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Final report

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1 Acknowledgments

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Photo: *A mature taro crop grown by a local farmer, near the Espiritu Santo field trial site*.

2 Executive summary

The aim of this project has been to understand the impact of climate change on key Pacific production systems - specifically those based on the staple root crops, taro and cassava. To this end, the project has aimed to address four specific objectives:

- To understand the responses of cassava and taro crops to existing environmental drivers (climate, soil and nutrient interactions).
- To understand the responses of cassava and taro crops to elevated atmospheric carbon dioxide (CO_2) concentrations
- To develop the capacity to model crop and cropping system responses within the Agricultural Production Systems Simulator (APSIM) framework.
- To identify promising strategies for farming systems adaptation.

To address these objectives we established field trials at VARTC in Espiritu Santo (taro only), at the Fijian Ministry for Primary Industries Koronivia Research Station in Suva (cassava and taro) and at the Head Office of Nishi Trading in Tonga Nukualofa (taro only). To understand the responses of cassava and taro to enhanced CO_2 conditions we established controlled environment experiments in Perth at the University of Western Australia. These trials were established to produce key growth and development data in contrasting environments necessary for the development of new APSIM cassava and taro crop modules.

As part of the field trials, frequent sequential destructive harvests (monthly) were undertaken since December 2012 at each of the Fijian and Vanuatu sites, and from 2015 at the Tongan sites, for the derivation of biomass production and partitioning model parameters. Weekly non-destructive monitoring was also undertaken over the same periods to provide critical leaf growth (i.e. leaf appearance, senescence and leaf dimension) and crop phenology parameters.

Traditional methods were employed to plant both the cassava (Fiji only) and taro crops using cuttings and tuber headsets planted to a depth of approximately 30cm. Local varieties of taro were used at each of the three trial sites; Tausala for the Fijian trial, Tarapatan for the Vanuatu trial and Lauila for the Tongan trial. For the cassava trail in Fiji, two varieties were grown: a low (Merelesita) and high (Beqa) cyanide-producing crop.

Fertiliser management was designed to ensure that nutrients were non-limiting, with both basal and top-dress applications at strategic intervals throughout the life of the crops. Evaporation pans were installed to monitor crop water status and to trigger irrigation (either hand or reticulated watering) once a critical deficit was reached.

Soil samples were collected monthly (at the time of each sequential destructive harvest) for the monitoring of soil moisture and mineral N concentrations throughout the life of the crop.

Climate stations were set up at each site to provide daily radiation, rainfall and temperature data, with 12 months of daily data recorded in Tonga and Vanuatu and 36 months of daily data recorded at Koronivia. This data has been amalgamated with nearby weather station data to produce a daily time series covering the period 1980 to 2015.

As part of the field trials we have collected the equivalent of one hundred and eight (108) weeks of non-destructive taro phenology data from the three sites as well as 27 months of destructive harvest information from the three sites. For cassava we have a more modest set of non-destructive phenology data (i.e. 72 weeks) and destructive harvest (i.e. 18 months) from the Koronivia site only.

With this data we have developed both a parameterised Taro module and a Cassava module that resides in APSIM. These modules are capable of simulating above ground biomass accumulation, leaf emergence and total leaf area accumulation. Using the Taro module, we have explored the sensitivity of the production implications of climate change at each of the three cases study sites for scenarios that included 5 to 15% less annual rainfall and temperatures 1 to 3°C warmer than present. However we cannot look at each of these factors in isolation and so ran simulations where temperature, rainfall and CO_2 concentrations were changed simultaneously. Six combined climate futures were considered. These included:

- 1°C warmer, -5% decline in annual rainfall and CO_2 concentrations of 420ppm;
- 2°C warmer, -10% decline in annual rainfall and CO_2 concentrations of 420ppm;
- 3°C warmer, -15% decline in annual rainfall and CO_2 concentrations of 420ppm;
- 1°C warmer, -5% decline in annual rainfall and CO_2 concentrations of 500ppm;
- 2°C warmer, -10% decline in annual rainfall and CO_2 concentrations of 500ppm; and
- 3°C warmer, -15% decline in annual rainfall and CO_2 concentrations of 500ppm;

We explored the effectiveness of a range of adaptation options (i.e. changed planting date, changes in planting density, changes in nitrogen (N) fertiliser management and introduction of irrigation) against the worst-case climate change scenario that produced the largest negative impact on production (i.e. 3°C warmer, -15% decline in annual rainfall and CO_2 concentrations of 420ppm).

At the Tongan site we also examined the potential production value of using a seasonal climate forecast (SCF) to inform management decisions such as time of planting, N fertiliser and spacing decisions as well as irrigation. This was tested across the period 1980 to 2015 to examine the value of the SCF over this period.

All yields are presented as corm fresh weights consistent with weights that would be obtained in the field. The APSIM model produces a dry weight estimate for the corms which is converted to a fresh weight approximation by multiplying the dry weight values by four (4). This assumes that 75% of the corm mass is water and is an approximation borne out of the field trial data collected at Fiji, Vanuatu and Tonga. The results from these analyses are summarised below for the effect of future climates and adaptation practices upon taro, cassava, and for the value of SCF to contribute to taro yields.

The results for taro yields in response to future climates and adaptation practices are summarised below:

- Baseline yields in Tonga are typically lower and more variable than for the other two sites in response to lower rainfall and temperatures.
- The high levels of organic matter and associated mineralisation rates account for the highest baseline yields occurring in Vanuatu.
- The impact of future rainfall decline on yield is typically small across all sites and can be attributed to the current high rainfall totals and intensity of individual rainfall events.
- For Vanuatu and Fiji, yield is little affected by temperature increases up to 2°C but there is a noticeable decline of 10-12% at 3°C. In Tonga, average yield is lower than baseline for all temperature increase scenarios but lowest for the 3°C projection (Table 1).
- Future temperature increase will speed up crop maturity and shorten the corm filling period. Maturity will be advanced by about two weeks for every 1°C increase in temperature across all sites (Table 1).
- Across all sites, yield increased with increasing atmospheric CO_2 concentration. This reflects the typical 'CO_2 fertilisation' response of C3 crops such as taro.
- In the combined future climate scenarios, the lowest yield is associated with the largest shifts in rainfall and temperature (-15% and +3°C) coupled with the lowest CO_2 concentration of 420ppm. Conversely, the highest yield is associated with the highest CO_2 concentrations (500ppm) and small/modest declines in rainfall (5%) and increases in temperature (1°C) (Table 1).

- Taro crops in Vanuatu and Tonga are essentially unresponsive to the doubling of N fertiliser under both the current and future climates. In contrast, there is a modest increase in yield on the alluvial soil in Fiji which has much lower organic matter levels.
- The introduction of irrigation generates substantial yield gains across all sites. In the case of Fiji and Vanuatu, irrigated yields under the future climate are almost comparable to rainfed yields under the current climate. In Tonga, the irrigated future climate yields exceed current climate rainfed yields.
- Aside from a small increase with a shift to a September to November planting window in Fiji, all other alternate planting windows resulted in yield declines under the future climate
- The response to increasing plant density varies across the three sites according to the amount of available resources. In Vanuatu, the higher mineralisation rates coupled with high rainfall can support a higher plant population resulting in higher overall yields (Table 1).

Table 1: Summary of changes in average, 10th and 90th percentile taro corm yields from the baseline (for simulations with historical climates) and from the future baseline (for simulations with future climate scenarios). Values highlighted in green represent improved corm yields compared with either the historical or future baselines. Values in red represent reduced corm yields compared with either the historical or future baselines. All values are corm fresh weights measured in tonnes per hectare (t/ha)

	Suva			VARTC			Tonga		
Scenario	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**
Baseline	**16.4**	**13.6**	**18.4**	**18.4**	**15.5**	**20.3**	**10.5**	**1.7**	**14.6**
Baseline + IRRIGATION	1.8	2.6	1.8	1.2	1.2	0.5	5.1	10.5	2.2
Baseline + EXTRA N	1	1.1	1.2	0.1	0.1	0.1	0.4	-0.3	1.2
Baseline + IRRIGATION + N	3	4	1.8	1.3	1.2	0.6	7.6	11.1	4.3
Baseline + 1.7 Pts/m2	0	0.1	0	1	1.2	0.7	-4.2	-0.4	-4.8
Future baseline 420ppm/+3°C/-15%	**13.9**	**10.2**	**17.5**	**16.5**	**13.7**	**19.2**	**9.6**	**1.3**	**14.5**
	-2.5	-3.4	-0.9	-1.9	-1.8	-1.1	-0.9	-0.4	-0.1
420ppm/+3°C/-15% + IRRIGATION	2	3.8	0.6	1.1	1.8	0.4	5.4	10.5	2.2
420ppm/+3°C/-15% + EXTRA N	1.1	1.5	1.5	0	0	0	0.3	-0.3	1.5
420ppm/+3°C/-15% + IRRIGATION & N	3.2	4.8	1.8	1.2	1.8	0.4	7.8	11.7	5.6
420ppm/+3°C/-15% + SON_Window	0.8	2.3	-0.6	-1.8	-5.7	0.6	-4.8	-0.5	-4.1
420ppm/+3°C/-15% + DJF_Window	-0.5	1.3	-2.7	-3.8	-4.5	-2.2	-1.9	0.2	-1.8
420ppm/+3°C/-15% + MAM_Window	-1	-0.3	-2.1	-2.1	-1	-3	-2.2	0.2	-2.6
420ppm/+3°C/-15% + 1.7Pts/m^2	-0.1	-0.2	-0.4	1.1	1.3	0.8	-3.8	-0.2	-5.4

For cassava, the simulated response of tuber yield to the individual and combined effects of climate factors was very modest for the simulated locations of Suva and Nadi in Fiji. Yields at both locations were unchanged relative to the baseline in response to changes in CO_2 concentrations, and there was a small (~0.1 t/ha) decline in yield for crops grown in response to a 5% decline in rainfall simulated in isolation. For all other scenarios (i.e. those associated with an increase in temperature), average yield increased relative to the baseline value by up to 4 t/ha at Suva and by up to 2 t/ha at Nadi.

The Taro module in APSIM was used to establish a set of Tongan baseline production statistics for the period 1980 to 2015. A further set of simulations was established by modifying the management rules in response to the APCC operational SCF forecast for the period 1980 to 2015. The results for taro yields simulated in response to SCF are summarised below:

- The use of rainfall forecasts to make stand-alone management decisions relating to sowing time, plant density and N management did not result in yield gains relative to baseline management.
- There were clear and substantial yield benefits from using irrigation in the Tongan growing environment relative to rainfed production.
- For farmers already using irrigation, the employment of rainfall forecasts to select the irrigation rate did not substantially improve yield performance, although there are potential savings in water consumption in years when lower rates of irrigation are selected.
- The highest average yield of 20.76 tons per hectare was achieved using the APCC rainfall hindcast data to modify a combined management scenario for the March to May sowing window. In this scenario, the forecast yield exceeded the rainfed baseline yield in 28 of 30 years. This average yield was much higher than the equivalent forecast yields for each of the standalone management scenarios indicating synergistic benefits from combining the various management responses.
- In some instance the difference between average yield for forecast and baseline simulations was small, however when the full distribution of yields was examined, the forecast simulations, for the most part, have much higher 25th percentile simulated yield values. This would suggest that the forecast information, and the management responses to it, have served to reduce loss of production in drier years.

Plants are affected by CO_2 directly via its effect on photosynthesis and indirectly via the impact on climate. The major impact of rising atmospheric CO_2 concentrations in the future will be through changes in global warming, changes to rainfall patters and rising sea levels. The primary aim of this part of the project was to understand how the concentration of CO_2 in the atmosphere directly affects taro and cassava. Several other experiments that examine climate-related experiments were also included. The results build on the findings of earlier experiments on the effect of drought and temperature on cassava funded by an earlier AusAID *Toxic crops in a high CO_2 world: Mozambique a case study*, led by Cavagnaro, Gleadow and Cliff.

