# Mining to Plant Enterprise (MINTOPE) on Christmas Island

*Report to Stakeholders*

**Professor John Howieson, Dr Graham O'Hara and Dr Katinka Ruthrof.**
**Edited by Helen Shortland-Jones**

Mining to Plant Enterprises (MINTOPE) was a tri-partisan research project conducted between 2012-2019 to determine the feasibility of transitioning mined land to agricultural land on Christmas Island. The project was jointly funded by the Department of Infrastructure, Transport, Regional Development and Communications (previously Department of Infrastructure, Transport, Cities and Regional Development), Murdoch University and Christmas Island Phosphates (CIP); and supported by the Water Corporation, the Shire of Christmas Island, the Chinese Literary Association, the Christmas Island Islamic Council and the Indian Ocean Group Training Association. MINTOPE was also awarded an Australian Research Council (ARC) Linkage grant in 2015: *'Transition from phosphate mining to an economically, environmentally and socially viable agricultural industry on Christmas Island (LP140100690)',* which assisted with funding for postdoctoral research on Christmas Island rhizobiology and PhD student research.

Phosphate mining has occurred on Christmas Island (CI) for over 100 years, with ex-mined land within the National Park slowly rehabilitated back to forest via a range of approaches. Mined land outside the National Park has not been prioritized for rehabilitation, until very recently. To date around 22% (3000 ha) of CI has been mined. Post-mining the soils are deficient for pant growth in carbon (C), nitrogen (N), potassium (K) and sulphur (S), but extremely high in phosphorus (P). Adding further complexity to agricultural pursuits is the tropical climate, with a variable wet season primarily from November to May and an average annual rainfall of around 2000 mm (1000mm-1500mm variation). However, post-mined soils are very porous, possibly requiring small and frequent applications of nutrients for plant growth.

MINTOPE's core objective was to establish the scientific basis to facilitate agricultural production on areas disrupted by mining. In doing so, suitable techniques were developed for the physical transformation of this land that facilitated broad-acre mechanized cropping, plant cultivation, microbial assessment, soil enrichment through waste recovery, forage production for animals, and value-adding activities for the community such as distillation, fermentation and pelletisation of gains for controlled fish and animal feed. This was the first time a modern agronomic research activity had taken place on the Island. MINTOPE concluded in September 2019 with numerous successful outcomes.

# Outcomes

## 1) Phase 1. Transform topography of ex-mined land to ensure heavy rainfall does not cause erosion, and make trafficable for agricultural machinery.

Through co-ordination with and training of CIP staff, 8.14 ha of appropriate disused mine site area was cleared of regrowth vegetation and prepared for broadacre cropping at four different sites (Figure 1). To capture rainfall in the soil profile and to reduce water erosion, the land was chisel ploughed, graded on the contours, levee banks formed around bays using a laser level, and roots and rocks removed by hand. The bay development was undertaken between September 2013 and January 2015 when the dry conditions allowed movement of heavy machinery supplied by CIP. The distinct bays at the sites differed somewhat in their soil characteristics, with most bays on the sites being calcareous and highly alkaline (pH 8.0–8.5) which might influence nutrient availability and uptake. Soil profiles were variable and several others were ideal for plant growth (pH 6.5–7.5).

**Figure 1.** Preparation of previously mined sites between September 2013 and January 2015.

### 2) Phase 2. Determine factors limiting plant production with multifactor experiments including trace elements, and response to nitrogen (N) and potassium (K).

Due to early indications of nitrogen deficiency, MINTOPE focussed on legumes, which when nodulated by nodule bacteria put atmospheric nitrogen back into the soil (e.g. beans, peanuts and soybeans). The subsequent growth of non-legumes such as cereals utilise the increased fertility (e.g. maize, millet, rice and sorghum). We investigated different sowing times to determine the best time of year in which to plant, the nitrogen fixation achieved, as well as managing pest problems and investigating ways in which nutrients and beneficial soil biota (rhizobium bacteria and mycorrhizal fungi) could help enhance plant establishment and growth.

Nutrient-addition trials were established at a number of sites in January 2015 to determine which were required for optimal plant growth (Table 1). A basal fertiliser was added, legumes were inoculated with effective strains of rhizobia and plants were treated with rates of nutrients in a factorial design. Following eight weeks of growth, some significant treatment differences were noted. Preliminary results suggested that potassium and inoculation was critical for increasing plant growth in the legumes such as Lablab (Figure 2).

