MINTOPE Science
Christmas Island

“Establishing the scientific basis for introduction of agriculture and plant economies onto Christmas Island, on expired mining leases”

a partnership between Murdoch University, Christmas Islands Phosphate and the Commonwealth.
MINTOPE report – The scientific production of agricultural legumes on Christmas Island

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Executive Summary

This document reports upon a research program funded jointly by the Minister for Regional Australia, Regional Development and Local Government through the Economic Development Fund, Murdoch University and Christmas Islands Phosphate (CIP) to evaluate the scientific basis for the introduction of agriculture to Christmas Island. This report presents experimental data that validates the suitability for legume-based agriculture at five sites on Christmas Island previously mined for apatite.

Grain legumes were chosen for the evaluation because they can “fix” atmospheric nitrogen (N), to provide organic additions of N to the soil, without the need to import nitrogen fertiliser. These legumes are commonly grown in the sub-tropics of the world as major food and feed crops. The legumes were sown after weed control provided by glyphosate, and with additions of minerals and trace elements commonly required for cultivation of crops on alkaline soils. The legumes were also inoculated with micro-organisms to assist nitrogen fixation (rhizobia) and nutrient solubilisation (PGPR). However, aside from these inputs, there was a minimal post-sowing intervention and the cultivation practice could be considered as “organic cultivation”.

Five sites were chosen representing different soils and landforms post-mining - Airport II, Airport III, Jindalee, East-West and Field 4 - and the data was collected through February – November 2013.

The legumes varied in response to sites and fertiliser applications across the island. The best yield of seed achieved was 2.8 tonnes per hectare of lablab cultivar Highworth. The best production of biomass achieved was 9.2 tonnes per ha of Rongai lablab. An understanding of the nutritional status of the soils was gained and how the soils might be amended for agricultural production.

A set of principles for agricultural development on mined sites was established, including recommendations for land management as part of the mining exit strategy.
Lessons learnt about the process of land preparation during the mining exit phase

- Residual soil – must not be removed, and any surface burden should be re-applied to topdress sites. This should be the second last activity of the mining phase

- Slope and drainage, contour banks – this needs to be the last activity of the mining phase. Contour banks need to be constructed where the fall is greater than 3% to ensure surface movement of water is controlled

- Timing – the sites must be prepared during the dry season to ensure trafficability for February sowings

- Rocks – any rocks greater in size than a cricket ball need to be removed prior to sowing

- Waste products – must be provided during the dry season, spread and sites prepared before the wet season

- Sink holes – the geology of sites needs to be reviewed to ensure agricultural sites are not located in a zone prone to the emergence of sink holes

Lessons learned about agriculture on Christmas Island

- The sub-tropical pulse legumes grown in other parts of the world are well adapted to the environment on Christmas Island, and can tolerate the extant pests and diseases to grow and yield favourably

- The best seed yield recorded was 2.8 tonnes / ha of Highworth lablab at Airport 3, on a quadrat basis. This probably represents a reasonable estimate of the capability of the Island for seed production of legumes in future economic assessments.

- Selection needs to be made for the right physiological adaptation among these legumes – daylength x temperature are the key factors that induce flowering in many determinant species. Cultivars with a very long cycle of growth would work well on Christmas Islands, as evidenced by the Highworth variety of Lablab.

- Soybean varieties that are not daylength responsive need to be sourced, and these are available from EMBRAPA in Brazil

- High levels of N fixation are achievable – probably in excess of 200 kg urea equivalents per ha, obviating the need to import N to the island.
• Rotation crops should be explored such as rice, cereals, fruit and vegetable crops to exploit this fixed nitrogen and increased fertility. Tree crops for timber, oil or other uses should also be considered as a longer term option following the first legume crop.

• Other legumes were seen in residential also gardens, such as the winged bean, and these could be investigated.

• The microbial inoculants such as rhizobia and the PGPR are useful products to increase plant growth on the soils of Christmas Island. However the response to the micro-organisms is species specific, so they need to be tailored to each of the legumes individually.

• Navy bean is not adapted to Christmas Island, perhaps because it is (like pigeonpea) obligate for mychorriza.

• Sulphur, boron and potassium are limiting nutrients for legume growth, but can be overcome by relatively small doses of 5 – 10 kg / ha. Phosphorus is in high concentration, but species seem to be able to tolerate this if other nutrients are well balanced.

• A Christmas Island fertiliser blend without N and P can now be developed for plant production. This will decrease fertiliser inputs to the Island dramatically.

• The soil has adequate manganese, but is very low in organic carbon and nitrogen. Both these elements can be improved by legume production.

• Simple agronomy such as weed and insect control should be practiced, but inputs required to produce excellent crops are low.

• There is the possibility for two growth cycles (or two harvests) per year by using short season cultivars (such as the soybean and mung bean varieties employed in these experiments), however it may be more desirable to maximise production in one growth cycle per year, with a harvest in the dryer months.