Four broad experiments were undertaken. These include:

(1) CO_2 trial using cassava and taro;

(2) N trial using taro;

(3) Cassava salinity trial using cassava;

(4) Taro salinity trial;

(5) Gene sequencing analysis of cassava from Oceania

All these experiments – seven (two additional sub-projects for the CO_2 research and two for the nitrogen trial) in all – were conducted by Honours students in the School of Biological Sciences at Monash University, supervised by Prof Ros Gleadow (Section 7.4). These fourth year undergraduate research projects run for approximately 8 months and the experiments provide valuable training in plant physiology while raising awareness of the climate-change related issues facing farmers in developing countries. The experiments described in this Final Report assessing the sensitivity of cassava and taro to salt, are the first work of its kind.

The project has resulted in a number of notable science and community impacts. Science outputs for the project include one PhD (nearing completion), one Masters (completed), seven honours projects, one book chapter, six peer-reviewed papers, 24 seminars, conferences and public lectures and two papers currently under preparation (See Appendix 1).

Members of the modelling team were also invited to join a global cassava model development initiative hosted by the International Center for Tropical Agriculture (CIAT) and Climate Change Agriculture and Food Security (CCAFS) initiative. This has led to sharing arrangements and attendance at two modelling workshops in Cali, Columbia in 2013 and 2014, and has facilitated improvements in crop parameterisation in both Decision Support System for Agrotechnology Transfer (DSSAT) and APSIM platforms.

In terms of community impact, this project has directly resulted in the enhanced capacity of the USP organic chemistry laboratory in Suva with the provision of equipment and training to allow rapid freeze drying of plant material. In addition, drying equipment and training were also provided to Nishi Trading in order to allow the drying of plant material. In both instances, this equipment facilitated the undertaking of further experimental work with other agencies.

Two formal APSIM training workshops were undertaken in 2016 in Tonga; one held from the 7th to the 10th of June 2016 and the other held on the 11th and 12th of October 2016. The first training workshop trained 22 participants, and comprised farmers, Government and private extension staff, and USP staff and students.

Photo: Participants in an APSIM training course undertaken in Tonga.

3 Background

The IPCC 5th assessment report identifies small island states as being the most vulnerable countries of the world to the adverse impacts of climate change (IPCC, 2014). In an earlier report produced by the World Bank it was identified that "*climate change holds the potential to radically alter agroecosystems of the Pacific in the coming decades and there is already evidence of devastating crop failures in some island countries. Over the long term, adapting and mitigating impacts from climate change will have to be a top priority for all countries in the region*" (World Bank, 2011).

Communities reliant on agriculture-based livelihood systems have been identified as particularly at risk from climate change, due to likely increases in crop failure, new patterns of pests and diseases, lack of appropriate seed and plant material, and loss of livestock (Taylor et al., 2016). In the Pacific region, recent shortfalls in agricultural production resulting from changing export markets, commodity prices, climatic variation, population growth and urbanisation, have meant a greater reliance on imported foods, thus contributing further to regional food insecurity concerns for the future (Taylor et al., 2016).

A number of activities are already underway in the Pacific region to identify ways to ameliorate existing climate risk and enhance current agricultural production. Whilst these activities are important to ensure long-term agricultural sustainability, there remains a significant degree of uncertainty as to how effective activities may be with an increasingly variable future climate.

Accordingly, the aim of this project is **to understand the impact of near-term climate change on key Pacific production systems** - specifically those based on the staple root crops, taro and cassava. To this end, the project has two broad objectives. These are:

- **To understand the responses of Pacific root crops to climate change** - involving the development of crop modules within an existing modelling framework (APSIM) to understand how specific taro and cassava varieties will respond to projected changes in climate in the Pacific; and
- **To identify strategies for farming systems adaptation** - which will involve using these crop modules to explore the effectiveness of a range of on-farm adaptation strategies to maintain and/or enhance farm production.

To achieve these objectives the project will undertake the following activities to underpin the priority goal for sustained yields and improved food security:

- Develop the capacity to model the physiological growth of specific taro and cassava varieties, and also their responses to changes in climate;
- Identify a number of taro and cassava varietal traits appropriate to farming systems and agro-ecological zones of Fiji and Vanuatu which are likely to remain viable under increasing climate variability and change;
- Select and evaluate a suite of effective management responses to offset likely negative impacts of climate change and confer this information to existing extension and research agencies.

CSIRO has led the project as part of the supported activities under the Climate Adaptation Flagship and more recently the Agriculture and Food Business Unit. In-country partnerships have been managed by our main collaborator, the SPC, and have involved partners at the Ministry for Primary Industries, Korinivia Research Station in Fiji, VARTC in Vanuatu and more recently, with Nishi Trading and MAFFF in Tonga.

Scientific impacts have included the better understanding of how Pacific staple root crops are likely to respond to climate change (either positively or negatively) while community-level impacts will arise in the longer term from insights into how cropping systems can be adapted for greater resilience or to maximise future climate conditions.

Producing enough food to meet the needs of an increasing global population is one of the greatest challenges facing the planet (FAO, 2011). In the context of looming fertiliser shortages (Cordell et al., 2009) and increasing global demand for food (Rosegrant and Cline, 2003), we need to understand how all facets of plant nutrient dynamics will respond to a changing climate. This is particularly true for developing nations, including the Pacific island countries, where over 75% of the poor live in rural areas and their livelihoods are directly or indirectly linked to agriculture and where staple crop production in these countries remains a critical method of ensuring food security.

At a global scale, cassava and taro represent staple crops of significance. In 2008, the FAO ranked cassava and taro as the third and fourteenth largest source of food carbohydrates in the tropics (FAO, 2011). In the Pacific, despite a growing reliance on imported flour and rice products, root crops such as taro, giant swamp taro, giant taro, tannia, cassava, sweet potato and yams remain critically important components of many Pacific Island diets. It is estimated that up to 68% of dietary energy and 42% of dietary protein in Pacific diets comes from the consumption of staple foods (FAO 2008).

In the Pacific the average total production of taro for the period 1991 to 2009 was estimated at just over 360,000 tonnes per year, with Papua New Guinea (PNG), Solomon Islands and Fiji the largest producers (FAO 2011). The production of cassava in the same period was estimated at 290,000 tonnes with PNG, Tonga and Fiji the largest producers (WRI 2008).

Pacific communities face an increasing number of challenges relating to sustainable agricultural production with total food production per capita declining by between 5 and 37% over the past twenty years across the Pacific (WRI, 2011). Much of this negative trend can be linked back to changing population growth and urbanisation as well as changing climatic risk factors, such as less reliable rainfall. For example, in recent years food shortages have occurred due to delays in summer rains and heavy rains during the harvest period. These shortages have contributed to price spikes for food and have even changed trade arrangements in some countries (i.e. export bans of some food stuffs; WRI, 2008).

Future climate change is likely to make the production of staple foods more challenging. Agriculture in Pacific island countries depends heavily on summer rains, but climate change projections suggest prolonged variations from normal rainfall (including water stress), as well as more pests and weeds, erosion and loss of soil fertility. Furthermore, increasing coastal inundation, salinisation as a consequence of sea-level rise and erosion may contaminate and reduce the size of productive agricultural lands.

A number of activities are already underway in the Pacific to identify ways to ameliorate climate risk and enhance current agricultural production. These strategies include examining options to increase crop diversity and selecting varietal traits that confer improved resilience to drought, pests, weeds and diseases. While these activities are crucial in ensuring long-term agricultural sustainability in the Pacific, there remains a significant degree of uncertainty as to how effective these management options will be under future climate change due to a limited understanding of how tropical staples will respond (either positively or negatively) to both changes in climate and increases in atmospheric CO_2.

Most of the work on understanding the responses of crops to climate change has been focused on temperate crops and regions. For instance, it is broadly understood that higher temperatures and elevated concentrations of atmospheric CO_2 (eCO_2) will increase crop productivity in temperate regions. It is less clear, however, what impacts climate change will have on tropical crops and regions with already-high temperatures. Moreover, crop quality (i.e. nutrient value) is as important as crop yield for future food security and production, and recent evidence suggests that increasing CO_2 concentrations for staples like cassava can decrease plant protein content and increase the concentration of plant toxins (Gleadow et al., 2009) although this work is far from definitive. It is clear that we need to develop a much better understanding of the complex interactions between crop yield and nutrition against a background of other influences, such as weed and pest invasion, temperature, rainfall and soil moisture.

The Pacific Food Summit (2010) stated that "*the evaluation of climate change impacts on agricultural production, food supply and agriculture-based livelihoods must take into account the characteristics of the agro-ecosystem where particular climate-induced changes in biochemical processes are occurring, in order to determine the extent to which such changes will be positive, negative or neutral in their effects*."

Accordingly, the aim of this project has been to understand the impact of near-term climate change on two major Pacific staple crops (taro and cassava) and explore the effectiveness of a number of farm management practices in sustaining and/or enhancing future farm production in the face of climate change.

The SPC with support from the Department of Climate Change and Energy Efficiency (DCCEE) have recently published a report “Food Security in the Pacific and East Timor and its vulnerability to climate change”. The report highlights the lack of knowledge and information to identify appropriate adaptive measures, in particular the resilience of existing crop production systems to specific changes in climatic variables. The SPC has a climate change engagement strategy to guide the organization in the implementation of several large projects which are focusing on climate change adaptation. Root crops, because of their importance to food security in the Pacific region, are a priority within the SPC Land Resources Division. This project has built on these existing activities and networks to extend the outcomes of this research.

Photo: *A mature cassava crop grown at Koronivia Research Station, Suva, Fiji*.

3.1 List of acronyms

Acronym	Definition
ACIAR	Australian Centre for International Agricultural Research
APCC	Asia Pacific Climate Centre
APSIM	Agricultural Production Systems Simulator
CCAFS	Climate Change Agriculture and Food Security
CIAT	International Center for Tropical Agriculture
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEE	Department of Climate Change and Energy Efficiency
DSSAT	Decision Support System for Agrotechnology Transfer
eCO_2	Elevated concentrations of Carbon dioxide
LAI	Leaf Area Index
MAFFF	Ministry of Agriculture and Food, Forests and Fisheries in Tonga
N	Nitrogen
RUE	Radiation Use Efficiency
SCF	Seasonal Climate Forecast
SPC	Secretariat of the Pacific Community
USP	University of the South Pacific
UWA	The University of Western Australia
VARTC	Vanuatu Agriculture Research and Technical Centre

4 Objectives

Within the broader development goal of sustaining and, where possible, improving the food security of Pacific islander smallholders and their communities in the face of climate change, the primary **aim** of this project is **to understand the impact of near-term climate change on key Pacific taro and cassava crop production systems and help islanders to learn how to mitigate likely negative production impacts in the face of this change**. This understanding and the tools developed to analyse these impacts will be available to a range of users including research and agricultural extension staff. To this end, the project has two broad objectives. These are:

Objective 1: To understand the responses of cassava and taro crops to existing environmental drivers (climate, soil and nutrient interactions)

1.1 Identify, scope and undertake field trials in Fiji and Vanuatu to understand the key physiological responses of taro to key climate and soil interactions

1.2 Conduct variable nutrient rate trials to be undertaken under controlled glasshouse conditions in Australia

Objective 2: To understand the responses of cassava and taro crops to enhanced CO_2 conditions

2.1 Quantify baseline key physiological responses of taro and cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia

Objective 3: To develop the capacity to model crop and cropping system responses (within the APSIM framework)

3.1 Translate the trial data and published literature into a module within the APSIM to simulate taro production

3.2 Finalise the integration of existing cassava trial information in Fiji and include enhanced understanding of crop response to climate and elevated carbon dioxide (eCO_2) into the APSIM Cassava and Taro modules

3.3 Benchmark and validate both the Cassava and Taro modules on yield data from trial sites in both Fiji and Vanuatu.

3.4 Provide formal APSIM training to in-country partners

3.5 Integrate the glasshouse nutrient trials into the APSIM framework in order to ensure nutrient partitioning is accurately represented in the Taro module.

