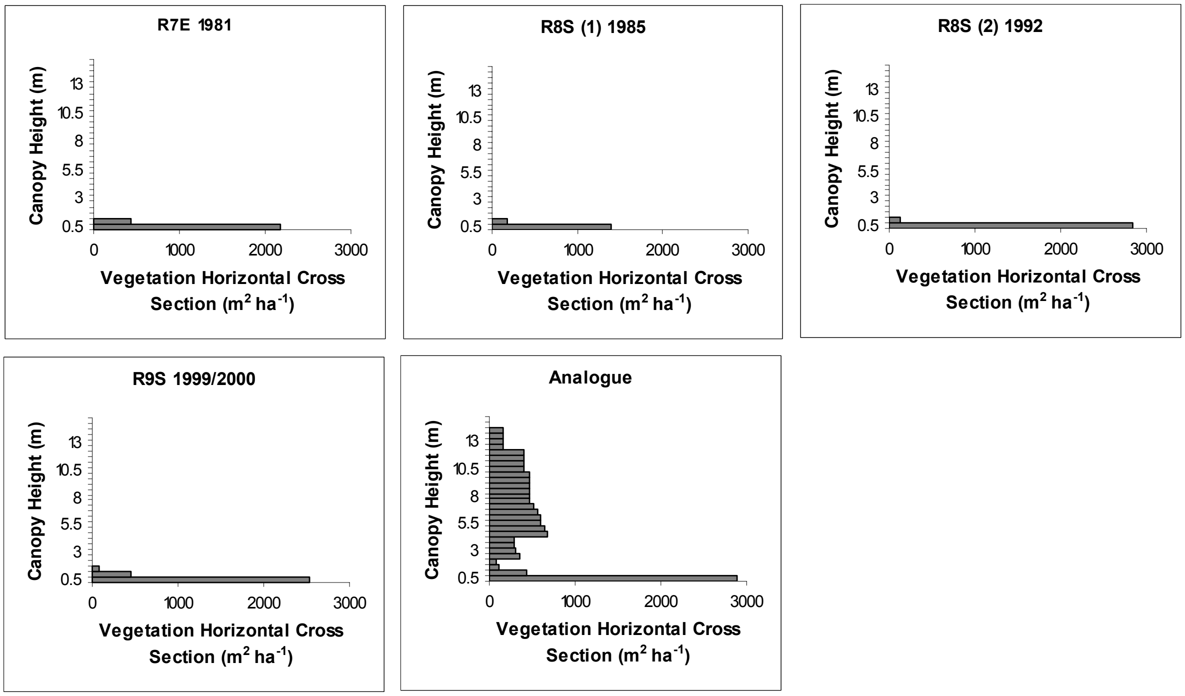


Fig 7.6.e. The vegetation horizontal cross section area for all sites at Gregory. The rehabilitation sites after about 20 years are similar to the analogue site for the cover to 0.5 m., but there is no tree canopy developing (by design), so the rehabilitation will always lag the surrounding woodlands.

7.7 Kelian Gold mine

7.7.A. Stability

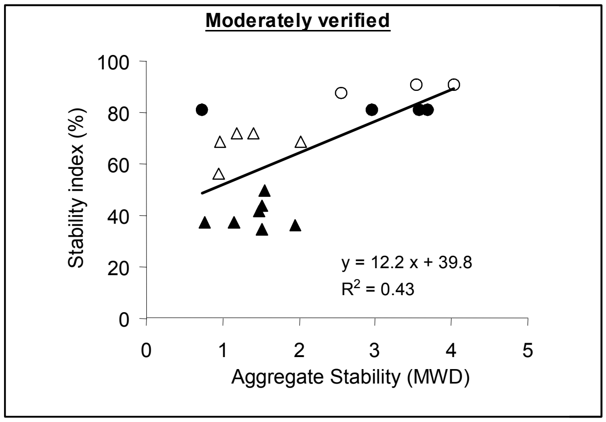


Figure 7.7.a. The relationship between the EFA stability index and aggregate stability.