**Table 1.** Nutrient trial design; established in January 2015.

| Site | Species | Nutrient trial |
|---|---|---|
| Airport 2 | Lablab *(Dolichos lablab)* | Potassium, sulphur/iron, phosphate |
| Airport 2 | Mung bean *(Vigna radiata)* | Potassium, sulphur, phosphate, micronutrients |
| Airport 4 | Sorghum *(Sorghum bicolor)* | Potassium, sulphur, iron, phosphate |

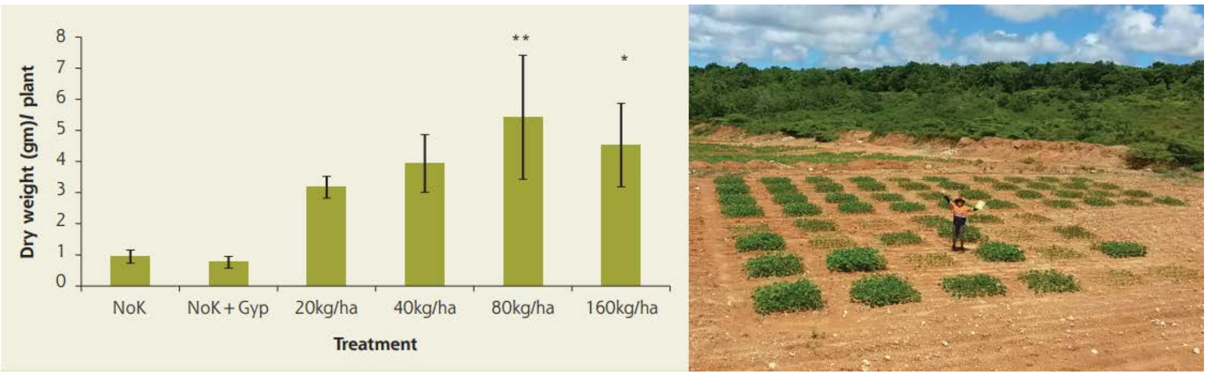


**Figure 2.** *Left*: Lablab dry weight (gm/plant) following eight weeks of growth in response to basal fertiliser plus different rates of potassium (as $K_2SO_4$). *Right*: lablab growth differences were clearly visible at different rates (see the front row of plots: with the highest application rate on the left to the lowest on the right).

However, few growth response differences were seen for the added sulphur/iron/ trace elements and phosphate. Significantly higher levels of growth were seen in mungbean in response to potassium (Figure 3), but no significant responses to increasing rates of sulphur, phosphate or micronutrients. Further trials showed that nitrogen was severely limiting the growth of cereals such as maize and dryland rice.

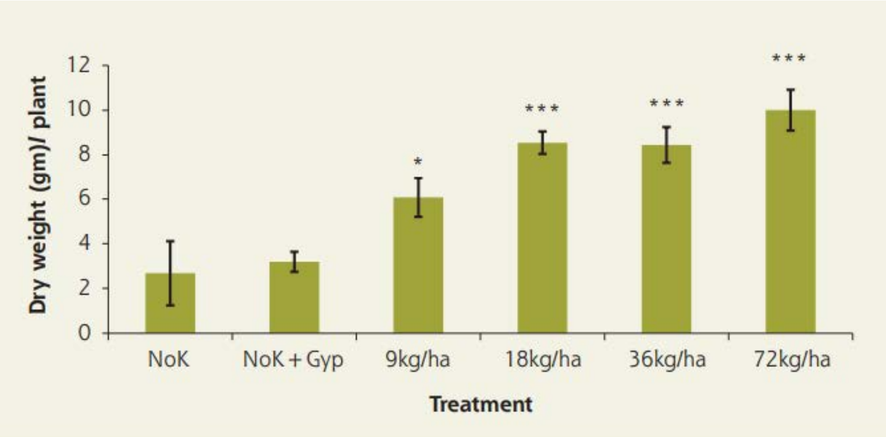

**Figure 3**. *Left*: mungbean dry weight (gm/plant) following eight weeks of growth in response to basal fertiliser plus different rates of potassium (as $K_2SO_4$). *Right*: close-up of a mungbean plot.

It was shown that nitrogen and potassium are severely deficient in the post-mined soils. Legumes can acquire nitrogen from rhizobia but must have high quality inoculation, with N fixation maximised by the addition of potassium fertiliser. There was no evidence for significant deficiencies of phosphate, sulphur, iron or other nutrients. Cereals required both nitrogen and potassium; however, to reduce the inputs to the island, nitrogen/cereal rotational experiments were undertaken to determine whether all N requirements could be met by rotations with legumes.

## 3) Phase 3. Rebuild soil fertility utilizing hardy legumes, nitrogen fixation, microbial capacity, carbon, nitrogen, and potash.