3.6 Undertake a comparative analysis of the growth parameters generated by the Fijian, Vanuatu and Tongan trials to highlight major physiological differences

3.7 Integrate current operational seasonal forecast information into the APSIM Taro model for assessment of forecast utility.

Objective 4: To identify promising strategies for farming systems adaptation.

4.1 Examine how agricultural production may respond to future changes in climate and atmospheric CO_2 concentration for a medium and high emission scenario in 2030 for Fiji and Vanuatu trial sites.

4.2 Establish workshops in both Vanuatu and Fiji to identify adaptation options

4.3 Examine the effectiveness (i.e. impacts on yield) of a small sub-set of these nominated options using both the Cassava and Taro modules in APSIM.

4.4 Present results of the scenario modelling to stakeholders, including extension staff and farmers in both Fiji and Vanuatu and provide materials that highlight most effective farm management options.

4.5 Undertake formal APSIM training courses in Tonga in order to build local capacity to run the modules and test the effectiveness of additional adaptation options

4.6 Identify a set of agronomic decisions that producers would like to make in response to SCF information. We will also capture how producers would modify those decisions in response to a "normal", "wet" and "dry" forecast

4.7 Examine the yield implications of using the SCF (for the period 1980 to 2013) to change agronomic management decisions and express the results in terms of profitability and downside risk

Photo: *A mature cassava crop grown by at Koronivia Research Station*.

5 Methodology

An overview of the activities discussed in Section 4, their sequencing and relation to the four key objectives are provided below.

5.1 Objective 1: To understand the responses of Pacific root crops to climate change

Field trials were established at sites in Fiji, Vanuatu and Tonga to collect measurements regarding light interception and radiation use efficiency (RUE), biomass allocation priorities and canopy development, water use efficiency and soil nutrient constraints in taro (Figure 1). These data were used to develop key model parameters in the Taro module.

In Fiji, field trials were undertaken at the Korinivia research station under the supervision of the Fijian Ministry for Primary Industries (Figure 1A). This trial included the planting, observation and harvesting of a common taro variety, to develop a standard set of modelling parameters. In Vanuatu, field trials were undertaken at the VARTC research station on Santo (Figure 1B). The same protocol used in Fiji was established in Vanuatu in order to ensure comparability. A different variety of taro was selected in Vanuatu based on those commonly grown in the region. In Tonga, field trials were undertaken at the Head Office of Nishi Trading on Nuku'alofa. As with the other two sites a standard field trial protocol was applied (Figure 1C).

A)

B)

C)

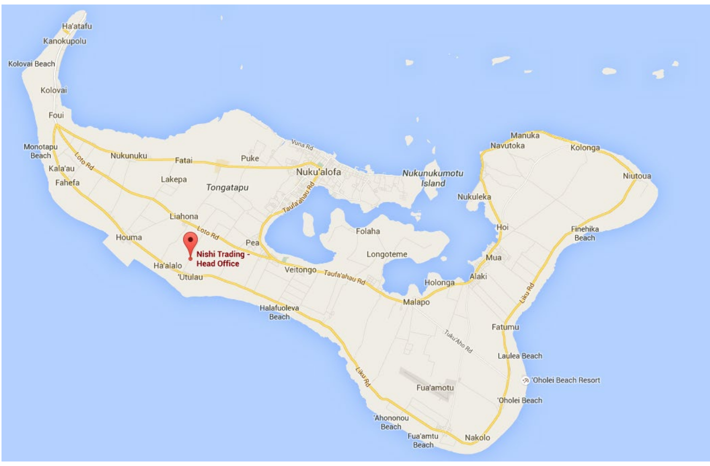


Figure 1. Maps of the location of the trial sites for A) Koronivia Research Station, Suva B) VARTC, Luganville, and C) Nishi trading offices, Nuku'alofa.

The field trials were managed under water and nutrient unlimited conditions with two sets of soil parameters measured (i.e. those which are unlikely to change over the timeframe and those which are more sensitive to management and climatic effects). The more stable soil parameters were measured once (e.g. bulk density, pH, EC, organic matter content, crop lower limit and drained upper limit), and the more variable soil parameters (e.g. soil water content, mineral N) were measured at intervals from sowing through to maturity, coinciding with destructive harvests.

In-trial management included ongoing irrigation (when required to prevent water stress) as well as pest and weed control. Fertiliser rates were based on the results of initial soil measurements in order to ensure nutrients were unlimited.

For each field trial the experiment consisted of 4 blocks each of 30 harvestable and 15 "spare" plants for each variety (total of 360 plants), in order to support monthly destructive harvests (20 plants) for the first four months and then every two months until full maturity at 8 months (total of 6 harvests) (Figure 2a). The trial used guard plants or buffer plants surrounding replicates to minimise edge effects relating to block edges and sequential harvesting. In Fiji and Vanuatu a second taro trial was undertaken with different planting densities (i.e. 0.5m, 0.7m and 1.0m) to determine the impact on corm size and suckering (Figure 2b)

A)

	B3D4		B3D2		B3D3		B3D6		B3D1		B3D5		B4D3		B4D6		B4D4		B4D1		B4D2		B4D5	
	B3D4		B3D2		B3D3		B3D6		B3D1		B3D5		B4D3		B4D6		B4D4		B4D1		B4D2		B4D5	
	B3D4		B3D2		B3D3		B3D6		B3D1		B3D5		B4D3		B4D6		B4D4		B4D1		B4D2		B4D5	
	B3D4		B3D2		B3D3		B3D6		B3D1		B3D5		B4D3		B4D6		B4D4		B4D1		B4D2		B4D5	
	B3D4		B3D2		B3D3		B3D6		B3D1		B3D5		B4D3		B4D6		B4D4		B4D1		B4D2		B4D5	
	B1D5		B1D6		B1D4		B1D1		B1D2		B1D3		B2D4		B2D2		B2D5		B2D6		B2D1		B2D3	
	B1D5		B1D6		B1D4		B1D1		B1D2		B1D3		B2D4		B2D2		B2D5		B2D6		B2D1		B2D3	
	B1D5		B1D6		B1D4		B1D1		B1D2		B1D3		B2D4		B2D2		B2D5		B2D6		B2D1		B2D3	
	B1D5		B1D6		B1D4		B1D1		B1D2		B1D3		B2D4		B2D2		B2D5		B2D6		B2D1		B2D3	
	B1D5		B1D6		B1D4		B1D1		B1D2		B1D3		B2D4		B2D2		B2D5		B2D6		B2D1		B2D3	

4 Blocks (B1 to B4)
5 replicate plants for each of the 6 destructive harvest events (D1 to D6)
3 replicate plants per block for non-destructive monitoring (cross hatched)
Buffer plants (yellow)
Total plant number for trial (325)

Total number of Harvest plants (120)

B)

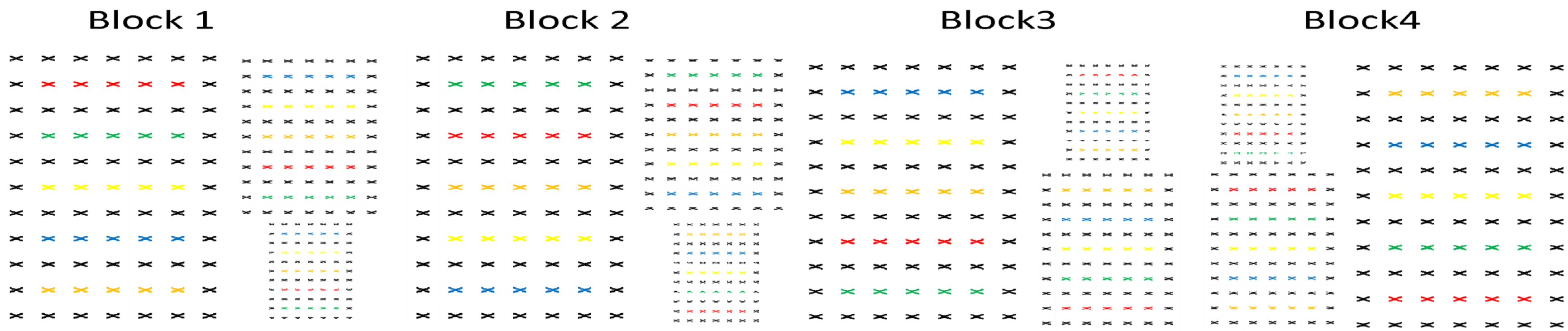


Figure 2. The generic layout of the crop experiments for a) cassava and taro, and b) taro density trial.

Each field trial was established and maintained under water and nutrient non-limiting conditions, in order to produce optimal growth parameters for the model. In order to achieve unlimited water and nutrient conditions, fertiliser was applied to each plant at time of sowing. For the cassava trial in Fiji this meant a basal application of fertiliser NPK (13:13:21) at the rate of 300 kg/ha, with a top-dress of 150 kg Urea (46%N) applied at 4 weeks, 8 weeks and 12 weeks after planting. For taro a basal application of fertiliser (NPK – 24-6-6) was applied at a rate of 20 g per plant at sowing with a follow-up application of the same amount of fertiliser at 2 months. The trial sites were watered following a period of 4 consecutive days without rainfall. Watering proved very labour intensive and so a basic irrigation systems were developed for each site. Dates of watering and estimates of total water use were logged and have been used to modify the existing climate files to represent rain events.

Weed control was undertaken by hand and was scheduled weekly, corresponding with the weekly phenology observations.

5.1.1 Data collection methodology

As part of each trial two types of observational data were collected. These include weekly phenological data and monthly or multi-month destructive harvest data.

Each week (although initially for the first four weeks, every second day), phenological measurements were taken in order to track crop development and to measure leaf dynamics (e.g. leaf expansion rates, senescence, canopy height etc.).

During each destructive harvest five plants were collected from each block and partitioned into major organs (e.g. petioles/stems, leaves and corms/tubers) to quantify standard growth parameters (e.g. partitioning coefficients, biomass accumulation, RUE and total leaf area index (LAI)).

Samples were weighed during harvests to provide a fresh weight estimate and then dried to provide a final dry weight. This provided estimates for model calibration. Tissue sub-samples were also collected for chemical analysis to determine nutrient partitioning between major organs (e.g. petiole/stem, leaf, corm/tuber and roots). These samples were dried and ground and returned to Australia for analysis with our partners at Monash University.

5.1.2 Destructive Harvest data

For each plant at each destructive harvest the following measurements were taken:

- Plant height – soil surface to the youngest fully opened leaf
- Leaf area
- Corm fresh weight
- Leaf fresh weight
- Petiole fresh weight
- Leaf number (expanded, expanding, senescent)
- Number of suckers and total fresh weight
- Photograph of leaves (Figure 3).

a) b)

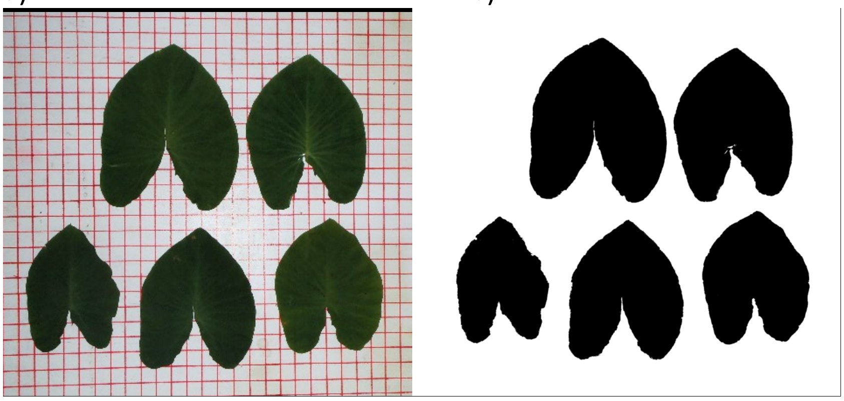


Figure 3. a) Taro leaf photographs taken at Tonga during destructive harvest 3, b) processed image used to calculate the total leaf via ImageJ software.