7.7B. Infiltration

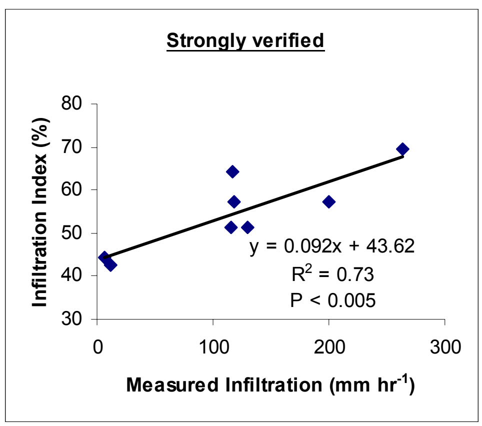


Figure 7.7.b. Relationship between the EFA infiltration index and measured infiltration. Note that data where measured infiltration was more than 300 mm hr^{-1} have been excluded from this graph. Those data were collected in paddock-dumped well-structured clay soils and some measurements indicated infiltration rates in excess of 3000 mm hr^{-1}. EFA was designed to identify soils with low infiltration, high runoff and erosion issues, and this figure shows a good relationship in those circumstances.

7.7.C. Soil Respiration .

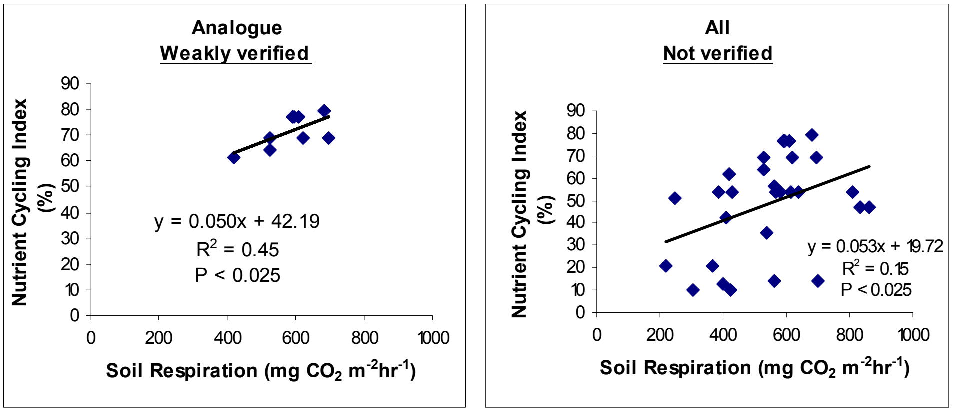


Figure 7.7.c. Shows the relationship between the EFA nutrient cycling index and measured soil respiration. This relationship, although having some significance is highly compromised in terms of representing verification. We did not have the appropriate instrumentation to run a full 24-hr respiration run for respiration rates this high. A further complicating factor was that the recently paddock-dumped soil piles retained their highly biological activity from their original location (a valley floor) because they were removed and dumped in a single operation. The EFA indicators (perennial plants and litter) for the nutrient cycling index had been destroyed in transport, giving them low values.

7.7D. Soil Nutrient Pool Size.

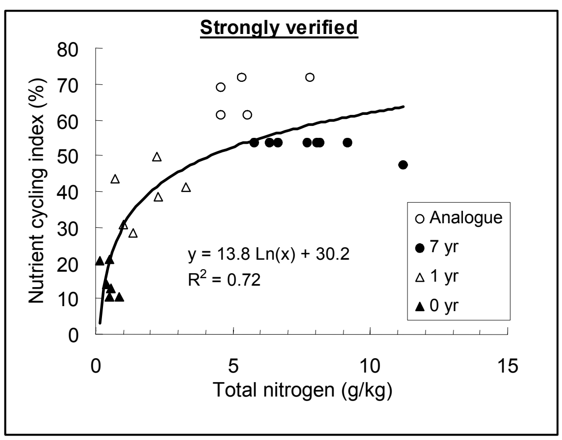


Figure 7.7.d.(i). Shows the relationship between the size of the organic nitrogen pool and the EFA nutrient cycling index for the 0-1 cm depth.