• The machine header was able to harvest dry pods of lablab in November, following desiccation.

• Where the legumes grew well, and where strongly established, weeds were smothered. This presents an organic option for weed control other than using herbicides.
In a marketing context, consideration should be given to growing crops organically to take advantage of the virgin sites, inherent P level and the natural N fixation from the legume crop.

Figure 1. Production of Cowpea and Sorghum on Christmas Island in 2015. The site at Airport 4 grew 70 tonnes (wet weight) of sorghum in 7 weeks.
Figure 2. Inspecting the mined site at Jindalee in 2013. Experiments were sown later that year.

Figure 3. Preparing the site for agriculture is critical to managing erosion from rainfall events.
The scientific production of agricultural legumes on Christmas Island

1. Site preparation, soil characteristics and sowing dates

Five sites which represented different examples of the mining exit strategy were chosen, each with different geological characteristics and that hence presented different challenges to agriculture. The general characteristics of the sites are summarised in Table 1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mining exit procedure</th>
<th>Soil characteristics and site usage</th>
<th>Sowing and sampling dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport II</td>
<td>Ex apatite dump, 2 ha, 5-10 degree slope, tiers constructed to control water run-off. Top tier prepared for irrigation</td>
<td>No surface soil remaining but friable surface, trafficable, machine sown experiment - 96 plots with 4 replicates,</td>
<td>Sown February 5-7 2013</td>
</tr>
<tr>
<td>Airport III</td>
<td>Pinnacle field, 1 ha, with 5 m drop off from access road; dryer dust dumped over pinnacles in attempt to create trafficable surface</td>
<td>Not immediately trafficable to seeding machinery as dust held moisture following rains–hand sown 16 x 5m lines +/- PGPR to assess dust as a medium for plant growth</td>
<td>Sown February 12. Lines of inoculated legumes, high rate of fertiliser, +/- PGPR</td>
</tr>
<tr>
<td>Jindalee</td>
<td>Surface mined 2 ha, leaving pinnacles which were then crushed and levelled with D9. Scarified with Shire grader, large rocks removed by grader and by hand</td>
<td>Higher quality residual apatite with higher iron concentration and surface soil profile; two machine sown strips of 5 legumes 20m x 200m and set for machine harvest</td>
<td>Sown February 11/12. Southern strip with 150kg fertiliser rate, northern strip with 150, 40 and 0 kg/ha.</td>
</tr>
<tr>
<td>East-West</td>
<td>Ex apatite dump of 2 ha, flat and trafficable, emerging presence of large sink holes indicating unstable surface,</td>
<td>Poor quality soil remaining after bunds built, very stony; machine sown experiment with 96 plots, 4 reps; remnant high quality soil in</td>
<td>Sown TOS1 Feb 9 TOS2 sown March 5</td>
</tr>
</tbody>
</table>
2. Scientific experiments and collection of plant growth data

Legume and nutrition experiments were sown at all five sites during February and March, with some additional experiments sown in the following months, using an “action research approach” to solve problems as they arose. Teams from Murdoch University visited the Island in March and May to plan further times of sowing and to harvest samples for biological yield and nodulation induced by the microbial inoculants applied in the February sowings. Support staff were accommodated on the Island continuously through June and July.

2.1 Airport II

At this site replicated experiments were implemented with a robust scientific design to enable comprehensive data to be collected and statistically analysed. The experiment investigated the response of eight different legume crops to three different levels of fertiliser, and to inoculation with rhizobia (the micro-organism that fixes N), in a factorial split-plot design.

The experiments also assessed the response of the legumes to inoculation with a plant growth promoting bacteria (PGPR) that solubilises rock phosphate and produces hormones that stimulate root growth. A further bank of uninoculated legumes was sown on the extreme south-eastern end of the site to allow an assessment of the background rhizobia i.e., nodulation achieved by rhizobia already in the soil.
The diagram below shows the experimental design and layout implemented both at Airport II and at the East-West site.

**Figure 2.1** The layout of the experimental plots at Airport II and East-West sites.

The site surface at Airport II was scarified with the rear tynes of a grader and then flattened with the seeder to produce a reasonable surface for sowing, although lack of February rains meant the soil was dry at the time of sowing. However 20 mm of rain fell within 24hrs of sowing and seedling...
emergence was excellent. As the rains continued through March some water erosion was experienced at the site, emphasising the need to leave surfaces with a minimal slope when exiting the mining operation.

2.2 Fertiliser content and rates

No soil data was available at the time of sowing to guide the fertiliser treatments. Hence, we developed a fertiliser blend designed to correct nutritional disorders commonly found on alkaline, mined apatitic soils. Common nutrient disorders expected were deficiencies of iron (chemical symbol Fe), manganese (Mn), copper and molybdenum trace elements (Cu, Md), phosphate (P), potassium (K) and sulphur (S).