5.1.3 Post-harvest sample data

Samples were either freeze dried (Fiji) or oven dried at 40ºC. All samples were stored in air-tight Ziploc® bags, with desiccant to ensure the materials remained dry. All the oven dried samples were weighed to determine the dry weight and leaf areas were calculated from the photographs taken at each harvest (Figure 3a, b).

5.1.4 Soil sampling for nutrient and soil water content

Soil samples were collected at the time of planting and at each of the destructive harvests. Soil water content was determined for each of the sampling events, but full soil macro and micro nutrient analysis was limited to selected samplings: starting soil samples (covering at least mineral N, total N, P, K, organic matter and carbon), Harvest 2 and Harvest 6 (ammonium and nitrate N only).

Six replicate, 1.5 m long intact soil cores were collected using the steel tubes hammered into the soil (Figure 4a). Two diagonal transects were followed across opposite ends of the trial site. The soil was separated out into 6 separate buckets to represent different soil layers (Figure 4b). These layers were:

- 0-15 cm
- 15-30 cm
- 30-60 cm
- 60-90 cm
- 90-120 cm
- 120-150 cm

After all cores had been sampled, the soil layer in each bucket was mixed and sub-samples were taken for water content and nutrient analysis (Figure 4b). All samples were oven dried at 40°C. Samples to be tested for nutrients were either shipped to Fiji (USP laboratories) or in the cases of Tonga sent to the Hills Laboratories in New Zealand.

Figure 4. a) Removal of the soil from the soil cores, and b) buckets containing the aggregated soil cores for each of the 6 soil layers.

5.1.5 Crop lower limit

The water content in each layer of the soil profile at which a crop is no longer able to extract water through its root system is called the crop lower limit. This was determined using a rain-out shelter constructed over an area of the mature crop. The rainout shelter is placed over a series of mature plants and is then left in place so that the plants can draw down on the soil water content until the CLL is reached. Once the crop has died from water stress, three replicate sample cores (as per soil sampling described above) were collected to measure the soil water content down the profile.

The shelter design consisted of a single pitched wooden frame (~4m X 4m) over which is attached heavy, clear plastic film (Figure 5). The sides were left partially open to allow air flow and a trench was dug along each side of shelter to divert water.

Figure 5. Image of a rainout shelter constructed at the trial sites.

5.2 Objective 2: To understand the responses of cassava and taro crops to enhanced CO_2 conditions

Most experiments of crop yield in response to elevated CO_2 have been done on temperate grain crops. These plants generally have a limited sink size, and so increasing photosynthesis would not necessarily increase yields. Moreover, plants use the concentration of sugars in the leaves as a signal for regulating photosynthetic rate by down- or up-regulating production of the photosynthetic enzyme, Rubisco. If there is limited capacity to store starch, then sugars build up in the leaves. This then signals to the plant to turn down production and so the CO_2 fertilization effect is less than might be otherwise expected. For plants with greater storage capacity, such as those with large underground storage organs, the accumulation of sugars in the leaves is less likely.

In this project we grew cassava and taro at elevated CO_2. This is the first study of its kind with taro. Cassava has been grown experimentally at different levels of CO_2 before, but results have been equivocal with reports of an increase, decrease or no effect on tuber yield. We grew the plants at four different concentrations of CO_2: 400 (control, ambient), 500, 700 and 900 ppm. At the current rate of growth in atmospheric concentrations of CO_2, the CO_2 concentrations will reach 500 ppm within 50 years and 700 ppm in about 70 years. At 700 ppm the earth would be 3-4°C hotter, likely outweighing the impact of the direct responses of plants to CO_2. We also included a very high level of 900ppm; any predictions for the response of plants to this concentration are clearly interpolations. In terms of practical applications of the results, comparisons between 400 and 500 ppm are the more relevant. All measurements were made using a similar protocol to the field trial to ensure the results are suitable for incorporation into the models of plants growth. In addition to measuring plant growth, we also assessed the nutritional value of the leaves and storage organs.

5.2.1 Plant material and growing conditions

Taro (*Colocasia esculenta* (L.) Schott) and cassava (*Manihot esculenta* Crantz) were initially grown at the Monash University School of Biological Sciences greenhouse complex under ambient CO_2 conditions with controlled temperature (20°C/28°C night/day) and a natural photoperiod (December- March) before being shipped to Western Australia for the experiment. Clones of the cassava variety MAus7 were established from stem segments (~3cm long of established plants (24/12/12) following Vandegeer et al. (2013). These plants remained small until transferred to potting mix. Taro suckers (variety Bun Long) were purchased from Tropical Exotics (Brisbane) and shipped from Queensland. MAus7 is a moderately sweet Australian cassava variety which was confirmed by gene sequencing to be identical to TMS 50395 (Merelesita variety) (Bredeson et al. 2016).

After one week of acclimation in a standard glasshouse at the University of Western Australia Plant Growth Facility under ambient conditions (natural photoperiod), 60 healthy plants of each species (taro and cassava) were randomly assigned to one of four CO_2 chambers (15 taro and 15 cassava per chamber), from a total pool of 82 taro plants and 79 cassava plants. Prior to the experiment a set of plants was harvested (N=7) to establish a base line from which relative growth rate could be determined (Figure 6). Harvest protocols are described below.

Figure 6. Growth room at the University of Western Australia with cassava (MAus7) (left) and taro (Bun long) (right) shortly after repotting into the large 45 L bags in May 2013.

After an interim destructive harvest (N = 8 per chamber at c. 3 months), the number of plants in each chamber was reduced to seven plants of each species. These plants were re-potted (Day 96-97) into 45L woven plant bags (380mm X 400mm, Garden City Plastics) to ensure there was space for normal root development (Figure 6).

Each growth chamber was identical in size and climatic conditions. Abiotic conditions in each room, including temperature (20°C/28°C night/day), humidity (72/90% day/night), light intensity (1100 µmole maximum) and CO_2 concentration, were controlled by sensors and used to provide an environment similar to a typical day in the Pacific (based on the 30 year average of Port Vila, Vanuatu, J. Hargreaves and S. Crimp, unpublished data). To avoid effects due to chamber and position within the cabinet, plants were rotated within rooms and pots rotated by 90 degrees every two weeks and interchanged between rooms monthly.

Nutrients and water were both applied to the plants so as to be non-limiting, as follows. Taro and cassava plants received fertiliser (1 g of Scotts fertiliser diluted into 200ml of H_2O) 13 days into the experiment. A complete fertiliser was added to each plant fortnightly (1g Peter's Professional fertiliser diluted into 200ml of H_2O, 20:20:20 N:P:K, with N supplied as Nitrate, Ammonia and Urea, 2:1:3) (ICL, Richgrow, Perth WA). The fertiliser application was doubled (4g in 200ml per week) after 85 days to ensure that the taro and cassava were not nutrient limited with increasing plant size. Since cassava is known to be rich in mycorrhizal associations in the field (Burns et al., 2012), a mixture of mycorrhizae (purchased commercially) was applied to the soil.

5.2.2 Phenology sampling

To track growth over time 6 cassava and 6 taro plants from each treatment were measured weekly during the 137 day experiment, starting at day 12, and with added details from day 41. Measurements included plant height, leaf number and the size of the first six fully unfurled leaves and general comments on plant health.

5.2.3 Destructive harvest and gas exchange measurements

At day 72 from commencement of the experiment, gas exchange was measured on expanded leaves of cassava and taro using a LI-COR 6400-40 Leaf Chamber Fluorometer (Li-Cor, Lincoln, Nebraska, USA). The algorithms generated from the LI-COR were used to determine the photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), stomatal conductance (mol H_2O m^{-2} s^{-1}), internal CO_2 (c_i, μmol CO_2 mol air^{-1}) and transpiration rate (mmoles m^{-2} s^{-1}) prior to the harvest. For each gas exchange time point there was a minimum of three replicate readings.

At day 76-84 from commencement of the experiment, 5 cassava and 5 taro plants from each CO_2 concentration treatment (total 20 plants per species) were harvested, The height of plants was measured first before all nodes were numbered (with and without leaves).

Plant material was partitioned into stem (young, mid and old), roots (fine and thick), corms/tubers (peel and inner flesh) and leaves (tips, expanding, fully expanded, senescent and dead) (Figure 7). Fresh mass of each tissue type was determined. Leaf area was determined by photographing the leaves in each category and measuring the area using image J, as described in the field experiment (Figure 7).

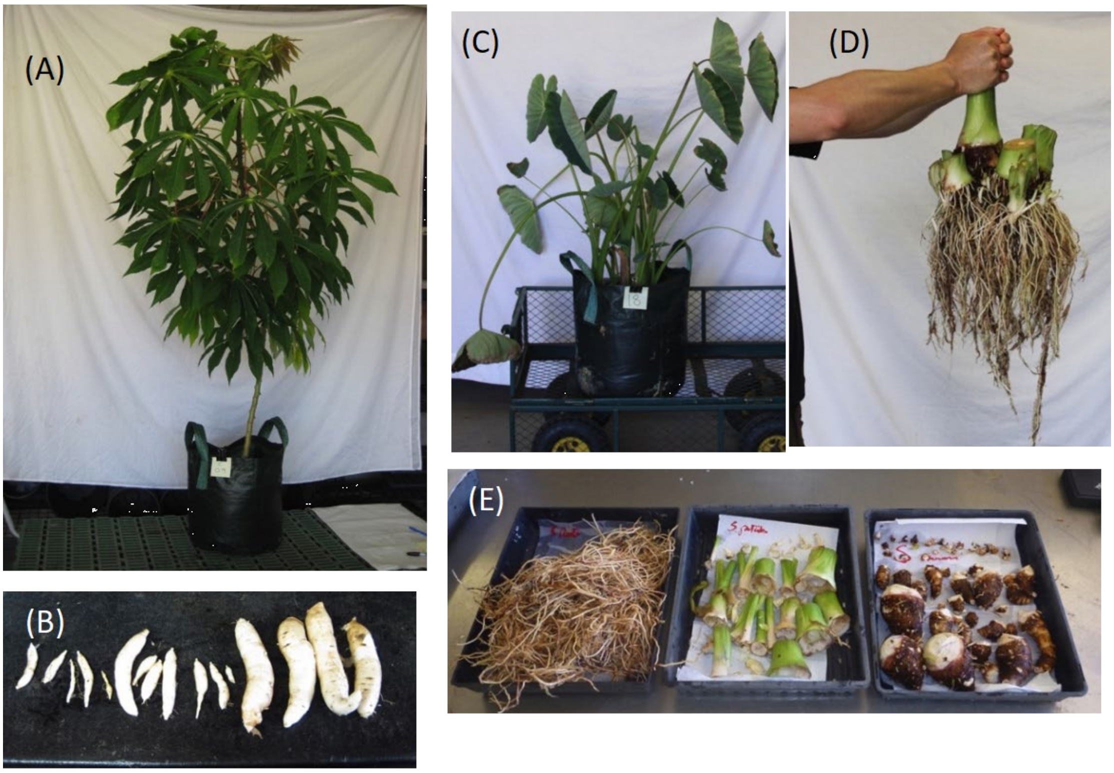


Figure 7. Examples of the cassava (A, B) and taro (C, D, E) plants from the 700 ppm CO2 treatment. Note the large numbers of tubers and corms.

5.2.4 Plant chemical analysis

Cyanogenic glucosides, oxalic acid and micronutrients

Total N (% dry mass) was used as a proxy for protein. In cassava, the concentration of cyanogenic glucosides was determined. For taro, we measured the concentration of oxalate as a proxy for total calcium oxalate. We also measured the concentration of macro- and micronutrients, as there have been reports of a decrease in these important elements in plants grown experimentally at elevated CO_2 (Cavagnaro et al., 2011). Cyanogenic glucosides were measured from cyanide evolved from ground tissue of cassava.

5.2.5 Taro Nutrient experimental results

This work was done by Laura Steel for her honours project in 2015. It is being prepared for publication in the highly regarded CSIRO journal *Functional Plant Biology*. Taro is sometimes called a 'neglected crop' in terms of plant science research. Even some of the most basic knowledge of effects of nitrogenous fertilisers on growth and photosynthesis are not well understood. In order to develop better predictive growth models it is important to understand how plants use and manage N.