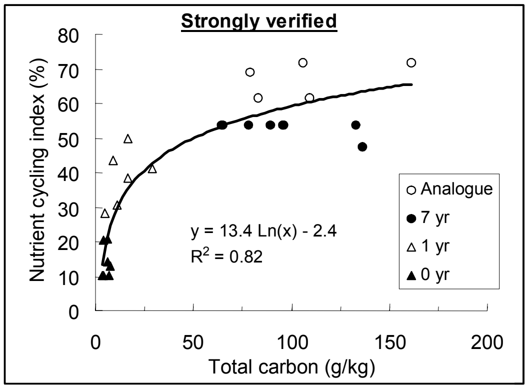


Figure 7.7.d. (ii). The relationship between the size of the organic carbon pool and the nutrient cycling index for the 0-1 cm depth .

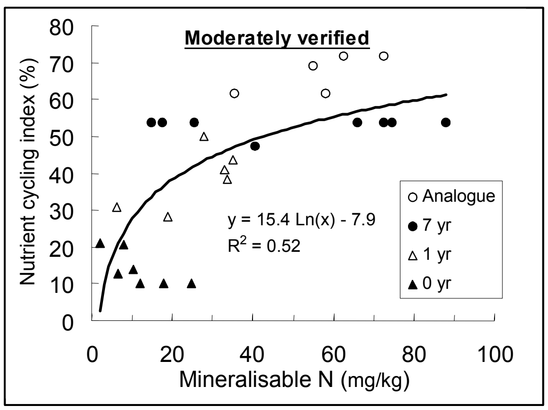


Figure 7.7.d. (iii). Shows the relationship between the size of the mineralisable nitrogen pool and the EFA nutrient cycling index for the 0-1 cm depth.

7.7.E. Functional Vegetation Index.

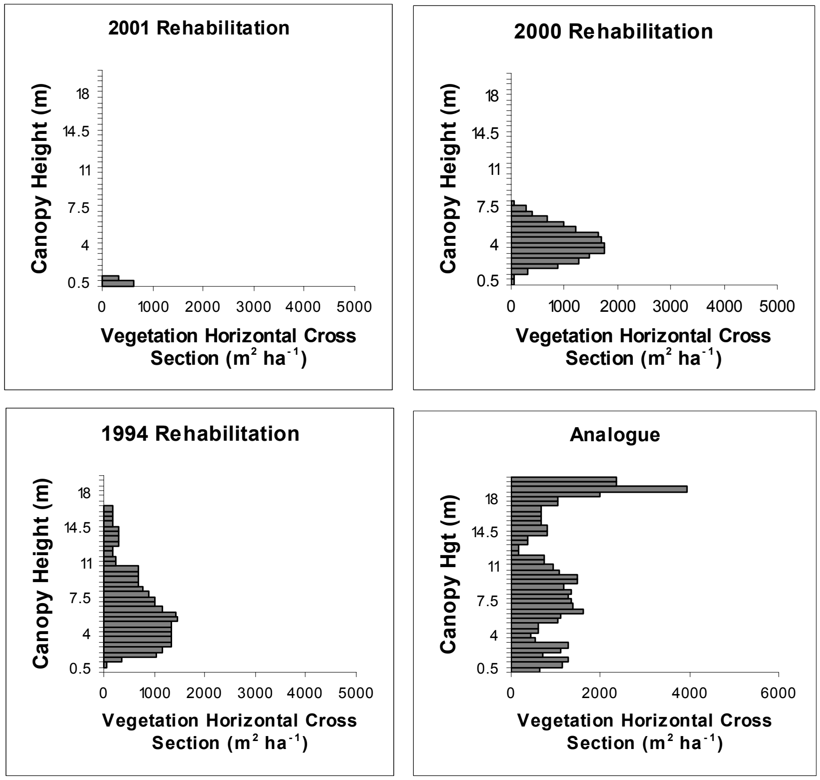


Figure 7.7.e. The horizontal cross sectional area of the canopy at the 4 sites studied at Kelian, showing a rapid mid canopy growth. Tree seedlings are being planted in the rehabilitation in a horticultural/forestry context, so vegetation is more highly managed through time here than at most mines.