The fertiliser treatments were thus:

Nil= no added fertiliser
Fert 1 = K sulphate @10 kg/ha+Fe Sulphate @5.0 kg/ha + P @10kg/ha + TEK* 2:1 @ 15kg/ha
Fert 2 = 5 x fert 1 rate designed to provide greatly increased Fe, P and K, as these were likely limiting nutrients on this soil type.

*TEK was a special pre-mix of P, S and K with added trace elements Molybdenum (mo), Copper (Cu), and Manganese (Mn). These elements are essential for plant growth but are frequently limiting on alkaline soils. The availability of the remnant P was unknown and incalculable, hence different levels of P were applied.

2.3 The legumes and rhizobia

Legumes are an attractive option for low input agriculture, because in association with rhizobia bacteria, they can take nitrogen (N) from the air and turn it into protein, for both animal and human consumption. N is almost always a major limiting nutrient in agricultural soils, but it is essential to supply it for plant growth. N fixation by legumes obviates the need to import expensive N fertiliser into farming systems.

Pulse legumes are a sub-group of legumes that traditionally supply the bulk of the dietary proteins to tropical and sub-tropical societies where animal protein is limiting. There are extensive breeding programs for these legumes in the major sub-tropical Institutions, because they are so important to humanity globally. It was considered that if any of the legumes performed in a promising manner, then we would be able to obtain a wide number of varieties in the future to develop the perfect fit for Christmas Island. Lablab is a “dual purpose” legume, whose leaves, pods and seeds are consumed by both animals and humans.
The legumes sown were:

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Soybean</td>
<td><em>Glycine max</em></td>
</tr>
<tr>
<td>B. Mung bean</td>
<td><em>Vigna radiata</em></td>
</tr>
<tr>
<td>C. Pigeon pea</td>
<td><em>Cajanus cajan</em></td>
</tr>
<tr>
<td>D. Lablab-highworth</td>
<td><em>Dolichos lablab</em></td>
</tr>
<tr>
<td>E. Navy Bean</td>
<td><em>Phaseolus vulgaris</em></td>
</tr>
<tr>
<td>F. Cowpea Caloona</td>
<td><em>Vigna unguiculata</em></td>
</tr>
<tr>
<td>G. Cowpea Ebony</td>
<td><em>Vigna unguiculata</em></td>
</tr>
<tr>
<td>H. lab lab rongai</td>
<td><em>Dolichos lablab</em></td>
</tr>
</tbody>
</table>

The first experiment was sown in early February and sampled in April (sample 1), and early June (sample 2) to assess plant growth and nodulation, as well as seed yield and response to fertiliser rates.

2.4 Early plant growth with both rhizobia and PGPR inoculation

After six weeks of growth, plots were sub sampled by a team from Murdoch University to assess production. Some of the data is presented in the graphs below, however all the data is available upon request. The green bars show plant growth when inoculated with both rhizobia and a growth promoting “PGPR”, whilst the blue bars show plant growth with the rhizobia only. The columns are arranged with increasing levels of fertiliser, from nil, low and high rates, running left to right. The data clearly show that fertiliser application is essential to obtain maximum growth from the legumes.

From the visual assessment of the nutrient deficiency symptoms in nil fertilised plots (see Fig 2.4), it is likely that the response in plant growth illustrated in Figures 2.2 and 2.3 below was to potassium, sulphur and iron, or combinations of these. However, analysis of the nutrients in the plant tops by CSBP and in the soil has guided our interpretation (see section 2.8).
Figure 2.2 The response of mung bean to application of fertiliser, and PGPR after 6 weeks of growth.
Figures 2.3 The response of soybean to application of fertiliser and PGPR after 6 weeks of growth.

Plant growth in soybean was increased markedly by the low rate of fertiliser, and marginally again by the high rate of fertiliser. The application of the PGPR bacteria also increased the plant growth, and it can be seen that the PGPR effect was significant. Mung bean growth was also boosted by the addition of fertiliser, at both the low and higher rates, as was lablab (data not shown), however there was no significant response to the PGPR for these two legumes at this site.

2.4.1 Plant growth assessment June

The data below shows the yield achieved by all of the legumes in a comprehensive sampling carried out in early June. One metre square quadrats were cut by hand and weighed fresh on a portable electronic balance. Representative samples were then dried in the CIP soil laboratory ovens to allow conversion to dry weights.
Figure 1. Shoot dry wt produced February - June (t/ha)

This June harvest captured the peak biomass accumulation for all species except highworth and rongai (Lablab), which continued to grow well into August. The data shows:

1. As was indicated by the first sampling, a large response to addition of a low rate of nutrients (brown bars) comprising K, S, P Fe, Mn, Mo and Cu. It is essential to provide these nutrients for significant plant growth to complement the remnant P in the soil.

2. It is not essential to provide a higher level of fertiliser (fert 2) to achieve significant plant production, primarily because of the P already residual in the soils. However, the small response observed (green bars) indicate a need to optimise K and Fe, as judged by the plant symptoms.