As part of this project we conducted the first ever N trial with taro. The aim of the taro N trial was to determine the optimum rate of N fertiliser, and to determine maximum growth rates. A literature review on taro and aroid lilies was conducted by this honours student, which brings together a lot of useful information on taro growth and likely impacts of climate change (see Appendix 2).

5.2.6 Plant material and growth

In October 2014, taro (N=110) (*Colocasia esculenta* L. var Samoan Pink) were established from suckers (supplied by El Arish Tropical Exotics Qld) in glasshouses at Monash University (24ºC min /30°C max, 75% humidity) grown under both natural light with tropical photo-period. Plants were transplanted into Debco® potting mix in 5 L pots in October 2014 and supplied with a complete nutrient solution two times per week (Thrive®). After one month (1 Nov 2014), 12 plants were harvested to provide baseline data for the experiment. Remaining plants were allocated to one of four nutrient treatments and watered using modified Hoagland's solution containing 2.5 mM, 5 mM, 10mM and 15 mM nitrogen. Plants were rotated around the glasshouse every two weeks to minimise position effects. After 3 months (30 Jan 2015) six plants of each treatment were destructively harvested as before above, then were dried and analysed for biomass determination. The remaining plants were potted up into 20L pots in order to allow the older plants to continue to grow (Figure 6). The final harvest was completed in early June 2015.

Time line for the taro N trial

Oct	Nov	Jan	April/May	May	June
Suckers planted 5 L pots	Baseline harvest; treatments begin	3 month harvest; 20L pots	6 month harvest	Gas exchange measurements	8 month harvest; Final harvest

Plants were watered at 2pm twice each week with 300mL of modified Hoagland's solution containing 2.5, 5.0, 10.0, and 15.0 mM N, supplied as ammonia and nitrate (1:6). As the plants matured, the rate at which nutrients were provided increased to 1000 mL twice a week from 20 Jan 2015 and then three times per week from 20 April 2015. To ensure that plants were not watered-stressed, plants were watered each morning at 10 am using an automated dripper system for 1 minute for the 5L pots (to Feb 2015) and 2 minutes for the larger 20L pots. This was sufficient to increase soil water levels without flushing the pots. To control aphids, plants were sprayed with white oil followed by Confidor® on 10 December 2014, 10 February and 20 April 2015.

5.2.7 Phenology

Plant development and architecture was monitored by measuring height, leaf number, leaf size (length by width as the widest point) and the number of senescent leaves weekly of a selected number of plants each week for the first 3 months and then fortnightly until the final harvest (Figure 8) . The procedure was similar to that used in the field taro trials.

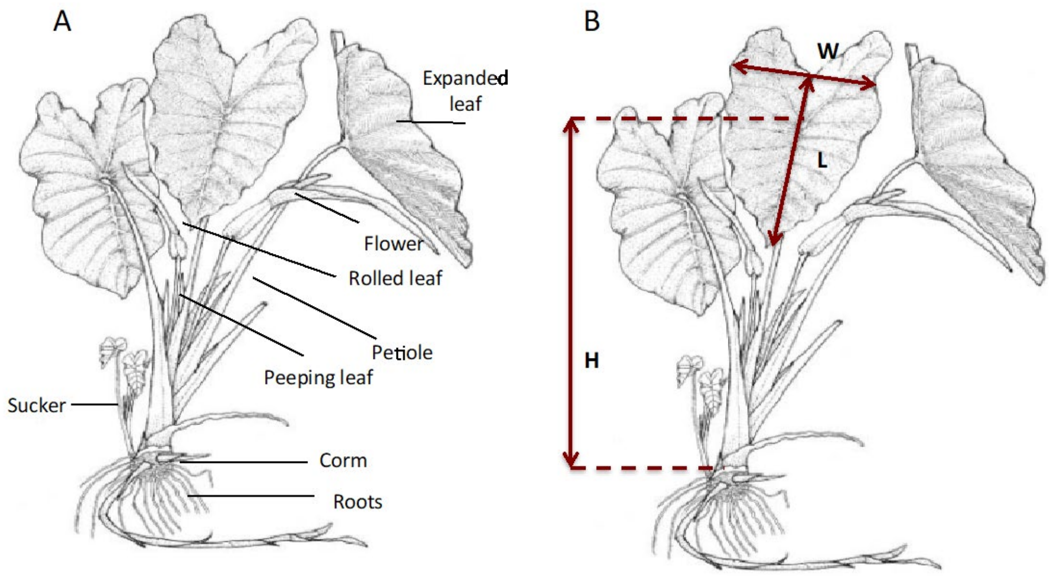


Figure 8. Diagram by Lebot (2009) annotated to show (A) how the various parts of the taro plants were named for phenological study showing and (B) how height and leaf size were determined. A similar process was used for cassava.

5.2.8 Harvesting and calculation of growth indices

The harvesting protocol for the taro nutrient experiments was the same as for the elevated CO_2 experiment, except that total leaf area (expanded and expanding) was measured with a Li-Cor Leaf area meter. Before harvesting, photosynthetic rates were measured on the first fully expanded leaf using a Li-Cor 6400 at 400 ppm CO_2, 25°C and PPFD of 500µmol quanta m^{-2} s^{-1}.

Growth indices at each harvest were calculated as follows:

Relative Growth Rate (RGR) = ln (final mass) – ln (initial mass) / time in days

Leaf Area Ratio (LAR) = Total leaf area / total biomass

Leaf Mass Area (LMA) = Leaf area / leaf mass [i.e. the inverse of the specific leaf area, SLA]

Root/Shoot ratio: total below ground biomass / total shoot biomass

5.2.9 Chemical analysis

Samples were taken of leaves and corms at the last harvest (June 2015), snap frozen in liquid nitrogen and freeze dried. These were analysed to determine the levels of nutritional and anti-nutritional compounds: protein, oxalic acid, total elemental carbon and N and micro- and macronutrients as described for the CO_2 experiment. Samples were tested for cyanogenic glucosides using a range of strategies but none were detected.

5.3 Objective 3: To develop the capacity to model crop and cropping system responses within the APSIM framework

The Potato2 module (using the Plant2 framework) of APSIM v7.6 was used as the basis for beginning the Taro module development. This followed on from existing activities to develop a Cassava module in APSIM (also based on the Potato2 module) as consistency between the Cassava and Taro modules was very important when using the modules to compare growth responses at the same case study site.

Parameterisation of key drivers of growth, such as leaf area, shoot and corm/tuber biomass, were undertaken using the observational data generated from the field trials. Weekly phenological observations and daily temperature data were used to derive node and leaf development rates and thermal times were used to identify key phenological stages. Leaf areas were derived from length and width measurements using calibrated data from actual leaf area measurements. Dry weights of the plant organs obtained from destructive harvests were used to derive specific leaf areas, RUE and to partition assimilate fractions to the organs. In-crop soil monitoring along with nitrogen concentration of the organs were used to derive stress functions. Testing and partial validation of the model occurred on portions of the trial data (see results section).

The development of a Cassava module in APSIM was finalised using field trial data from the Korinivia Research Station. Data from the final harvests was incorporated into a working prototype version of the Cassava module to validate results.

5.4 Objective 4: To identify promising strategies for farming systems adaptation.

A daily climate file was used in APSIM that contained information on maximum and minimum temperature, rainfall, evaporation, solar radiation and vapour pressure. Scaling of the existing daily historical climate information was undertaken in order to consider a number of possible future temperature and rainfall scenarios.

The APSIM Taro and Cassava modules were run for a twenty year 'benchmark' period from 1990 to 2010. The climate change projections were applied to the historical climate information and corm/tuber weights were compared across both the historical and the projected future climate periods to provide estimates of likely changes in both taro and cassava production. The relative growth response of each of the three taro varieties (one for each country) and one cassava variety were documented and compared.

The effectiveness of a number of management options were examined for both the taro and cassava production for both baseline (1990 to 2010) and a worst case scenario future (2030) climate.

The effectiveness of each management option was assessed in terms of corm/tuber yields.

An SCF was also incorporated into the modelling for Tongan taro production in order to examine the yield and economic consequences of using the forecast to modify farm management.

6 Achievements against activities and outputs/milestones

6.1 Objective 1: To understand the responses of cassava and taro crops to existing environmental drivers (climate, soil and nutrient interactions)

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
1.1	Identify, scope and undertake field trials in Fiji and Vanuatu to understand the key physiological responses of taro to key climate and soil interactions	Site preparation undertaken and completed at each trial site.	July 2012	Sites were identified at Koronivia (Fiji) in August 2012 and at Espiritu Santo (Vanuatu) in September 2012. Standard site preparation guidelines were established in order to ensure that both trials were undertaken under non-limiting nutrient and soil water conditions. Row spacing and block design were finalised at the September 2012 Inception meeting.	NA
		Standard field trial protocol established and signed off by in-country partners. Finalised trial plan sent to ACIAR.	July 2012	An inception meeting was held in Suva between 04 and 06 September 2012. Project members from Fiji, Australia and Vanuatu attended the meeting. A standard field protocol was established and signed off by all participants. The protocols were sent to ACIAR as an attachment to the September 2012 ACIAR trip report.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
1.1	Identify, scope and undertake field trials in Fiji and Vanuatu to understand the key physiological responses of taro to key climate and soil interactions	Planting material sourced and initial planting completed.	August 2012	Planting material was sourced from commercial growers for both trial sites with instructions around corm size and petiole thickness provided to ensure homogenous plantings. In the case of Koronivia the Tausala variety was selected and at Espiritu Santo the Tarapatan variety was selected. Planting commenced in Espiritu Santo in late November 2012 and at Koronivia in October 2012. Replanting of both sites was undertaken in December (Koronivia) and February 2013 (Espiritu Santo) respectively. The replanting in December was as a result of herbicide over-spray. The protocol at all sites was modified to identify mechanical weed control as the preferred management response to weeds. The replanting in February 2013 was as a result of poor field maintenance during the Christmas break. Staff were retrained and these problems did not arise again.	NA
		3, and 6 month destructive harvest (Year 1) observations collated.	June 2013	By the end of June 2013 three destructive harvests were completed in Fiji and two completed at Espritu Santo. Data from these harvests was collated in Excel spreadsheets and quality controlled to see if any measurement or observational discrepancies could be identified. Any discrepancies were discussed with each case study group and resolved.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
1.1	Identify, scope and undertake field trials in Fiji and Vanuatu to understand the key physiological responses of taro to key climate and soil interactions	Remaining year one as well as 3, 6 and 9 month destructive harvest (Year 2) observations collated and reported to ACIAR.	June 2014	All destructive harvest material has was collected from Fiji and Vanuatu by June 2014. The data was processed, error checked and analyses were performed. Similarly the weekly phenology observations from both sites have been collated, error checked and analysed. Parameter estimates for the APSIM model have been produced from these data sets and are presented in the 2013, and 2014 reports.	NA
		Case study trials are completed and all measurements and observations provided to the modelling team.	January 2015	All destructive harvest material was collected from Fiji and Vanuatu by January 2015. Data quality control was finalised and final parametrisation results presented in the 2014 Report.	NA
		Chemical analysis of plant material completed and documented.	April 2015	A comprehensive set of chemical analyses was undertaken as part of the experimental nutrient trial undertaken at Monash University. The results of these analyses are documented in the 2014 report. In addition a limited set of analyses was undertaken on plants grown under elevated CO_2 conditions. Results from these analyses are contained in the 2014 report.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
1.1	Identify, scope and undertake field trials in Fiji and Vanuatu to understand the key physiological responses of taro to key climate and soil interactions	Site preparation undertaken and completed for Tongan trial site.	July 2015	On 28 July 2015 CSIRO and Nishi Trading reached an agreement to undertake the Taro trial near the main office facilities due to access to water for irrigation (see 2015 Report). Staffing arrangement were also discussed and finalised with Ms Ella Gabriel and Ms Monica Hamilton assigned to undertake the weekly phenology observations and ensure scheduled weeding, irrigation and destructive harvests.	NA
		Planting material sourced and initial planting completed.	July 2015	The local Taro variety "Lauila" was sourced from Eua and planted in September 2015. In total 340 headsets were shipped across from Eua to the trial site. Planting material was not available from Tongatapu due extensive drought conditions since 2014.	NA
		3, 6 and 9 month destructive harvest (Year 1) observations collated and a report compiled for ACIAR.	July 2016	Both weekly phenology and destructive harvest data for 3, 6 and 9 growth stages were collated over the 9 months to June 2016 have been collated and analysed. The results are contained in the 2016 report. The parameter estimates were compared with against earlier sample data from Fiji and Vanuatu.	NA
1.2	Variable nutrient rate trials to be undertaken under controlled glasshouse conditions in Australia	Glasshouse facilities confirmed	May 2014	Nutrient experiments were undertaken at the Clayton Campus of Monash University by a Masters Student supervised by members of the Plant Ecophysiology Group in 2014 and 2015. Results are contained in the 2014 and 2015 reports. A summary is contained in this Final Report.	NA
		Standard trial protocol established	June 2014	A standardised experimental design was established in June 2014. The design was discussed in the 2014 report.	NA
		Planting material sourced and experiment underway.	July 2014	Planting material used in the CO_2 experiments was propagated from materials at Monash University and shipped to UWA in July 2014 for the purposes of this experiment.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
1.2	Variable nutrient rate trials to be undertaken under controlled glasshouse conditions in Australia	2,4 and 6 month destructive harvest observations collated and a report compiled for ACIAR	June 2015	Variable nutrient experiments were undertaken at the Clayton Campus of Monash University by a Masters Student supervised by members of the Plant Ecophysiology Group. The results are contained in the 2015 and 2016 reports. A summary is contained in this Final Report.	NA