7.8 Nabarlek Uranium Mine

7.8.A. Stability

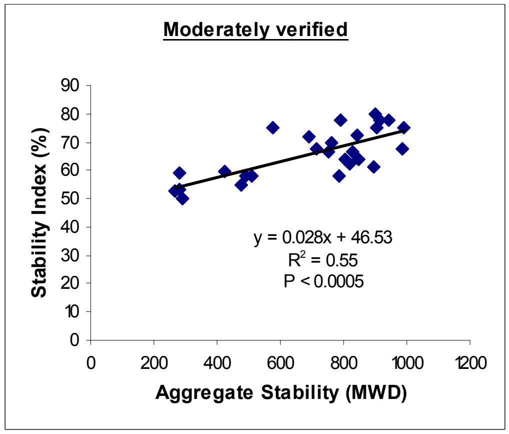


Figure 7.8.a. The relationship between aggregate stability as measured by mean weight diameter and the EFA stability index .

7.8.B Infiltration

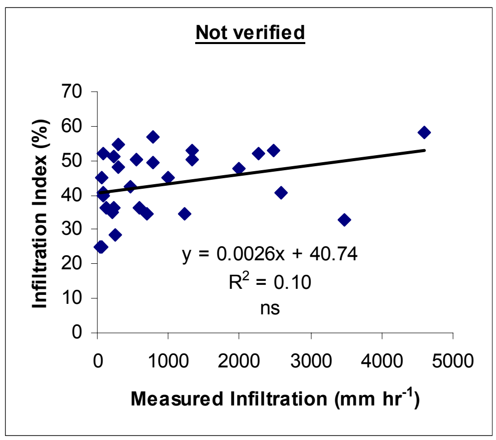
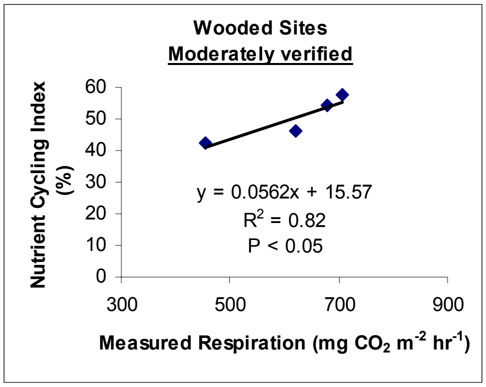


Figure 7.8.b. The infiltration index was not verified at the Nabarlek site. This was mainly due to extremely high infiltration rates (in excess of 2000 mm hr^{-1}) being measured on the dry, well-structured clay soils. Anecdotal and informal evidence suggests that these soils do become saturated in the wet season and measurement of saturated hydraulic conductivity at this time would be an appropriate way to verify the index in these soils. Other sites had too high a proportion of rock to install out infiltrometer ring without major disturbance.

7.8.C. Soil Respiration.



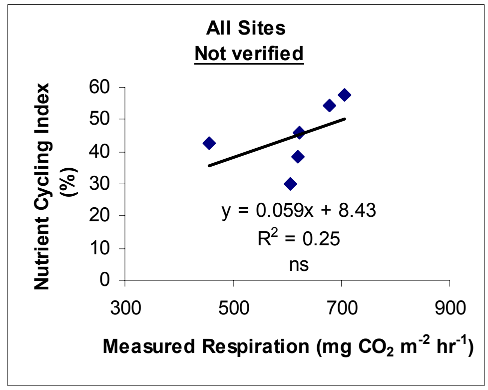
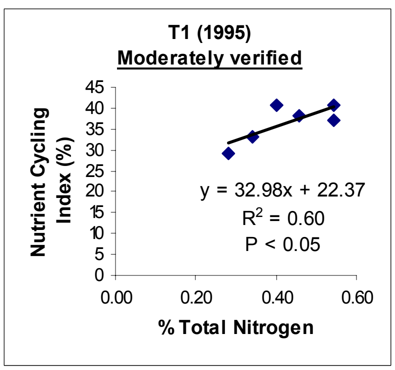
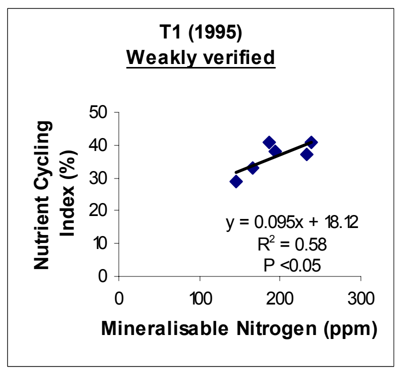


Figure 7.8.c. Mean respiration rate vs. mean EFA nutrient cycling index for wooded sites alone (left) and with grassy sites added (right). There was more biological activity under the grassland than the indicators suggested. It is possible that algal slimes were activated by the measurement process.