Agricultural pursuits in post-mining environments are becoming increasingly important globally as many regions are challenged with food security and post-mining land-use legacies. Although there are many advantages for agricultural production at post-mining sites, these substrates have abiotic and biotic challenges for plant growth, including poor fertility, heavy metals and lack of beneficial soil microbes. These challenges can hamper plant growth, affecting yield and potentially food safety.

In post-phosphate mining substrates, such as those found on Christmas Island, our previous work has demonstrated that nitrogen is a key limiting nutrient for cereals and although legumes are planted prior to cereals, nitrogen supplementation may still be necessary. An analysis was undertaken to identify the endemic N-fixing rhizobia present in Christmas Island soils. Further, for legumes, we have shown that potassium (K) is a critical limiting nutrient. Given the tropical conditions with high humidity and high rainfall on Christmas Island and the potential for leaching of traditional, fast-release fertilisers, the use of slow release fertilisers (SRF) that could benefit plant growth by having greater longevity than the fast release fertilizers were evaluated. A further challenge for agriculture in these post-phosphate mining substrates globally, is to reduce the uptake of naturally occurring cadmium (Cd).

### 3.1) Nitrogen rates for cereals

Preliminary experiments indicated that 160 kg/ha urea produced maximum biomass outcomes in cereals, and this rate was used to compare *Sorghum bicolor* plant growth with different nitrogen SRF. After four weeks of growth, there was a significant difference in biomass, with Macracote® and 160kg/ha urea treatments producing higher biomass than the control plants. After 14 weeks of growth, there was also a significant treatment response, with 160kg/ha urea, Macracote® or Sulsync® resulted in equivalent, and higher biomass than the control plants. It was also noted that the SRF used in this trial had the advantage of not clumping, which is often seen in urea (which is probably due to the hydrophilic nature of urea and the tropical conditions it was used in). Cadmium analysis was undertaken after 14 weeks of growth on seed material, with no significant treatment responses, but levels were within an acceptable range.

Cereal responses to applied N were greatly reduced if cereals were grown after successive legume crops.

**3.2) Potassium rates**

Experiments in 2015 and 2016 demonstrated that *Lablab purpureus* has a high K demand and that SRF increased *L. purpureus* biomass and reduced cadmium concentrations compared with the control treatment. We thus tested the responses of *L. purpureus* (including biomass, heavy metal concentrations) to different rates of $K_2SO_4$ 9-month SRF, and a combination treatment composed of both SRF and $K_2SO_4$. The combination treatment (half SRF, half $K_2SO_4$: 80kg/ha each) and the 160kg/ha $K_2SO_4$ increased early biomass compared with the control plants. The Cd concentrations in plant material were not significantly altered by any fertiliser treatment.

We have shown that although post-phosphate mining substrates are poor in K and are severely limiting legume growth, high biomass can be attained with SRFs containing K, or the traditional $K_2SO_4$ at 160kg/ha. Optimising nutrient input for agriculture in post-mining environments is critical for developing successful, safe and sustainable crops.

**3.3) Microbial prospecting**

MINTOPE aimed to identify well-adapted existing microorganisms that facilitate plant growth, nitrogen fixation, and phosphate solubilisation. The beneficial characteristics of some microorganisms can include the ability to fix N, suppress plant pathogens and increase availability of poorly soluble plant nutrients. Rhizobia and mycorrhizal fungi are usually absent from severely disturbed soils and reintroduction of these beneficial symbionts can aid in soil remediation. Legumes are valuable in revegetation as their symbiotic associations with bacteria and mycorrhizal fungi aids plant growth through nitrogen fixation and P solubilization, respectively.

We undertook initial characterisation of naturally occurring rhizobia that can infect the legumes cultivated (section 3.3.1 below). This is important as background rhizobia may not be able to fix nitrogen and yet may compete with the elite inoculant strains for nodulation. In addition, we assessed whether mycorrhizal fungi were naturally present in the soils, both mined and undisturbed. We also investigated whether any other P solubilizing bacteria were naturally present in the soils to aid in the solubilising of the phosphorus. A fungal audit of the soils was also undertaken, the first of its kind on Christmas Island.

To determine the presence of naturally occurring rhizobia, legume seed was rinsed with alcohol to remove any cells of rhizobia adhering in the dust. Inoculated and uninoculated seeds were then sown across the key experimental sites. Plants were carefully excavated in May 2016 and the nodules scored, then removed and stored over silica gel. Soils were collected from the sites and with the nodules transported to the Centre for Rhizobium Studies

(CRS) quarantine glasshouse at Murdoch University, on the Western Australian mainland. The soils were assayed for their content of mycorrhizae and nodule bacteria via assays of root colonisation, and nodules were examined for their content of rhizobia with standard procedures.