3. The species of legumes differed in their ability to grow at this site, however only navy bean could be considered as a failure. The reason for this failure is unknown, but it is a consistent result across all sites.

4. The cultivars of cowpea, mung bean and soybean did not grow for long enough to fully exploit the rainfall. These cultivars have been selected for Northern Qld, whereas cvs selected for lower latitudes would be more suited to Christmas Island.

5. Highworth lablab, in contrast, is a semi-determinant cultivar that appears to have the right maturity for Christmas Island.
6. The biomass of Mungbean was greatest at the mid-level of nutrition, indicating that only low levels of inputs of P, K and trace elements are required for cultivation of this legume at this site.

2.4.3 The application of a bacterial PGPR

The PGPR applied in these experiments is a bacteria that solubilises P in the root zone of the legumes, as well as releasing plant growth hormones to the roots. The data on the impact of the PGPR was collected and analysed by Murdoch university PhD candidate Mrs Rebecca Swift.

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![Figure 1.2 Shoot dry wt February-June (t/ha) with PGPR (mungfert 1 @ 50%)](image)

- The legume growth was differently affected by the addition of the PGPR bacteria. A comparison of plus and minus PGPR at the fert 2 level of nutrients is shown below.
Figure 1.3 – a comparison of the effect of the PGPR at the fert 2 level of nutrients on plant growth at Airport II (g/sq m fresh weight)

- The figure shows how some legumes benefitted from the PGPR, such as Mungbean and Ebony Cowpea, whilst some were negatively affected, such as the two cultivars of lablab - highworth and rongai.

- This means that different production packages need to be developed for the different legumes, according to their preference.

- The second time of sampling coincided with the end of the biomass production cycle for Mungbean, but was too late for soybean, which had dropped leaves and pods at the time of harvest.

- The experiment confirmed that the agricultural production of legumes is possible on remnant mine sites on Christmas Island, however there must be selection for the cultivars adapted to the particular day length and temperatures of this latitude.

2.5 Symptoms of nutritional deficiencies

Fertiliser was added at two rates, with the low rate providing adequate trace elements Fe, Mn, Cu and Mo and macro elements K and S, whilst also adding sufficient soluble P to alleviate any potential P deficiency. The high rate of fertiliser application was designed to provide optimal P, and K, in the scenario where the apatite P might be insufficiently available.
Where no fertiliser was added, plant growth was very poor, with leaves yellow and chlorotic, with symptoms of chronic deficiency of Fe, S and K, and possibly other nutrients.

At the low level of fertiliser, these symptoms were greatly reduced, for all species. However, some interveinal chlorosis remained, indicative of K or Boron (B) deficiency. Fe deficiency was generally relieved by the application of Fe Sulphate to the soil.

It would be worthwhile to pursue further experiments to assess if Fe and B deficiency can be corrected by spraying of dissolved minerals onto the leaves, perhaps in conjunction with the control of grazing caterpillar insects.

2.6 Seed yield of the legumes

At the first time of sampling, mature pods and seeds of soybean and mungbean were available for harvest. Soybean flowered and set seed by April, which was perhaps too early to exploit all the seasonal rainfall. However, despite this, yields were at the upper end of expectations for these legumes exposed to the minimal agronomy provided.
The best soybean yields were produced at the highest level of fertility – some 2.3 t/ha. This is above the average yields achieved in Australia and double that achieved in Africa.

Whereas the biomass of soybean was not assisted by the PGPR, it can be seed that at the second level of fertiliser, soybean seed yield was increased from 1.5 t/ha to 2.1 t/ha in the presence of the PGPR, an increase of 40%

This yield of soybean was at the upper end of expectations. Selection of a longer season variety more suited to the latitude of Christmas Island, plus improved agronomy, would give even higher yields.

Seed yield of Mung bean
Mung bean also flowered within the first 8 weeks of sowing, responding directly to the day length and temperature of Christmas Island. Mature pods were available for harvest at 12 weeks. The hand harvested yields in Fig. 1.5 show a strong response to the highest level of fertiliser input. This does not reflect the plant production at the highest level of fertiliser input, which was only marginally better than at the low level of fertiliser. The yields approached 2.5 t/ha, which is at the upper end of expectations. The selection of a longer growing cultivar adapted to this latitude is recommended, as well as a further assessment of the interaction between nutrition and PGPR.