7.8.D. Soil Nutrient Pool Size





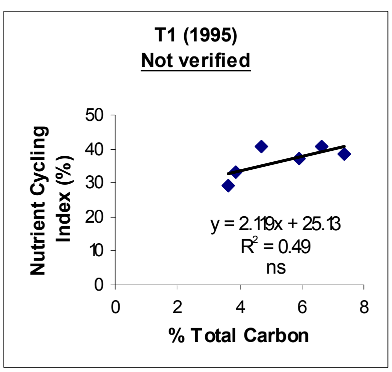


Figure 7.8.d. Shows the relationship between the measured soil nutrient pool and the EFA nutrient cycling index for the dense grass site. All the rehabilitation at Nabarlek was done at a similar time, using a mix of soil materials. As the time for the establishment of a new nutrient profile is only about 6 years, a strong relationship was not expected. There was a low dynamic range in the EFA index, militating against more useful relationships.

7.8.E. Functional Vegetation Index

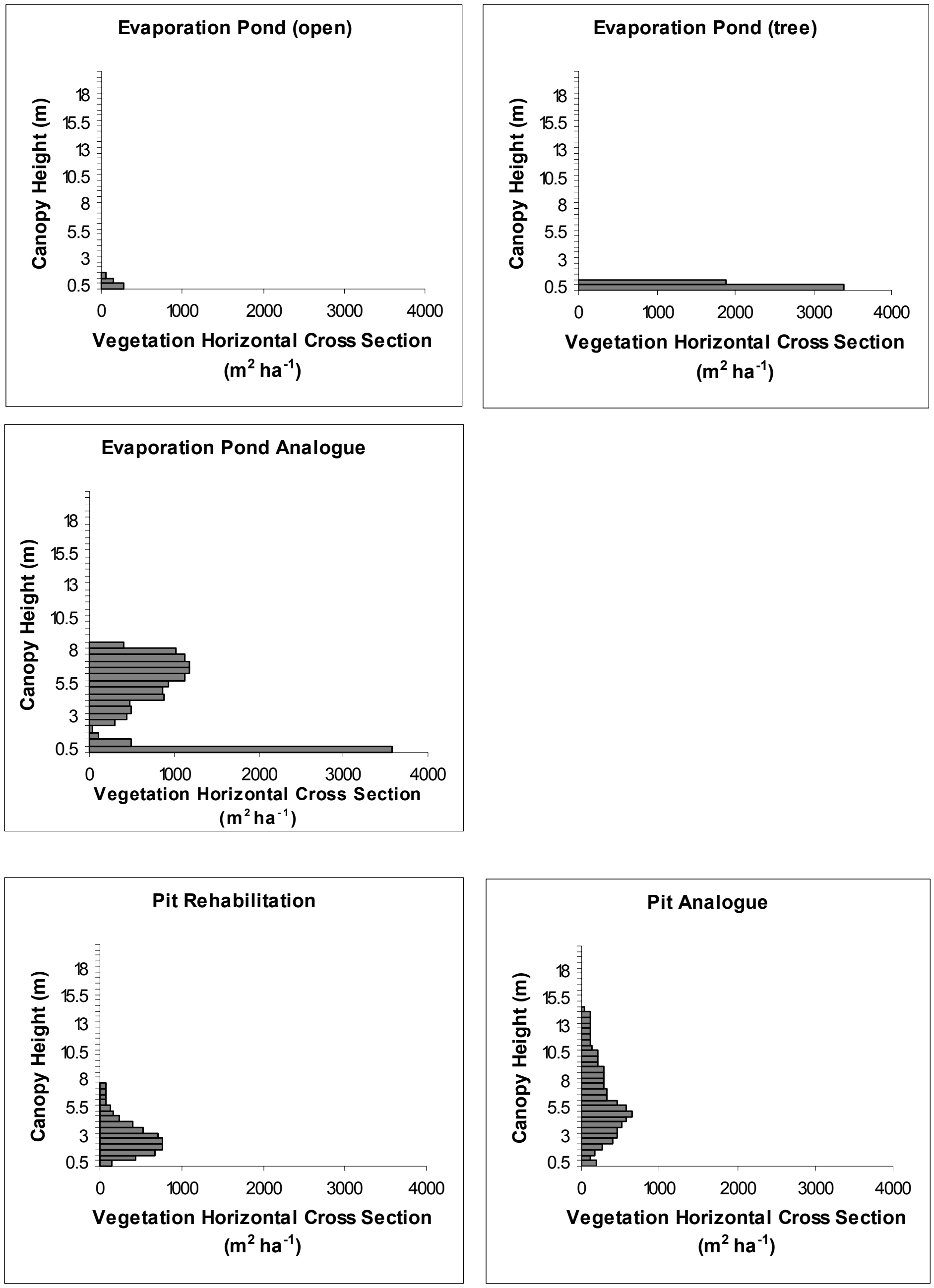


Figure 7.8.e.(i) Vegetation horizontal cross section area (m^2 ha^{-1}) differentiated into 0.5 m height classes for all study sites at Nabarlek. Note that the grassy *Melaleuca* analogue site for the evaporation pond is still very different to the rehabilitated sites and any convergence is still a long time off.