Previous research on CI rock phosphate by Panhwar et al. (2011) reported that addition of two P solubilizing bacteria to aerobic rice significantly improved P uptake from CI rock phosphate, resulting in an increase in dry matter yield. MINTOPE found that soybean and chickpea failed to grow well and nodulate without the application of their specific inoculant. Lablab, cowpea and mungbean did achieve some nodulation with bacteria that were already present in the soils. Twenty-five isolates were taken from these nodules to be assessed and identified for N-fixation capacity at the CRS quarantine glasshouse, where bacteria (and mycorrhiza in undisturbed and disturbed soils) from CI were inoculated onto legume/cereal host-plants, and then identified. More research is required to determine the capacity for future development of the microbial communities at the site.

**3.3.1) Rhizobial diversity**

An investigation was undertaken to identify the endemic rhizobia on CI associated with legume crops including bean (*Phaseolus vulgaris*), chickpea (*Cicer arietinum*), cowpea (*Vigna unguiculata*), lablab (*Lablab purpureus*), mungbean (*Vigna radiata*), peanut (*Arachis hypogaea*) and soybean (*Glycine max*), and the exotic legumes including hairy indigo (*Indigofera hirsuta*), *Leucaena leucocephala*, *Mimosa diplotricha*, *Mimosa pudica* and siratro (*Macroptillium atropurpureum*).

In total, 84 isolates were obtained from seven sample sites across CI. Phylogenetic analysis using 16S rRNA and *recA* gene sequences revealed a large diversity of bacteria belonging to the genera *Bradyrhizobium*, *Cupriavidus*, *Ensifer* and *Rhizobium* (Table 2).

**Table 2.** Summary of endemic rhizobia isolated from plants growing at several sites on Christmas Island, based on 16S rRNA analysis. M: *Mimosa*; I: *Indigofera*; L: *Leucaena*; Brady: *Bradyrhizobium*; Cupri: *Cupriavidus*; Rhizo: *Rhizobium*; NA: Not analysed.

| Plant species | Sample sites | | | | | | |
|---|---|---|---|---|---|---|---|
| | Airport 2 | Airport 4 | Casino | East West | Jindalee | Stockpile | Stockpile 2 |
| **Cowpea** | *Brady.* | *Brady.* | NA | NA | NA | NA | NA |
| **Mungbean** | *Brady.* | *Brady.* | NA | NA | NA | NA | NA |
| **Lablab** | *Brady.* | *Brady.* | NA | NA | NA | NA | NA |
| **Peanut** | *Brady.* | NA | NA | NA | NA | NA | NA |
| ***M. pudica*** | *Cupri.* | NA | NA | *Cupri.* | NA | NA | NA |
| ***M. diplotricha*** | *Cupri.* | NA | NA | *Cupri., Rhizo.* | *Cupri.* | NA | NA |
| **Siratro** | *Brady.* | *Brady., Ensifer* | NA | *Brady., Ensifer* | NA | *Brady., Rhizo.* | *Brady.* |
| ***I. hirsuta*** | *Brady.* | NA | *Brady.* | NA | NA | NA | NA |
| ***L. leucocephala*** | NA | NA | NA | NA | *Ensifer* | NA | NA |

From a selection of strains, both the *nodC* (nodulation) and *nifH* (nitrogen fixation) symbiosis genes were sequenced for phylogenetic analysis. Both genes showed congruent phylogenies with 12 and 11 groups for *nodC* and *nifH*, respectively (Figure 4). There was no relationship between site or host plant with the *nodC* or *nifH* alleles.

There appears to be a large diversity of endemic rhizobia present on CI. These can be further investigated to understand their nitrogen fixation capacity and potential use as future inoculants for agricultural crops. In addition, this set of strains could be investigated for potential competition capacities against imported inoculant rhizobia with high nitrogen fixation capacity. This combined knowledge can be levered to improve legume production on CI and successful establishment of legume crops.