2.7 Nodulation in response to inoculation with rhizobia

The legumes require specific strains of inoculant rhizobia (genus bradyrhizobia) to enable them to fix atmospheric nitrogen. The strains were applied as peat cultures immediately before sowing. An uninoculated set of treatments was sown first, allowing us to examine the soils for the presence of other nodulating organisms. The strains of inoculant applied were:

- Group H CB1809 Soybean
- Group I CB1015 Mungbean
- Group J CB1024 Pigeonpea
- Group J CB1024 Highworth lablab
- CC511 Navy bean
- Group I CB1015 Ebony cowpea
- Group I CB1015 Caloona cowpea
- Group J CB1024 Rongai lablab

2.7.1 Nodulation assessment in the absence of inoculation
Soybean (A) achieved very little nodulation in the absence of inoculation, while pigeon pea (C) and lablab (D) achieved only a low level of nodulation in the absence of inoculation. This indicates that the rhizobia carried in the soil on Christmas Island are not vigorous nodulators of these legumes and hence they may need to be inoculated with appropriate rhizobia. In contrast mung bean (B), navy bean (E) and to a lesser extent cowpea (F) were nodulated by the background rhizobia.

The data below on plant growth gives an indication of whether these background rhizobia are capable of nitrogen fixation with the legumes they nodulated.
Mung bean (B), lablab (D) and cowpea (F) grew well without inoculation indicating that the background rhizobia were compatible with these legumes. Navy bean, although nodulating well, grew poorly, which may indicate an inappropriate rhizobia in the soil for this legume. It is difficult to displace a rhizobia resident in the soil by an inoculant, and under these circumstances it may be that cultivation of Navybean cannot be recommended at this site.

2.7.2 Nodulation in response to inoculation.
Soybean responded extremely well to inoculation with rhizobia, increasing its nodule score from less than 1 in the uninoculated plots (see figure 3) to above 6 in all treatments of fertiliser. PGPR did not affect this nodulation, indicating that the growth effects of the PGPR measured previously did not relate to nodulation.

2.8 Plant analysis for nutrient content

A very useful tool to understand the response to the fertiliser treatments is to analyse plant tops for their nutrient content. This was undertaken for the soybean and lablab material grown at Airport II by Mrs Rebecca Swift. Figure 8 shows the level of Phosphorus (P) in the young leaves, with soy on the left and lablab on the right. The effect of the P solubilising PGPR is in the green bars. The data shows that plant available P is high at this site, and is likely to be at close to toxic levels. The reduction in P concentration as the fertiliser rates increase (left to right in the figure) is because by removing other limitations to plant growth (such as K or S) the legume can grow bigger, effectively diluting P in the plant, so it becomes less toxic. This is seen in the next Figure which shows potassium (K) levels. Plants differ in their nutrient requirements. The soil K level appears to be deficient for LabLab (based on other laboratory data), but sufficient for soybean. By adding extra K to the soil, the lablab achieved better growth, thereby diluting the P content to a manageable level.
Figure 8. Tissue phosphorus content* in soy (left series) and lablab (right series), with PGPR treatments in green. *The legume critical levels for each nutrient were obtained from Reuter DJ, Robinson JB (eds), 1997, Plant Analysis an Interpretation Manual, 2nd Edition, CSIRO Publishing, Collingwood.
Figure 4. Potassium deficiency in lablab (above).

Figure 9. Tissue potassium content in soy (left series) and lablab (right series), with PGPR treatments in green.

Figure 4. Potassium deficiency in lablab (above).

Figure 9. Tissue potassium content in soy (left series) and lablab (right series), with PGPR treatments in green.
Figure 10. Tissue manganese content in soy (left series) and lablab (right series), with PGPR treatments in green.

Manganese is an element that is sometimes limiting on alkaline soils, hence we added it to the fertiliser regime. The figure above indicates that Mn is adequate on this site, without the need for adding it to the fertiliser blend as we did. It may be that Mn was added in toxic amounts in fertiliser 3, and this may have compromised plant growth for some species.

Figure 11. Tissue Boron content in soy (left series) and lablab (right series), with PGPR treatments in green.

The data suggests that Boron was below the critical levels required for soybean growth, and just adequate for lablab. Soil Boron levels were marginal at this site (0.17 mg / kg), and it may be that the cultivar of soybean sown was sensitive to Boron levels. An addition of boron to the fertiliser may be required on Christmas Island for the viable production of some legumes.

We have learned from these experiments that a Christmas Island fertiliser blend containing K, S, Ca, Fe, Mg and B should be developed. Nitrogen is not required, because of N fixation from the legumes, and P is sufficiently available in the soil, or can be solubilised with an appropriate PGPR.

2.9 Pests and diseases
Previous reports highlighted the prevalence of insects likely to damage crops grown on Christmas Island. There was constant grazing of the leaves of all the legumes at this site by caterpillars (see figure x), although lablab and cowpea appeared the most resilient. The site was sprayed once with an organic insecticide in March, and this was efficacious in providing some control. The agricultural production of these legumes would be enhanced with several sprays of organic insecticides throughout the life of the production cycle. This is a low input activity.

Nematode galls were noted in the roots of native plants at this site, but they rarely affected the roots of the legumes when assessed in March and June. However it is possible that the poor growth of Navybean was because of early root pruning by nematodes.

2.10 Machine harvest by experimental header

The mechanical header was able to access plots of the successful species lablab and cowpea in November, after the soils had dried and the legumes had senesced. The yields expressed on a per hectare basis are shown below.