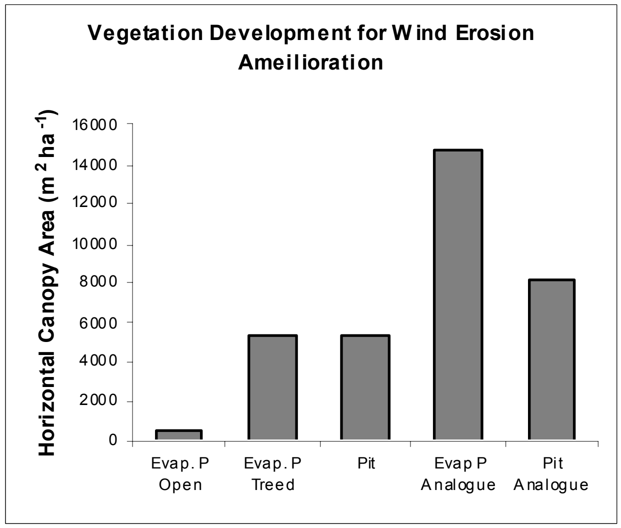


Figure 7.8.e (ii) The vegetation cross section area cover for all sites at Nabarlek. This clearly shows the contribution of foliar cover of woody species compared to grasses.

7.9 New Celebration Gold Mine

7.9.A. Stability

This index was not verified at New Celebration because the samples were destroyed during transport and re-visiting the site for this purpose was not financially possible.

7.9.B. Infiltration

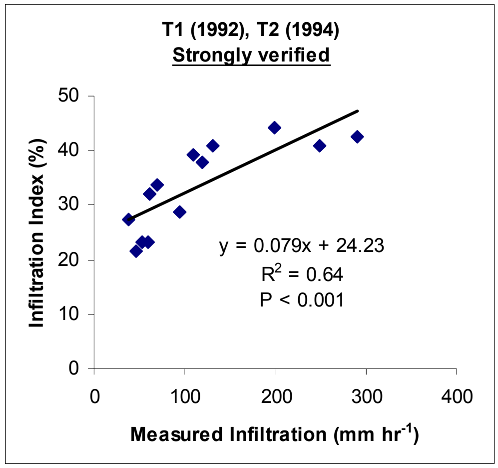


Figure 7.9.b.(i). Verification of the EFA infiltration index with measured infiltration. Pernatty WRD: upper and lower lifts combined. Too few measurements were possible at the Mt Marion site for verification purposes, due to the low mechanical strength of the soil in many places, which was unable to carry the weight of the infiltrometer. The form of this graph suggests that an exponential fit would improve the relationship.