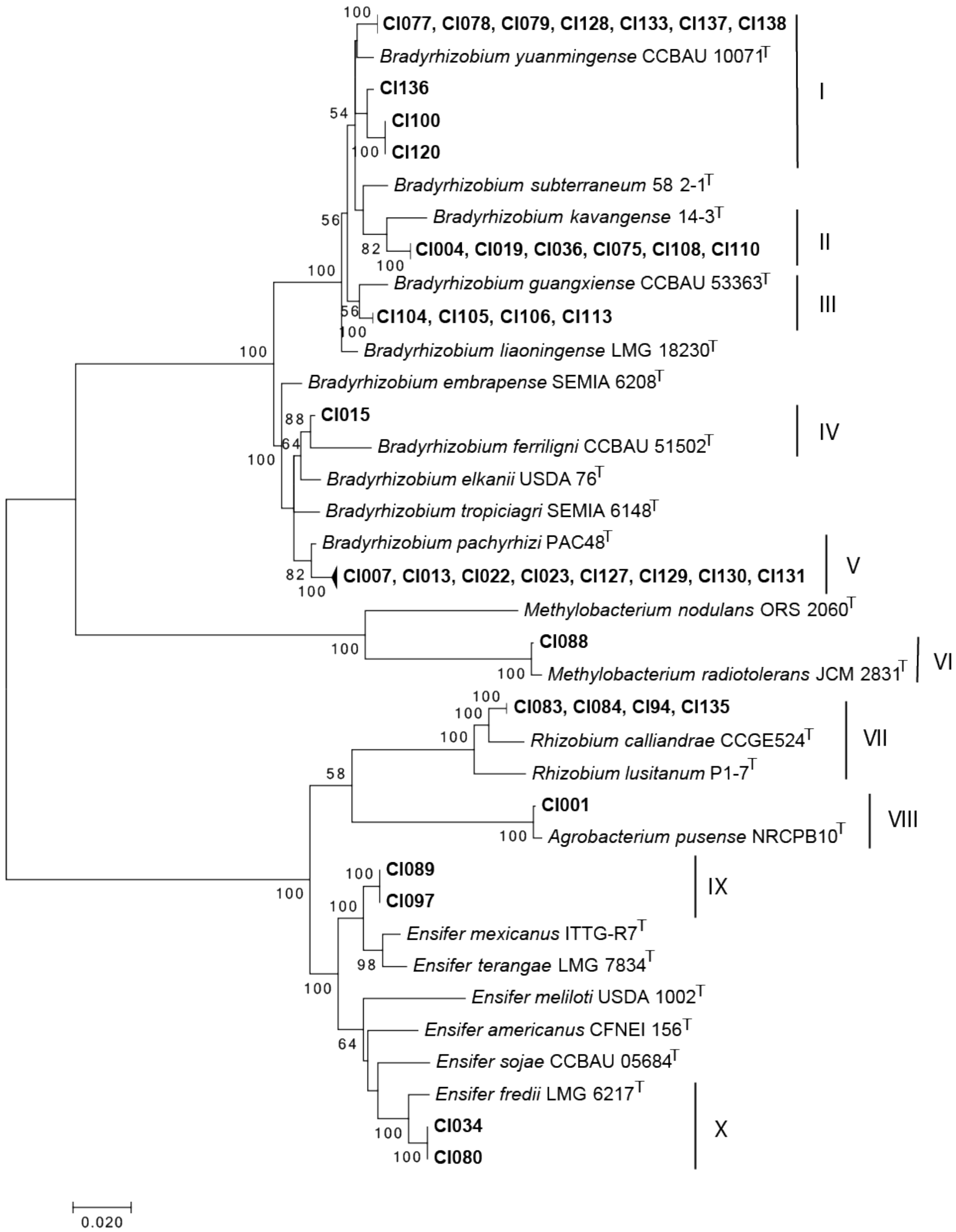


**Figure 4.** Maximum likelihood tree based on the concatenated 16S rRNA and *recA* gene sequences (1,644bp) of the alpha-rhizobia and phylogenetic related species. Bootstrap values after 500 replicates are expressed as percentages, values less than 50% are not shown. The scale bar indicates the fraction of substitutions per site. Roman letters (I to X) refer to the MLSA grouping.

## 3.4) Waste Recovery Trial

Solid bio-wastes are a by-product of treated wastewater or sewage sludge that originate from humans and industry. Approximately two-thirds of treated solid bio-wastes is applied to land in Australia as fertiliser, soil conditioner or soil replacement product. The aim of the waste recovery trial on CI was to research the potential for combining green waste (organic mulch) and solid bio-wastes (sludge currently dumped at the tip) from CI in combination with the excess dryer dust from Christmas Island Phosphates (CIP) to 'rebuild' soils to support the growth of agricultural plants over a limestone base. The soils that result might then be used in land revegetation, pinnacle field in-fill, vegetable production or agriculture as the soils mature. Water quality monitoring via piezometers occurred throughout the waste recovery trial to enable monitoring of microbes, nutrients and heavy metal contaminants potentially draining to groundwater.