This data provides evidence that machine harvesting of the legume pods is possible on Christmas Island, and also shows the response in yield to appropriate addition of fertiliser.
3. Airport III

At this site we compared the growth of the legumes on the CIP dryer dust waste which had been dumped into the pinnacle field to provide a flat surface. The site had not settled sufficiently for machine traffic, hence lines of the inoculated legumes were sown by hand; either with or without the PGPR.

3.1 Biological yield

Growth was assessed by cutting 1 sq m of each plot 15 weeks after sowing, and weighing the fresh material on a vertical electronic suspension balance.

![Figure 3.1](image)

**Figure 3.1** Fresh weight (t/ha) of legumes after 15 weeks of growth

At the time of sampling soybean and mungbean had finished their growth cycle, whereas highworth lablab and ebony cowpea were still actively growing, producing in excess of 70 tonnes and 60 tonnes fresh weight of material respectively. These are massive yields in the 15 week growing period and prove that the dryer dust is an excellent medium for plant growth when trace elements, and macro-nutrients are added. There was an insignificant, minor negative effect of the PGPR at this site, perhaps associated with luxury levels of P.

3.2 Seed yield
The Highworth was in full seed production during November and had spread up to 4m from the original row. 4 quadrats were taken and seed was extracted by hand. The yield was an outstanding 2800 kg/ha.

The capacity of the dryer dust to produce plant growth without additional P should be investigated further. The small particle size of this medium means the P is likely to be more readily solubilised by microbial activity and weathering than when in the rock form. The 70 tonnes of lablab highworth fixed approximately 200 kg of N, expressed as Urea equivalents.

4. Jindalee

4.1 Plant growth

This site was established as a broad-acre demonstration of the viability of the region for agriculture. Although not replicated, two plantings, each of 0.2 ha were sown with the tractor-drawn seeder after the site was levelled with a D9, ripped with a grader, then hand-picked for rocks to prepare the site prepared for machine harvest in November. Plant growth was very vigorous at this site with top dry weight sometimes double that of the legumes at Airport 2. In the graph below, top dry weight from the three levels of fertiliser are shown for soybean, mungbean, pigeon pea and lablab. The data shows little consistent response to added fertiliser, which suggests fertility at this site, post mining, was adequate for legume growth.

Several of the legumes (soybean, mungbean and cowpea) had already produced viable pods at the time of the March sampling. Flowering was vigorous and for cowpea the indeterminate nature of the legume indicated that several phases of seed production might be possible. For the determinate species, several harvests might be possible from different times of sowing.
Figure 8. Plant growth from Jindalee for soybean (A), mungbean (B), pigeon pea (C) and lablab (D) sampled 6 weeks after sowing. Fertiliser 1-3 represents decreasing levels of fertiliser applied. Plant growth was at times double that of the experiments at Airport 2 and East West in the experimental plots sown during the same week, indicating that the soil at Jindalee presented an excellent substrate for legume production.

Growth of lablab, cowpea, soybean and mungbean was exceptionally vigorous on this soil, with little response to added fertiliser. Dry matter production was estimated at 5 tonnes for cowpea and lablab, the two legumes most adapted to the latitude of Christmas Island.

4.2 Weed control

At Jindalee, and also Airport 3, weeds were significantly out-competed where legume establishment was successful, and subsequent legume growth was strong. This provides an alternative strategy for weed control on the mined sites.

4.3 Machine Harvest of Lablab
The header was able to access the highworth lablab at the three levels of fertility applied to Jindalee in the north east sowing. The yields shown in the figure below indicate a response to the middle level of fertility applied, even though this was not clearly evident in the earlier plant sampling.
5. East-West experimental site

5.1 Times of sowing

The 96 machine-sown plots were planted on February 9 -10. Growth over the following five weeks was poor relative to other sites, and there was no response to fertiliser. In early March plots were attacked by caterpillars, which were subsequently well controlled with an organic spray of *Bacillus thuringiensis*. This was an effective treatment, however sink holes then appeared across the plots and this, combined with water erosion, meant it was not possible to sample the trial comprehensively. However observations of the plots between February and June indicated that this land form and remnant soils was less able to support legume growth than at all other sites. One possible reason for this was that much of the soil was scraped from the surface of the site to create bunding around the perimeter of the site, leaving very shallow soil for plant growth. This bunding can be seen in Figure 5.1. An exit strategy from this geological feature would require replacement of surface soil to grow the food legumes. However other, more sturdy plant species, such as *Leucaena*, could possibly be supported in this environment.

![Figure 5.1. The poor growth of the legumes after five weeks at East-West, with the bunding created by removal of top soil seen in the background.](image)

5.2 Second time of sowing

As it became evident that the machine-sown experiment was compromised, a second experiment was sown by hand at the west end of the site. This piece of land had previously held a dump of high quality apatite, and had a deeper soil profile with less limestone rocks.