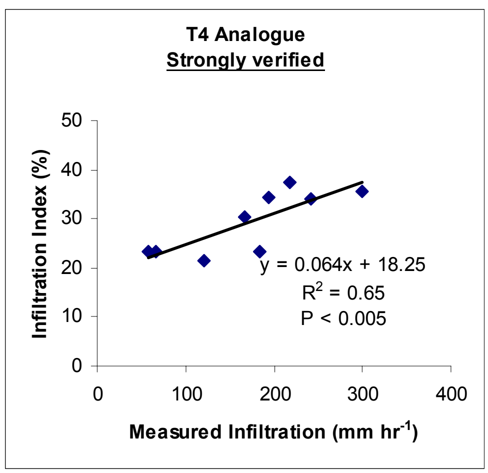


Figure 7.9.b. (ii). Shows the relationship between the EFA infiltration index and measured infiltration for the analogue site alone. Note that the rehabilitated sites and the analogue have different slopes and intercept values, so that the use of the infiltration index would need to be cross-calibrated to be of the highest precision.

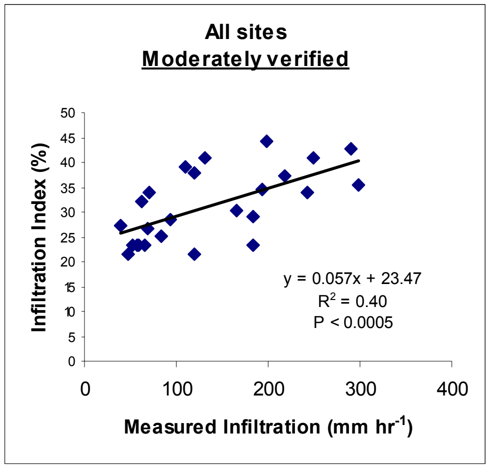
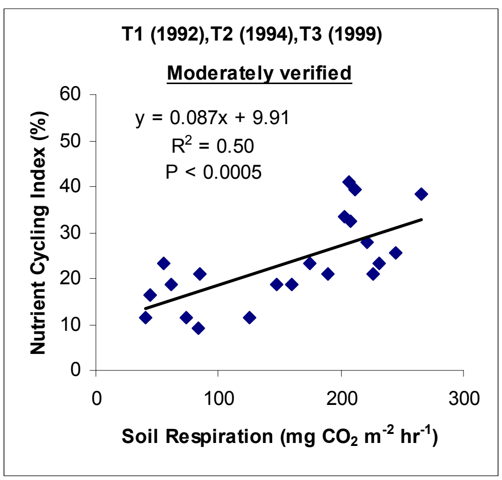


Figure 7.8.b. (iii). The relationship between the EFA infiltration index and measured infiltration for all 4 sites at New Celebration.

7.9.C. Soil Respiration.



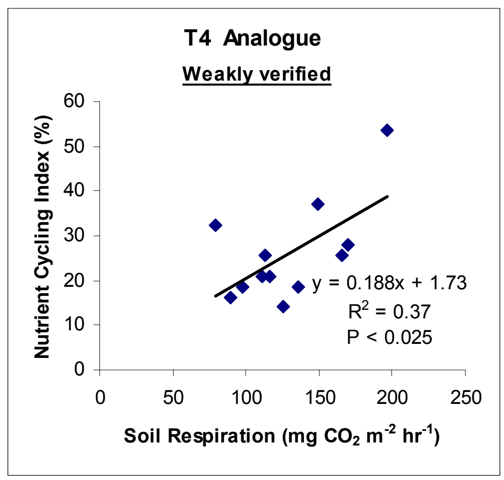


Figure 7.9.c. The rehabilitation sites (left hand graph) have an internally consistent relationship with the LFA nutrient cycling index and soil respiration rate but different to the analogue site (right hand graph), that is also internally consistent. This prevents a simple overall verification relationship, but cross correlation is possible. The explanation for this difference lies in the maturity and species composition of the vegetation at the analogue site.