With assistance from the Water Corporation, bio-wastes were deposited onto a prepared site in January and April 2018 (Figure 5). After the last deposit, the sludge was raked flat, covered in mulch and then phosphate dust waste (Figure 6). Crops were sown in late January, late February and late April 2018. Yields after 12 weeks of growth from the first sowing were 40 tonnes/ha of forage sorghum (including 6.8 tonnes of seed) and 7.5 tonnes/ha of forage sorghum after 6 weeks of growth from the second sowing (Figure 7).

**Figure 5.** Deposit of bio-wastes (sludge) by Water Corporation in 2018.

**Figure 6.** Spreading mulch and phosphate dust over biosolids.

**Figure 7.** Forage sorghum at 13 weeks (background), grain sorghum at 6 weeks (middle) and millet at six weeks (foreground).

These results indicate that the use of bio-wastes in agriculture on CI may be a viable option in assisting with the reconstruction of soils on limestone; however best practice guidelines and standards, including regular groundwater quality monitoring, need to be implemented to minimize risk to the receiving environment. Ground water monitoring of this experiment has indicated minimal coliforms and is ongoing.

## 4) Phase 4. Selecting crops that are well adapted to the environment (insect pressures, soil characteristics, rainfall patterns) and that have food, feed or other economic potential.

**4.1) Broad acre and rotational legume cropping**

Four cereal crops (maize, sorghum, millet, and dryland rice), and five legume crops (lablab, cowpea, mungbean, chickpea, and soybean) were planted on three sowing dates between January and April 2016. A variety of crops such as chia, quinoa, peanuts, and guar were also investigated as potential rotational crops. Multiple sowing dates enabled the collection of data on the most suitable sowing time for each species in relation to moisture, daylength, and insect predation, how many crops could be grown in one calendar year, and which crops were most adapted to the soils and climate. All legumes were inoculated with the appropriate rhizobium for that species to ensure optimal nitrogen fixation.

All crops were fertilised with a custom 'MINTOPE fertiliser mix' which was developed over 2013–2014 from soil tests (i.e. potassium sulphate 40 kg/ha, iron sulphate 5 kg/ha, superphosphate 10 kg/ha, and TEK phosphate 2:1 at 15 kg/ha to deliver trace elements Cu, Mo, Zn plus 1 kg/ha boric acid). Cereals were also provided an additional application of urea 40 kg/ha. Trial design was in randomised block with four replicated, sown with a seeder of 1.8 m width. Finally weed control immediately before planting included scarification and application of glyphosate at 2L/ha.

The dramatic response of all crops to K was notable, particularly for lablab, as in previous studies. Mungbean also responded very strongly to application of K fertiliser. There were striking effects of K deficiency on leaf size and colouring in the crops. The soybean failed to thrive (producing only 0.35 t/ha in 8 weeks), relative to the lablab (which produced 2.2 t/ha), illustrating the different adaptation of the legumes to the CI soil types post mining when under nutritional stress. These results indicate that the areas that were previously used to dry and store the rock phosphate prior to shipping are suitable for cultivation of lablab if K is applied. There were no statistically significant responses to S or P applications to lablab, mungbean, or sorghum, with the inference that the postmined soil has sufficient reserves for these crops on the island. In addition, the legumes and cereals did not respond to additions of the trace elements Mo, Co, Cu, Zn, or B, although there was a clear N deficiency in the soils.

**4.2) High value crops (a)**

The vegetable program component combined local knowledge and MINTOPE experience to improve horticultural techniques. This included communications with the local gardeners to assess the vegetables they considered to be of high value. Leaf and fruit sampling from local gardens was undertaken for a nutritional analysis between December and April. Cultivation of a selection of the vegetable species enabled assessment of their response to the fertility of soils, the fertilisers and pests, and then their yield potential. Trials were sown by hand in February to May 2017 at the Airport 2 and 4 sites and received daily attention. Plants sown included snake bean, yam bean, sweet potato, pumpkin (five varieties), peanut (three varieties), sweet corn, culinary lablab (10 lines selected from a related project on Cocos Island, and 2 new lines identified from work in Tanzania), chia, quinoa, and chickpea (desi and Kabuli types). As post-mining phosphate soils can contain higher levels of heavy metals, particularly cadmium, due to the inherent characteristics of the extant soil, which may be accumulated in plants, crop samples were analysed, both washed and unwashed, to determine heavy metal levels with and without dust contamination.

Experiments were also undertaken on the agronomy of Industrial Hemp, via the work of PhD candidate Luca de Prato (Figure 8). Data are available from the MINTOPE team upon request, however growing conditions affected the abundance and distribution of the 10 most common cannabinoids in Industrial Hemp.

**Figure 8.** PhD student Luca de Prato at the Industrial Hemp experimental site.

## 5) Phase 5. Demonstrate agronomic production of crops, harvest and quantify yields, grain management for storage and manufacturing processes.