5.2.1 Response to fertiliser and PGPR at East West in the second time of sowing.

Lines of inoculated legumes (20m) were hand-sown at East West in early March to complement the earlier machine sown experiments. The PGPR and two levels of fertiliser were applied (nil, high) to legumes inoculated with rhizobia as per the diagram below. Tops from these plots were harvested in late April, dried in the CIP ovens, then weighed.
5.3 Plot layout in second time of sowing at East West

East West Trial Site
Planted:
March 2013

5.3 Plot layout in second time of sowing at East West

East West - top dry weight

Average SDW (g)
Figure 9. Data from East West TOS 2. A, soybean; B mungbean, C, pigeonpea, D, highworth lablab, E, navybean, F, caloona cowpea, G, ebony cowpea, H rongai lablab.

In the data above, the green bars show the response to PGPR, whilst within each set of coloured bars (blue or green) we have the two rates of fertiliser (nil or fert 2).

The standout result here is that at the sampling time (5 weeks after sowing) there was no consistent response to fertiliser addition, indicating that this site has sufficient nutrients to support early growth of the pulses after the mining operation. Soybean (A) and Lablab (d) were the most vigorous of the legumes at this site and there was no obvious response to PGPR. However, as the plants moved into a later growth stage they were sampled again.

Figure 5.2.1 Yield of legumes at East West TOS2 (t /ha wet weight) as affected by fertiliser addition at June 19.

The growth of all the legumes at this site remained strong into the 12 week stage. However, fertiliser applied (at the high rate) compromised the growth of cowpea and lablab, whilst boosting the growth of soybean, mungbean and pigeon pea. The compromised production of cowpea and lablab in the presence of the high level of fertiliser was probably caused by excessive P, given the soil here had residual high grade apatite.

The legumes clearly varied in their capacity to extract P from the residual apatite, and this can be exploited in future agricultural pursuits on Christmas Island. Lablab and Cowpea will require much lower inputs than soybean, mungbean and pigeon pea. It is also important to acknowledge that the indeterminant species such as lablab were advantaged in all the trials sites on Christmas Island, as those such as soybean flowered early, set seed, then senesced prematurely.
Figure 5.2.1 Yield of legumes at East-West TOS 2 (t /ha wet weight) in response to application of PGPR in the absence of fertiliser (t /ha wet weight) at June 19.

The legumes again varied in their response to the PGPR, with those species that proved capable of extracting P at this site (lablab and cowpea) compromised by application of the PGPR, whilst those requiring the higher nutrition responding to the application of PGPR. It appears that on this soil with higher residual P, lablab and cowpea cannot down-regulate P uptake and are thus at higher risk of P toxicity than the other legumes. This variance in the legume species in their ability to extract P can be matched to the different sites, according to residual P in the soil, post-mining.
6. Plant production at Field 4

Field 4 was a small area of approximately 1 ha left relatively flat following mining. Here it was decided to trial the use of waste products from the Water Authority, combined with the CIP dryer dust waste, as substrates for plant growth. To prevent leaching of any toxic materials from the organic waste, the site was lined with a 10 cm deep bed of crushed limestone. Organic waste was dumped onto this base and spread by hand, then the dryer dust was dumped over the top, to a depth of 40 cm. Plants were sown onto the surface of this mix of waste products, both with and without fertiliser treatments, in May.

Figure 6.1 Production of legumes growing on waste materials at Field 4 (t/ha wet weight) after 12 weeks without added fertiliser or inoculation. The soybean, mungbean and pigeonpea had flowered and senesced by this date of harvest.

Despite the absence of applied fertiliser, or inoculant, plant growth was very good on this combination of waste products. There was no indication of toxicity from either the dryer dust, or from the organis wastes provided by the Water Authority.
The yield of highworth lablab was increased 100% by addition of fertiliser and inoculant, and that of Ebony cowpea by approximately 40%. The other species had senesced by the time of harvest (12 weeks). However a seed harvest was possible from the Soybean, and this was calculated at 2.03 tonnes per ha.

The response to fertiliser on these waste products indicates that plant nutrition needs to be optimised to realise the full growth potential of the legumes growing in this environment. This probably relates to levels of K and Fe, which are the most commonly limiting nutrients on these alkaline soils.

### 7. Soil analysis

During the course of the year we were able to access soil samples from the sites, adjacent to the experiments, and have them analysed in a quarantine approved facility.