Photo: Of the destructive harvest of cassava at Korinivia Research Station.

6.2 Objective 2: To understand the responses of cassava and taro crops to enhanced CO_2 conditions

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
2.1	Quantify baseline key physiological responses of taro and cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia.	Student commences review of available literature on existing taro experiments under variable CO_2 conditions.	Feb 2013	A review of key literature was undertaken by the Monash research team. Key findings from the review of experimental data was: • Nothing is known about how taro responds to higher CO_2 or climate change. • Under field conditions, cassava has the potential to have large increase in tuber yield in response to higher concentrations of elevated CO_2. This is largely due to increased accumulation of carbohydrates. • Protein concentrations are lower, and cyanogens are approximately the same in response to higher Co2 concentrations. • Cassava is highly dependent on forming associations with arbuscular mycorrhizae in the soil to enable nutrient uptake, but is otherwise reasonably tolerant of poor soils. • Cassava is able to withstand drought and high temperatures, but adversely affected by water logging. • Tuber cyanogens rise to high levels when soil moisture is low, but higher growing temperatures appear to have little effect. • Little is known about the effect of increases in rainfall on cyanogen levels.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
2.1	Quantify baseline key physiological responses of taro and cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia.	Student begins eCO_2 growth chamber experiments on cassava and taro. Report developed on initial setup and final design for milestone report.	July 2013	Controlled environment experiments were established at the UWA glasshouse complex in Perth. Sixty taro and sixty cassava cuttings were planted from April 9 through to April 23 2013. Four controlled environment chambers were established with CO_2 concentrations set at 400ppm (baseline), 500ppm, 700ppm and 900ppm. All other growth conditions were identical between chambers in order to understand the varying CO_2 effects. Sampling protocols were developed in line with the field trials i.e. both weekly phenology and destructive harvests, so as to ensure the data collected is directly applicable to the development of the model. The design was included in the 2013 report.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
2.1	Quantify baseline key physiological responses of taro and cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia.	Nutritional analyses on growth chamber trials commences	June 2014	• Nutrient analysis were undertaken on both cassava and taro crops over the course of the project. • The results of the experiments are summarised and contained in this Final Report.	NA
2.1	Quantify baseline key physiological responses of taro and cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia.	Key cassava and taro growth responses documented and parameterised.	June 2014	As above.	NA
		Key cassava and taro nutrient responses documented and parameterised.	Dec 2014	The results of the CO_2 chamber experiments are documented the 2015 report. In summary, the results from this experiment shows: Cassava shows distinct positive tuber growth response at 700 and 800ppm respectively. Under elevated CO_2 conditions cassava protein concentrations are lower, and cyanogens are approximately the same. Taro does not show the same growth response as cassava, with above ground biomass production enhanced more extensively than corm development.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
2.1	Quantify baseline key physiological responses cassava to enhanced CO_2 conditions through controlled environment experiments conducted in Australia.	Paper outlining similarities and differences between taro and cassava CO_2 responses developed and submitted.	June 2015	In relation to this component of work a paper was developed that has examined the effects of CO_2 on Cassava. A conference abstract was also presented on the response of taro and cassava to elevated CO_2. See Appendix 1	NA

Photo: Of the destructive harvest of cassava at Korinivia Research Station.

6.3 Objective 3: To develop the capacity to model crop and cropping system responses (within the APSIM framework)

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
3.1	Translate the trial data and published literature into a module within the APSIM to simulate taro production	Taro crop observations parameterised from year 1 trials	June 2014	Data from the taro trial has served to enhance the simulation response for rate of leaf emergence, rate of total leaf area accumulation and rate of petiole growth. This was an on-going process culminating in the sensitivity simulations produced for Tonga in the 2016 report and the broader set of simulations for all three sites that is contained in this Final Report.	NA
		Potato 2 module converted to Taro module through inclusion of taro crop parameters.	June 2014	Prior to undertaking the trials the modelling team had decided that the new Taro module would be based on the APSIM-Potato module. This was largely because of the existing tuber parameterisation. After the analysis of the trial data the team decided to use the APSIM-Banana module. The rationale is that the Banana module has the same structure and growth habit as Taro but the model ignores the underground corm and suckering. Potato has a very different structure and growth habit but has underground tubers. The Banana module has closest structural similarity to Taro and so was the basis for the taro development.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
3.1	Translate the trial data and published literature into a module within the APSIM framework to simulate taro production	All available parameterisation contained in peer reviewed literature relating to water use efficiency (WUE) and transpiration efficiency (TE) responses of taro is extracted, evaluated and incorporated in to Taro module.	Sept 2013	All available parameterisation contained in peer reviewed literature was used to establish the WUE and TE functions. Discussion were held with CIAT and CCAFS colleagues at two face-to-face meetings to discuss these and other parameterisation. The resultant functions are closely aligned with the revised DSSAT Taro model released in 2016.	NA
		WUE and TE parameters tested against baseline data.	June 2014	This testing was done using the results from the 6 month harvest to predict the yields in the 12 month harvest. Whilst not a truly independent data set, the testing allowed a baseline response for both parameters to be established.	NA
3.2	Finalise the integration of existing cassava trial information in Fiji and include enhanced understanding of crop response to climate and eCO_2 into the APSIM Cassava and Taro modules	Results from controlled eCO_2 experiments on nutrient responses in taro corms and leaves parameterised and incorporated in the module	June 2015	The results from the controlled chamber showed clear positive changes in in transpiration efficiency, RUE and biomass accumulation for mid-range CO_2 elevations. Nutrient partitioning at very high levels results in smaller plants and corms/tubers as well as fewer suckers. These responses have been incorporated in the model via modified transpiration and radiation use relationships. Sensitivity analyses are documented in the 2016 report.	At this stage the CO_2 responses in the Cassava and Taro modules represents a variation on the existing APSIM response function. Further analysis of the CO_2 chamber work is required until a more extensive response function can be included.

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
3.2	Finalise the integration of existing cassava trial information in Fiji and include enhanced understanding of crop response to climate and eCO_2 into the APSIM Cassava and Taro modules	Nutrient response parameters tested against baseline data.	Aug 2014	The results from the model simulations for 2030 include both a with and without CO_2 effect, in order to highlight the moderating influence of elevated CO_2 The results suggest a buffering of between 2 and 7% on biomass accumulation under modest changes in temperature and declines in rainfall.	NA
		Independent benchmarking undertaken against eCO_2 data.	Aug 2014		Further interactions were undertaken with the international cassava modelling team at CIAT and CCAFS to share CO_2 chamber trial data. Trial data exchange agreements were established for trial data from South American. Unfortunately the data quality was not sufficient to allow independent baseline or comparison studies.
3.3	Benchmark and validate both the Cassava and Taro modules on yield data from trial sites in both Fiji and Vanuatu.	For Cassava module independent benchmarking undertaken against the 18 month trial observations.	June 2013	Cassava model development continued via the use of data collected as part of the 2010 to 2012 AusAID/SPC supported cassava trials at Koronivia. At June 2013 two beta version Cassava models were operational in APSIM, one for a non-branching variety of cassava, namely Merelesita and one for a branching variety, namely Beqa. Since the development of the APSIM PLANT 2 platform all modules are required to be transferred in order to ensure they will be accessible to future users.	Unfortunately once the branching module (Bega) was transferred to APSIM PLANT 2 the simulation results were no longer representative. This is as a result of the branching function and PLANT 2 incompatibility. To resolve this problem both PLANT 2 developers and the project team would need to work together. For this reason only a non-branching variety is currently represented in APSIM.

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
3.3	Benchmark and validate both the Cassava and Taro modules on yield data from trial sites in both Fiji and Vanuatu.	For Taro module independent benchmarking undertaken against year 2 trial data.	Dec 2014	Independent benchmarking was undertaken for the Vanuatu site only. This was because the year 2 trial at Koronivia was compromised by poor irrigation management. Strong block effects resulted in the trial data and so the data was not used as a benchmarking data set but used to refine some parameters.	NA
3.4	Provide formal APSIM training to in-country partners.	Workshop process undertaken and completed in Fiji. Workshop process undertaken and completed in Vanuatu.	Sept 2015	As an alternative activity APSIM training was undertaken with Poasa Nauluvula (a USP PhD student supported by this project) as well as a USP Masters student Mr. Pakoa Leo (also supported by this project). In the case of Mr Leo, the model is being used to complete a Masters degree at USP on the effects of variable nutrient application rates on taro corm production in Vanuatu. Mr Leo is due to complete his studies in December 2015. In the case of Mr Poasa Nauluvula the model is being used to complete a chapter for his PhD.	APSIM training courses were not undertaken with MPI or VARTC staff due to limited capacity as well as a significant changes in extension activities in Fiji.
3.5	Integrate the glasshouse nutrient trials into the APSIM framework in order to ensure nutrient partitioning is accurately represented in the Taro module.	Results from the experiments on nutrient responses in taro corms and leaves parameterised and incorporated in the module.	June 2015	Data from the nutrient analysis undertaken at Monash University has been successfully used to validate existing above and below-ground biomass relationships in the APSIM Taro module. A working bee was held at Monash University in March 2016 to extract the relevant data for use in APSIM. Nutrient sensitivity analyses were presented in the 2016 report, but are also contained in this Final report.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
3.6	Undertake a comparative analysis of the taro growth parameters generated by the Fijian, Vanuatu and Tongan trials to highlight major physiological differences	*Key parameters will be tabulated and compared between the three sites. Commonalities and significant differences between the three varieties will be reported.*	July 2016	Phenology and destructive harvest information have been collated and analysed. Where feasible, comparisons have been made across the three taro varieties in terms of rate of leaf appearance, biomass accumulation, corm weight, canopy height etc. Results have been tabulated and appear in the 2016 Annual Report (Table 2).	NA
3.7	Integrate current operational seasonal forecast information into the APSIM Taro model for assessment of forecast utility.	Historical rainfall time series information from the APCC and current Tongan operational will be extracted and incorporated into the release version of the APSIM Taro model.	July 2016	Daily climate information for the period 1980 to 2016 was compiled for the Tongan trial site location from a climate data logger situated at the site, nearby climate information from the International airport and climate re-analysis data. In addition the research team have collated data from the operational APCC seasonal forecast for the period 1980 to 2015. This data takes the form of tercile probabilities for each month for the period 1980 to 2015. This data is included in the APSIM Tongan toolbox and forms part of the experimental release model.	NA

Photo: Of the destructive harvest of taro at Korinivia Research Station.