7.9.D. Nutrient Pool Size

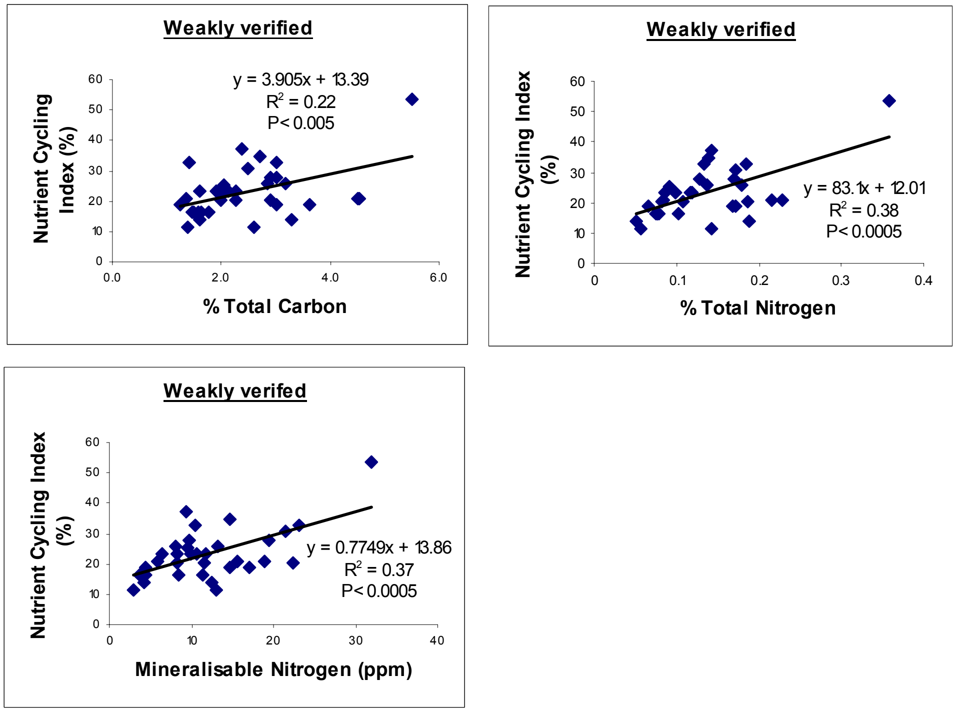


Figure 7.9.d. The relationships between the EFA nutrient cycling index and measured concentrations of soil total carbon, soil total nitrogen and mineralisable nitrogen.

7.9.E. Functional vegetation Index

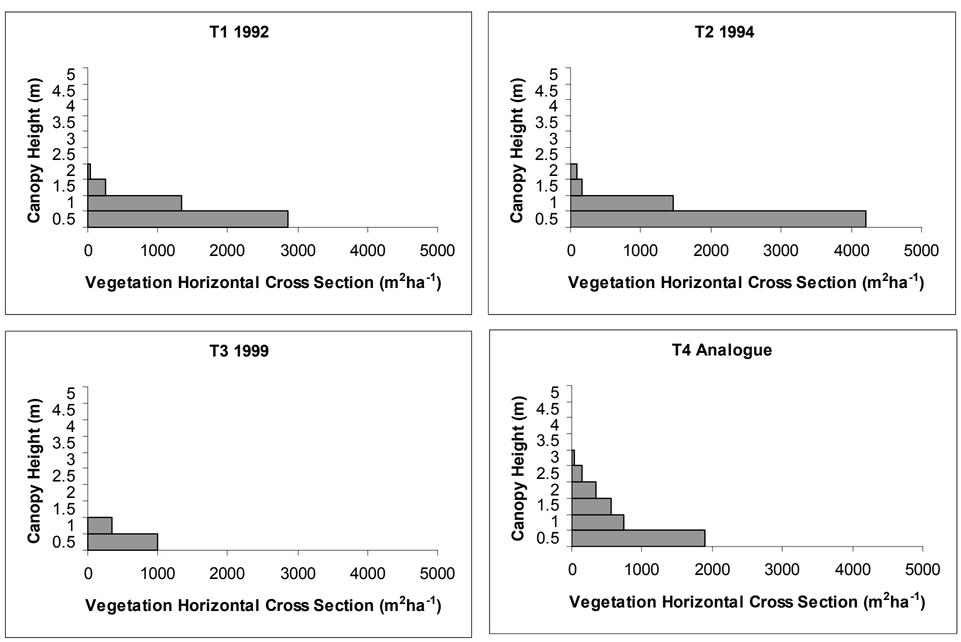


Figure 7.9.e. Horizontal cross section vegetation cover (m^2 ha^{-1}) resolved into 0.5 m height increments for each site shows how the vegetation has developed to regulate ground surface flows (0-0.5 m) and create wind turbulence at other heights. The analogue site clearly has taller vegetation and lower ground cover than the rehabilitation sites due partly to age of rehabilitation and partly to the analogue site being a woodland.