<table>
<thead>
<tr>
<th>Name</th>
<th>Ammonium Nitrogen mg/Kg</th>
<th>Nitrate Nitrogen mg/Kg</th>
<th>Phosphorus Colwell mg/Kg</th>
<th>Potassium Colwell mg/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>east west</td>
<td>&lt; 1</td>
<td>10</td>
<td>180</td>
<td>26</td>
</tr>
<tr>
<td>jindalee</td>
<td>2</td>
<td>10</td>
<td>522</td>
<td>18</td>
</tr>
<tr>
<td>airport 2</td>
<td>1</td>
<td>1</td>
<td>299</td>
<td>&lt; 15</td>
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<tr>
<td>airport 3</td>
<td>&lt; 1</td>
<td>12</td>
<td>311</td>
<td>19</td>
</tr>
</tbody>
</table>
The soil analysis data show:

1. very low levels of organic matter, magnesium and nitrogen

2. low levels of Sulphur, Boron and Calcium

3. very high and possibly toxic levels of phosphorus available to the plants

This analysis, combined with the tissue analysis in section 2 of this report, allows a scientific evaluation of an appropriate fertiliser design specifically for Christmas Island, and tailored to different legume crops.

8. Rhizobia naturalised on Christmas Island

Rhizobia, like legumes, have come to Christmas Island by chance, in aerosol, in soil and on seeds prior to significant quarantine arrangements becoming commonplace on the Island. Murdoch University undergraduate student Tom Edwards undertook a study of the naturally nodulated legumes on Christmas island during 2013. This represents the first audit of the rhizobial micro-flora on the island, and will help in interpreting legume nodulation data.
Mr Edwards isolated rhizobia from Leucaena and Mimosa, and then sequenced the 16s ribosomal RNA genes of the isolates to identify the nodulating bacteria. Leucaena was found to be nodulated by *Sinorhizobium*, and Mimosa by *Cupriavidus*. Neither of these organisms would be expected to nodulate the introduced pulse legumes, so the source of the background nodulation detected on these legumes is yet to be identified.

9. Lessons learnt about the process of land preparation during the mining exit phase

- Residual soil – must not be removed, and any surface burden should be re-applied to topdress sites. This should be the second last activity of the mining phase

- Slope and drainage, contour banks – this needs to be the last activity of the mining phase. Contour banks need to be constructed where the fall is greater than 3 % to ensure surface movement of water is controlled

- Timing – the sites must be prepared during the dry season to ensure trafficability for February sowings

- Rocks – any rocks greater in size than a cricket ball need to be removed prior to sowing

- Waste products – must be provided during the dry season, spread and sites prepared before the wet season

- Sink holes – the geology of sites needs to be reviewed to ensure agricultural sites are not located in a zone prone to the emergence of sink holes

10. Lessons learned about agriculture on Christmas Island

- The sub-tropical pulse legumes grown in other parts of the world are well adapted to the environment on Christmas Island, and can tolerate the extant pests and diseases to grow and yield favourably

- The best seed yield recorded was 2.8 tonnes / ha of Highworth lablab at Airport 3, on a quadrat basis. This probably represents a reasonable estimate of the capability of the Island for seed production of legumes in future economic assessments.
• Selection needs to be made for the right physiological adaptation among these legumes – daylength x temperature are the key factors that induce flowering in many determinate species. Cultivars with a very long cycle of growth would work well on Christmas Islands, as evidenced by the Highworth variety of Lablab.

• Soybean varieties that are not daylength responsive need to be sourced, and these are available from EMBRAPA in Brazil.

• High levels of N fixation are achievable – probably in excess of 200 kg urea equivalents per ha, obviating the need to import N to the island.

• Rotation crops should be explored such as rice, cereals, fruit and vegetable crops to exploit this fixed nitrogen and increased fertility. Tree crops for timber, oil or other uses should also be considered as a longer term option following the first legume crop.

• Other legumes were seen in residential also gardens, such as the winged bean, and these could be investigated.

• The microbial inoculants such as rhizobia and the PGPR are useful products to increase plant growth on the soils of Christmas Island. However the response to the micro-organisms is species specific, so they need to be tailored to each of the legumes individually.

• Navy bean is not adapted to Christmas Island, perhaps because it is (like pigeonpea) obligate for mychorriza.

• Sulphur, boron and potassium are limiting nutrients for legume growth, but can be overcome by relatively small doses of 5 – 10 kg / ha. Phosphorus is in high concentration, but species seem to be able to tolerate this if other nutrients are well balanced.

• A Christmas Island fertiliser blend without N and P can now be developed for plant production. This will decrease fertiliser inputs to the Island dramatically.

• The soil has adequate manganese, but is very low in organic carbon and nitrogen. Both these elements can be improved by legume production.

• Simple agronomy such as weed and insect control should be practiced, but inputs required to produce excellent crops are low.

• There is the possibility for two growth cycles (or two harvests) per year by using short season cultivars (such as the soybean and mung bean varieties employed in these
experiments), however it may be more desirable to maximise production in one growth cycle per year, with a harvest in the dryer months.

- The machine header was able to harvest dry pods of lablab in November, following desiccation.

- Where the legumes grew well, and where strongly established, weeds were smothered. This presents an organic option for weed control other than using herbicides.

- In a marketing context, consideration should be given to growing crops organically to take advantage of the virgin sites, inherent P level and the natural N fixation from the legume crop.