### 5.1) Broad acre and rotational legume cropping

The growth of lablab, cowpea, millet, sorghum, and maize was exceptional (Figure 9). Above ground biomass eight weeks after sowing in mid-March 2015 was 16 t/ha (dry weight) for the sorghum and 5.2 t/ha for cowpea (Figure 10). These yields are comparable with the best production areas anywhere in the world. A further 5t/ha of sorghum regrowth was harvested on April 15 confirming the potential for multiple cuts of forage varieties. The differential suitability of soybean cv Stuart (4t/ha) relative to cv Leichardt (2.7t/ha), with mungbean cv Jade (1 t/ha) reflected their respective sensitivities to both insect predation and K deficiency. The dryland rice performed the weakest of the crops, likely as a result of N deficiency, but also because of the significant insect predation.

**Figure 9.** Millet cereal crop harvesting in 2016.

**Figure 10**. Bay 2 where after 8 weeks of growth the sorghum and cowpea achieved 16 and 5.2 t/ha (dry matter) in 2015, respectively.

## 5.2) High value crops (b)

In terms of vegetable yield, the experimental plot of peanut produced 3.2 tonnes/ha; pumpkin 8.6 tonnes/ha; and chickpea achieved an impressive yield of 1.6 t/ha in the most productive areas. Also assessed were chia and quinoa, which grew very well and suffered only very minimally from insect predation. In contrast, the sweet corn was very susceptible to insects, likely due to its sweetness relative to the forage maize. These analyses allowed MINTOPE to commence a guide for vegetable production on CI, including a risk assessment schedule for selected crops, fertiliser recommendations, insect sensitivity and control measures, photos for deficiency recognition, and the nutritional value of plant parts.

The CI community was invited to the MINTOPE sites during field days held in 2015, 2017 and 2019; and the yam bean, peanut, and sweet potato were consistently very popular (Figure 11). As part of the community engagement, the leaves of all 12 culinary lablab lines were evaluated by a sensory tasting panel, assessing “sweetness, hairiness and bitterness”. Pods of the best three lines were picked when green in June and preserved for analysis.

The vegetable crops grown were analysed for heavy metal concentrations. In general, levels of the heavy metals were below Australian health standards. However, some samples returned some high levels (above World Health Organization recommended levels). For example, lablab appeared to accumulate the cadmium that naturally occurs in the soil in its leaves and pods on several sampling occasions. Dust contamination was analysed to determine if washing the plant material had any effect on heavy metal analysis. The results showed it is unlikely that samples were contaminated with soil or dust prior to being prepared for analysis. Also examined was the effect of optimal nutrition of potassium on heavy metal accumulation. The initial results indicated that heavy metal concentrations for cadmium, chromium, lead, and nickel decreased with K fertiliser additions. As K functions as an osmoregulator in plant cells, it is likely that maintaining optimal K nutrition minimises uptake of heavy metals by roots. The research on heavy metal concentrations will continue to further expand on the early positive results associated with optimal K nutrition, and to further understand the natural levels of each contaminant in the soils to ensure safety is maintained.

**Figure 11.** Remarkable successes in the fields and with the local community: yam bean, coffee and peanuts.

**5.3) Fermentation Studies and 'Gin' Distillation**

Developing value added products from agricultural crops is a critical step in increasing food security and income for Christmas Islanders. The sub-tropical cereal grain sorghum, maize and Dwarf Setaria/Foxtail millet red panicum were successfully grown on CI during the MINTOPE program. These grains can be used to develop products such as gluten free flour for baking goods, domestic animal feed, and fermented products from the result of malting to make alcoholic beverages such as beer and spirits.

In 2018 the MINTOPE team successfully demonstrated that sorghum and Dwarf Setaria/Foxtail millet red panicum can be malted, brewed and distilled into 'gin' that, with various flavour infusions, performs very favourably against commercial gins (Figure 12).


**Figure 12.** *Left*: Air Still in operation producing 50-60% clear alcohol after double distilling. *Centre*: Flavour infusion achieved by soaking and then filtering locally sourced (CI) and imported ingredients into 50ml of 60% alcohol. *Right*: The finished product 1) no infusion; 2) Juniper berries, dragon fruit, dried lime peel, Kaffir lime leaves; 3) Juniper berries, soursop (custard apple), dried lime peel, dried orange peel; 4) Juniper berries, lemon grass, coriander seed, star anise, cinnamon; 5) Juniper berries, Japanese cherries.