6.4 Objective 4: To identify promising strategies for farming systems adaptation.

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
4.1	Examine how agricultural production may respond to future changes in climate and atmospheric CO_2 concentration for a medium and high emission scenario in 2030 for Fiji and Vanuatu trial sites.	Baseline daily climate files modified to reflect climate conditions likely by 2030 (based on outputs from 2 global climate models and two emission scenarios.	June 2014	A scoping meeting was held in September 2012 with all the project partners in Suva. Local MPI extension staff, interested NGO's and MPI selected farmer groups attended and information regarding local crop rotations, current management practices and possible future practices to build resilience to climate change we identified. A series of simulations have been developed for all three sites that identify the possible impacts of temperature, rainfall and associated CO_2 changes. In addition a series of adaptation options have also been examined to determine promising management strategies for the future. The results from this set of simulations are contained in this Final report.	NA
		The APSIM Taro and Cassava modules run for the baseline period 1990 to 2010.	Jan 2015	Validation and calibration results are presented in this Final report. Simulations have also been undertaken for the period 1990 to 2010. The model captures seasonal variations well and is able to highlight periods of water stress associated with ENSO conditions.	NA
		Above and below ground growth statistics generated for the baseline period.	Jan 2015	See above	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
4.1	Examine how agricultural production may respond to future changes in climate and atmospheric CO_2 concentration for a medium and high emission scenario in 2030 for Fiji and Vanuatu trial sites.	The APSIM Taro and Cassava modules run with baseline daily data modified to reflect predicted 2030 climate conditions.	Jan 2015	Sensitivity analyses have been undertaken and are presented in the 2016 report. Simulations of taro production for both Koronivia and VARTC are presented for a number of plausible 2030 climate scenarios. At higher CO_2 concentrations (i.e. 700ppm and above) the effects of drier and warmer conditions are enhanced due to the responses observed in the chamber experiments and translated into the model.	NA
		Above and below ground growth statistics generated for this period and compared against baseline simulation statistics	Jan 2015	See above	NA
4.2	Establish workshops in both Vanuatu and Fiji to identify adaptation options	Undertake workshop in Fiji to present information regarding projected climate change for each island and undertake a facilitated process of eliciting information from attendees (farmers and local extension staff) about on-farm adaptation strategies that could be used to maintain and/or enhance farm production.	July 2012	A scoping meeting was held in September 2012 with all the project partners in Suva. At this meeting the team finalised all aspects of the trial and controlled environment experiments and took the opportunity to present the project to local MPI extension staff, interested NGOs and MPI selected farmer groups. At this meeting the team gained an understanding of adaptation options of interest. Results from simulation activities were presented to these farming communities on 13 June 2017. The results from this work is contained in the Final Report.	NA
		As above but for Vanuatu.	Sept 2012		Unfortunately the level of community engagement was very limited. For this reason the results of the modelling activities have not be presented to local farmers.

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
4.3	Examine the effectiveness (i.e. impacts on yield) of a small sub-set of these nominated options using both the Cassava and Taro modules in APSIM.	APSIM manager logic modified to incorporate sub-set of farmer nominated adaptation option.	July 2015	A range of farmer adaptation options have been identified and reported in May 2014. These responses have been examined and tested as a range of simulations. These results have been completed and are contained in the Final report	NA
		Taro and Cassava modules run for both baseline (1990 to 2010) and future (2030) climate conditions.	July 2015	As above	NA
		The effectiveness of each management option assessed via analysis of the below ground biomass response.	July 2015	As above	NA
4.4	Present results of the scenario modelling to stakeholders, including extension staff and farmers in both Fiji and Vanuatu and provide materials that highlight most effective farm management options.	Annual science updates conducted to inform researchers and extension organisations of research progress.	Sept 2015	A series of presentations, conference abstracts and papers have been completed as part of this project. Staff have contributed to a series of meetings with stakeholders from SPC, USP, MPI and VARTC. The meetings with VARTC and MPI were largely informal but involved between 3 and 12 farmers from the local regions.	NA
		Communication of research outcomes undertaken at the regional policy level to inform on the potential for the technologies to impact on food security and the livelihoods of individual farmers.	Sept 2015		Communication and extension activities have been limited in Fiji and Vanuatu due to declining extension capacity in both locations. Whilst a range of farmer adaptation options have been identified, extension in Vanuatu has not occurred. The results of the simulation studies have been compiled and are contained in the Final report. A workshop was undertaken with local Suvan farmers on 13 June 2017.

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
4.4	Present results of the scenario modelling to stakeholders, including extension staff and farmers in both Fiji and Vanuatu and provide materials that highlight most effective farm management options.	3-4 scientific papers written for inclusion in journals and conference proceedings	Sept 2015	Science outputs for the project include one PhD (nearing completion), one Masters (completed), seven honours projects, one book chapter, six peer-reviewed papers, 24 seminars, conferences and public lectures and two papers currently under preparation (see Appendix 1).	NA
4.5	Undertake formal APSIM training courses in Tonga in order to build local capacity to run the modules and test the effectiveness of additional adaptation options	The model will be used at a training workshop with local MAFF extension staff and Technical staff from Nishi Trading company. Workshop participants will be taken through a formal 2 day training course to on how to use the APSIM model and will be taught how to run simulation studies using local examples	March 2017	An APSIM training course was undertaken in Tonga over the period 8 to 10 June 2016. The course had 21 participants from government agencies, extensions organisations, commercial farms and universities. Participants learnt how to run the APSIM software and to construct a number of simulations. These included: • determining water and nutrient flows in the soil; • Long-term crop rotations; • Irrigation impacts of plant production; • Constructing yield probabilities form simulation data; and • Climate change sensitivity and adaptation simulations. The participants have formed three working groups and prepared further simulations in preparation for a second workshop held in October 2016. This meeting had fewer participants but each of the participants was able to use the model and run a series of simulations independently.	NA

No.	Activity	Outputs/ milestones	Completion date	What has been achieved?	What has not been achieved?
4.6	A set of agronomic decisions will be identified that producers would like to make in response to SCF information. We will also capture how producers would modify those decisions in response to a "normal", "wet" and "dry" forecast	Workshop participants will be asked to identify a set of agronomic management decisions that they would potentially modify in response to a SCF. The workshop participants will also be asked to determine how they would modify the nominated agronomic management decisions in response to a "wet", "normal" and "dry" rainfall season.	March 2017	During the course of the 3 day training course, the participants were asked to identify a series of agronomic management decisions they would like to examine. A list of these agronomic decisions is contained in this Final report. In addition the participants were asked to identify a number of decisions that they would modify in response to a SCF system and how they would make changes based on a tercile probability SCF. These ideas are also be presented in the Final report and have formed the basis for an evaluation of the skill of SCF information for taro production.	NA
4.7	Examine the yield implications of using the SCF (for the period 1980 to 2013) to change agronomic management decisions and express the results in terms of profitability and downside risk	The management responses to SCF information will be parameterised into APSIM, along with a baseline management strategy	July 2017	An evaluation of the SCF was undertaken using a number of nominated management responses. The results are contained in the Final report.	NA
		Simulations of APSIM will be undertaken for the period 1980 to 2013 and annual yield values will be produced. Yield variation will assessed across the different management strategies and converted to an economic variable, namely Gross Margin (GM).	July 2017	Gross Margin information was obtained from commercial farmers (i.e. Nishi Trading and Tinopia Farms) and aggregated to represent the costs and prices for the simulation activity. The results were combined with the APSIM taro simulation to provide indicative Gross Margin information.	Farm scale gross margin information was not available to the project team and so the evaluation of the SCF has been undertaken by looking at resultant yield responses only.
		The GM outcomes will be compared across the different management strategies to determine the value of the SCF	July 2017	As above	NA

7 Key results and discussion

In the sections that follow we present a summary of the field trial activities and development of the APSIM Taro and Cassava modules; we provide an overview of the possible impacts of climate change on both taro and cassava, as well as the effectiveness of adaptation options to mitigate climate change impacts. In addition we also present an assessment of the value of using an operational SCF in Tonga to moderate farm management decisions for taro production and present a synthesis of the experimental work on crop sensitivities to changes in CO_2 concentration, nutrients and salinity.

7.1 Field trials

7.1.1 New growth parameters developed for APSIM

Weekly Phenology has been collected at all three sites. An example of the results is contained in Figure 9. The data allows the calculation of leaf emergence, leaf senescence, height and total leaf area.

Add Row! -> D B P S L New Week

Date	Time	Density	Block	Plant	Sucker*	Leaf	Leaf state	Length	Breadth	Plant Height
08/10/15	09:20	NA	1	1	0	1	> 50% yellow	22	17.5	78
08/10/15	09:21	NA	1	1	0	2	< 50% yellow	25	17.4	
08/10/15	09:21	NA	1	1	0	3	< 50% yellow	30	21.5	
08/10/15	09:21	NA	1	1	0	4	Unrolled	39	28.1	
08/10/15	09:21	NA	1	1	0	5	Unrolled	38	26.5	
08/10/15	09:21	NA	1	1	0	6	Unrolled	38	25.3	
08/10/15	09:21	NA	1	1	0	7	Unrolled	47.5	33	
08/10/15	09:21	NA	1	1	0	8	Unrolled	52	35	
08/10/15	09:24	NA	1	1	0	9	Tip visible / not emerged			
08/10/15	09:24	NA	1	1	1	1	Unrolled			7
08/10/15	09:25	NA	1	1	1	2	Tip visible / not emergec	4	3.6	
08/10/15	09:29	NA	1	2	0	1	Detached			70
08/10/15	09:29	NA	1	2	0	2	< 50% yellow	18.5	13	
08/10/15	09:29	NA	1	2	0	3	Unrolled	23	17	
08/10/15	09:29	NA	1	2	0	4	Unrolled	30.5	22.5	
08/10/15	09:29	NA	1	2	0	5	Unrolled	32	22.6	
08/10/15	09:29	NA	1	2	0	6	Unrolled	36.1	23	
08/10/15	09:29	NA	1	2	0	7	Unrolled	48	30.7	
08/10/15	09:29	NA	1	2	0	8	Unrolled	46.6	32	
08/10/15	09:30	NA	1	2	0	9	Tip visible / not emerged			

Figure 9. An excerpt from the weekly phenology observations spreadsheet for 08/10/2015.

Figure 10 shows the empirical relationship established from the weekly phenology observations taken for taro at the Tongan case study field trial, for leaf area and thermal time for the whole trial. The Leaf Area Index (LAI) is a dimensionless quantity that characterises plant canopies. It is defined as the one-sided green **leaf area** per **unit** ground surface **area** (LAI = **leaf area** / ground **area**, m^2 / m^2) in broadleaf canopies.

This relationship is important to characterise as it determines the rate of leaf emergence and how quickly the plant can reach maximum photosynthetic potential. In Figure 10 there is some decline in LAI in response to some unplanned water stress during January.

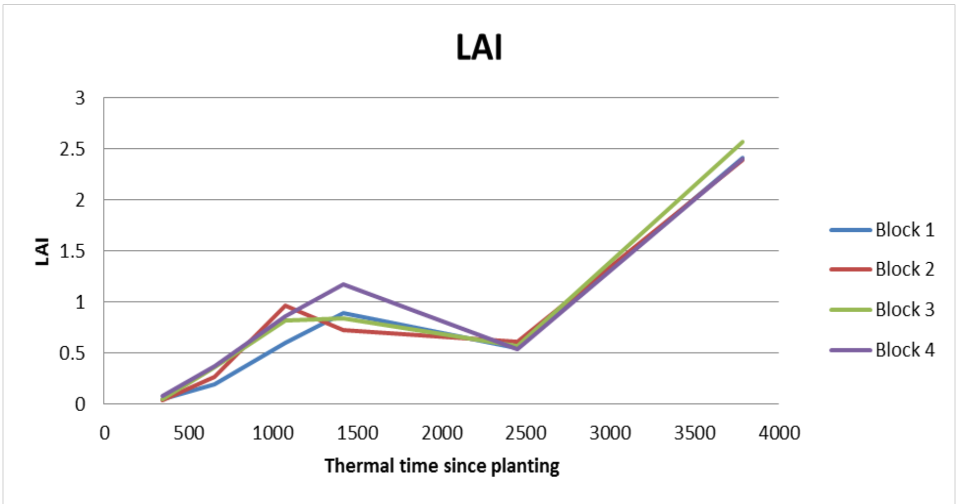


Figure 10. The relationship between LAI and thermal time since planting for the entire trial period, for taro grown at the Tongan field site.