### 5.4) Infrastructure

The MINTOPE processing facility was developed which has a purpose built, dehumidifying cool room to store harvested grain and processed feeds. Power generation for the seed storage room and mobile seed cleaning unit is carbon-free (Figure 13), as power requirements are largely met by solar panels, now combined with a 2.5 kw wind turbine to provide back-up during the periods of cloud coverage (Figure 14). The power operation is linked to the NBN and battery operation can be monitored from the mainland.

**Figure 13**. *Left*: Solar panels combined with wind-turbine provide power to the MINTOPE site. *Right*: mobile seed-cleaning unit.

**Figure 14.** Wind turbine installed on MINTOPE processing shed, February 2019.

## 6) Future Directions

The MINTOPE team has demonstrated that agronomic endeavours on Christmas Island's disused mining areas are highly achievable, as well as providing small family enterprises the opportunity to succeed with niche value-adding activities such as beer, gin or coffee making from locally grown crops. From the perspective of economic diversification, a clear consensus has also been reached suggesting that CI and Cocos (Keeling) Islands exemplify 'Living Laboratory' characteristics ideally located for higher education activities targeting our historic, economic and strategic partners in Singapore and the higher education market in Asia generally.

To this end a Memorandum of Understanding (MOU) between Murdoch University campuses in Perth and Singapore, the Harry Butler Institute in Perth and Singapore's Temasek Polytechnic has been signed. The parties to this MOU are also referred collectively as the Indian Ocean Learning Communities (IOLC). The IOLC want to collaborate, under the auspices of the 2015 Australia-Singapore Comprehensive Strategic Partnership (ASCSP), in establishing a higher learning research and innovation field Hub (the Hub) to enhance food security in Singapore and the Australian Indian Ocean Territories (IOT), namely CI and the Cocos (Keeling) Islands. The IOLC will prioritise learning, research and innovation disciplines such as, but not limited to, the following: bio-security, bio-prospecting, intensive agribusinesses, urban farming, brewing and distillation, land and marine aquaculture, ecological diversity monitoring and adaptation, micro-sustainable energy, mining land rehabilitation, sustainable mine transformation, productive forestry management, environmental land management, food business development and food for eco-tourism.

## 7) Further Information

Stakeholders are directed to the Centre for Rhizobium Studies website for access to PowerPoint and video presentations of material from the MINTOPE project.

www.crs.murdoch.edu.au

## MINTOPE Research Outputs

### 1) Publications in refereed journals

De Meyer S.E., Ruthrof K.X., Edwards T., Hopkins A.J.M., Hardy G., O'Hara G., Howieson J. (2018) *Diversity of endemic rhizobia on Christmas Island: Implications for agriculture following phosphate mining.* Systematic and Applied Microbiology 41: 641-649. DOI: doi.org/10.1016/j.syapm.2018.07.004

Howieson J., Calmy H., Ballard N., Skinner P., O'Hara G., Skinner L., Ruthrof K.X., Swift R., Ballard V., Hardy G., McHenry M.P. (2017) *Bread from stones: Post-mining land use change from phosphate mining to farmland.* The Extractive Industries and Society 4: 290-299. DOI: dx.doi.org/10.1016/j.exis.2016.11.001

Ruthrof K.X., Fontaine F.B., Hopkins A.J.M, McHenry M.P., O'Hara G., McComb J., Hardy G.E.St.J., Howieson J. (2017) *Potassium amendment increases biomass and reduces heavy metal concentrations in* Lablab purpureus *after phosphate mining.* Land Degradation and Development 29:3. DOI: doi.org/10.1002/ldr.2866

Ruthrof K.X., Steel E., Misra S., McComb J., O'Hara G., Hardy G., Howieson J. (2018) *Transitioning from phosphate mining to agriculture: Responses to urea and slow release fertilisers for* Sorghum bicolor. Science of the Total Environment 625:1-7. DOI: doi.org/10.1016/j.scitotenv.2017.12.104

### 2) Theses

Swift, R.G. (2016) *Plant growth-promoting bacteria from Western Australian soils.* PhD thesis, Murdoch University. Supervisors:

De Plato, L. (current) *Genotype x environmental interactions of* Cannabis sativa *L. in the tropics.* PhD candidate, Murdoch University. Supervisors:

**Acknowledgements:** This project was jointly funded by the Department of Infrastructure, Transport, Regional Development and Communications (previously Department of Infrastructure, Transport, Cities and Regional Development), Murdoch University and Christmas Island Phosphates (CIP); and supported by the Water Corporation, the Shire of Christmas Island, the Chinese Literary Association, the Christmas Island Islamic Council and the Indian Ocean Group Training Association. MINTOPE was also supported by ARC linkage grant LP140100690.