Table 2 quantifies the thermal time durations for key leaf growth stages for the taro crop. Data for peeping to full leaf expansion was based on the first months monitoring which occurred every second day.

Table 2. Table of thermal time and leaf emergence stages.

Start	End	Average	Median	Notes
Peeping	Full expanded leaf	78.63	69.00	Estimates limited
Full expanded leaf	<50% senescence	337.57	345.00	Pre-January only to avoid water stress
Full expanded leaf	>50% senescence	431.44	445.00	Pre-January only to avoid water stress
>50% senescence	Detachment	119.71	99.00	Pre-January only to avoid water stress

Figure 11 shows the whole plant (sucker plus mother) partitioned biomass for the full suite of harvests undertaken at Koronivia and VARTC. The data shown is an average across all plants and blocks.

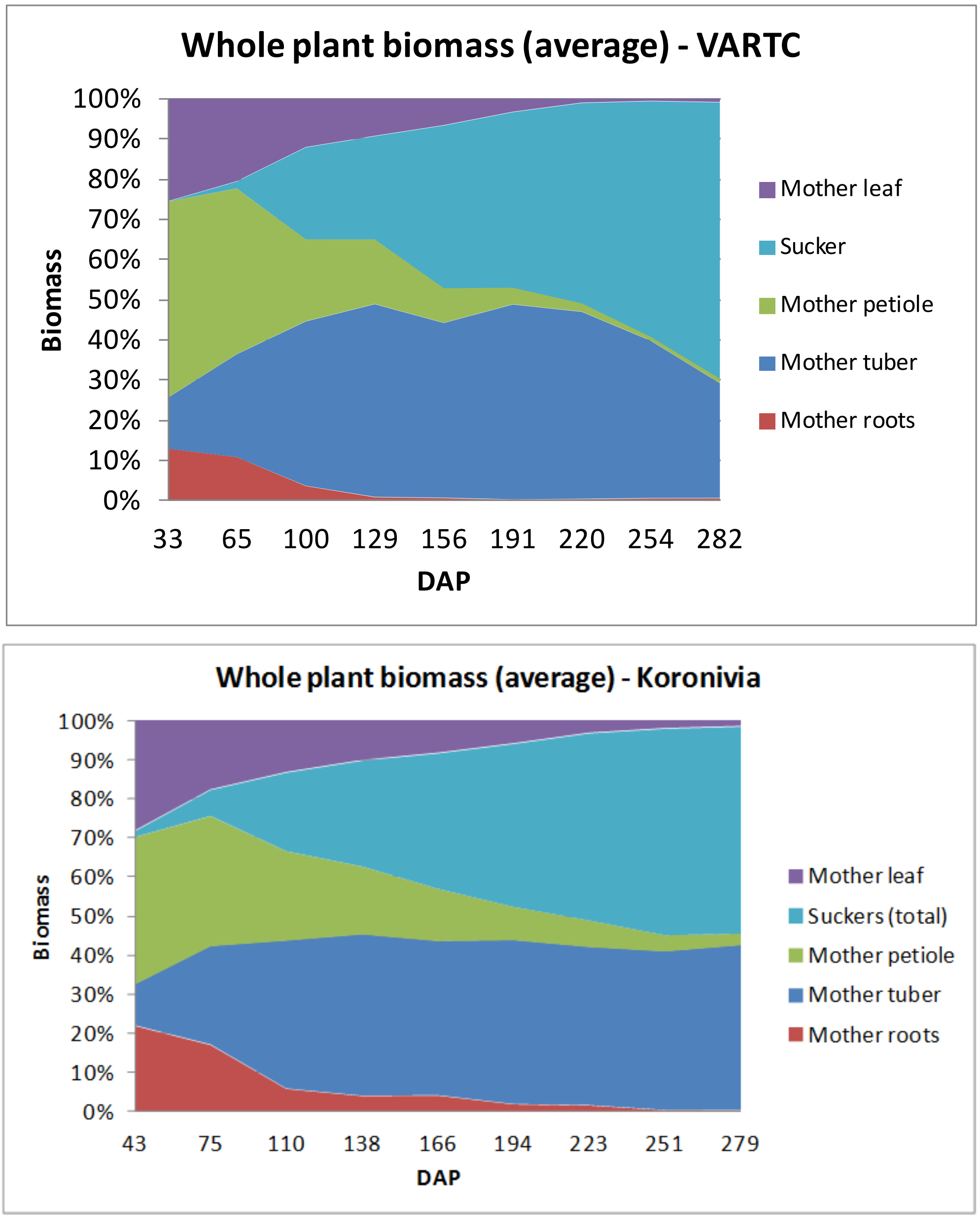


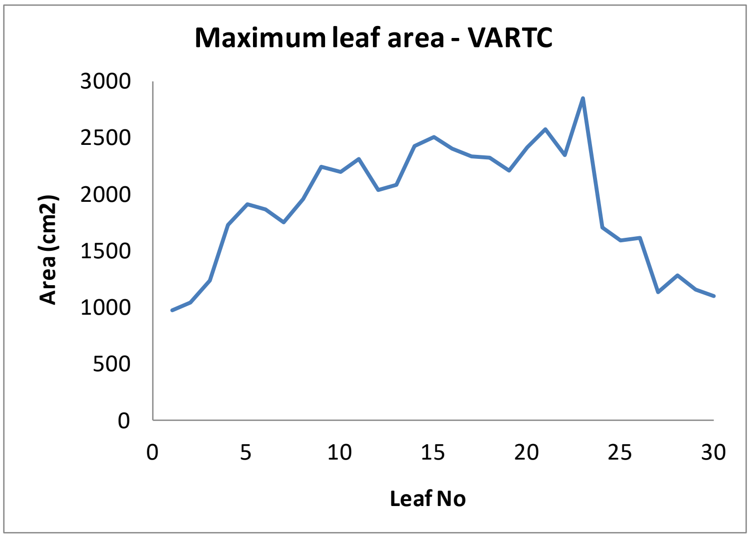
Figure 11. Biomass partitioning of the mother plant derived from trial data from Vanuatu – VARTC Research Station and Fiji – Koronivia Research Station.

Table 3 represents a synthesis of important parameters in the Taro module derived from data from each of the three field trials (i.e. all six destructive harvests and weekly phenology observations from each site). The trials conducted in Fiji and Vanuatu were undertaken across multiple years and so in the case of Fiji we have one calibration and two validation datasets; and for Vanuatu we have one calibration and one validation data set. In Tonga, funding and time allowed only a single, simple trial to be established, over a single season and for a single planting density. This information was used to modify the Taro model developed as part of the work in Fiji and Vanuatu.

Table 3. A table containing the model parameters for the 3 trials. Note. Strong block effects in Fiji mean that this data has not been included in the APSIM module.

	Tonga	**Vanuatu**	**Fiji**
Variety used	Lauila	Tarapatan	Tusala
Base Temperature (°C)	10	10	10
Opt Temperature (°C)	33	33	33
Max Temperature (°C)	42	42	42
LAR (dd/leaf)	1mX1m = 105	1mX1m = 128 0.7mX0.7m = 140 0.3mX0.3m = 179	1mX1m = 135
Lag to commencement of suckering and sucker leaf growth (dd)	1178	1mX1m =1251 0.7mX0.7m = 1467 0.3mX0.3m = 1977	1mX1m =1269 0.7mX0.7m = 1498 0.3mX0.3m = 1992
Sucker number per plant (Tarapatan modelled using a linear relationship with thermal time from planting).	2.4-3.3	1mX1m No. 0 16 TT 1251 4412 0.7mX0.7m No. 0 8 TT 1467 4412 0.3mX0.3m No. 0 4 TT 1977 4412	1mX1m No. 0 16 TT 1269 4412 0.7mX0.7m No. 0 8 TT 1498 4412 0.3mX0.3m No. 0 4 TT 1992 4412
Time to full expansion from peeping (dd)	79	67	35
Fully expanded leaf to start senescence (dd)	338	572	498
Start senescence to 50% senescence (dd)	97	150	115
Time from 50% senescence to detachment (dd)	120	45	77
Specific leaf area	~24000mm2/g	~24000mm2/g	~24000mm2/g
Leaf area profile – piecewise linear (LA, leaf no.)	500,1 1800,8 2000,17 2500,21 (estimate only)	1000, 1 1850, 5 2600,23 1000, 30	500,1 2000,5 3400,22 2000,28
Maximum green leaf number		~30	
Extinction coefficient	0.68	0.68	0.68

The maximum leaf area estimates for the Tongan Variety are based on estimates only as the plants were not grown beyond their maximum maturity. In the two other trials we have grown the plants beyond their maximum maturity and so were able to accurately ascertain this value (Figure 12). As the Tongan trial was time constrained we were not able to determine this value as the observations had not begun to plateau. The estimate is therefore based on the values from the Vanuatu site.



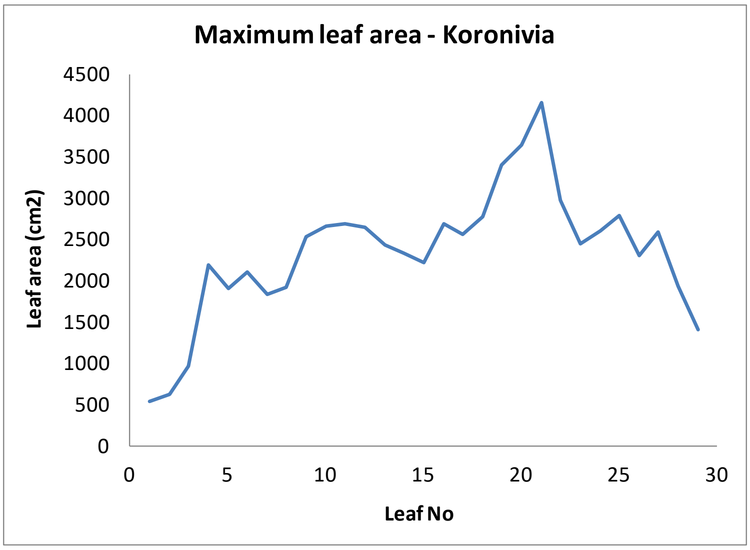


Figure 12. Leaf area profile for mother plant derived from trial data from VARTC Research Station, Vanuatu, and Koronivia Research Station, Fiji.

7.1.2 APSIM Model development

Figures 13 to 17 provide an insight in to the calibration and validation undertaken for each of the Taro and Cassava modules. Figure 13 highlights the observed versus predicted dry weight for the Merelesita cassava crop. The dots represent the aggregation of observed data from each of the four block/replicates as well as the five plants measured in each block. The continuous lines represent the biomass accumulation for each component of the plant, namely tuber (yellow), stem (blue), leaves (red) and roots (green). In Figure 13 the observations were made from an independent set of data for cassava grown in a second trial. The model results show a very close fit with the observational mean data.

In Figure 14 the mean biomass estimates from the Tongan trial are compared against an unconstrained model simulation. The blue dots represent the mean leaf and petiole biomass observations from across the four blocks and the red dots represent the mean corm biomass observations from across the four blocks. The yellow and green lines represent the daily biomass estimates from the Taro module. The period of water stress in January 2016 is clearly reflected in both the observations and simulation data. The leaf and petiole estimates are slightly under-estimated at full maturity (i.e. May 2016).

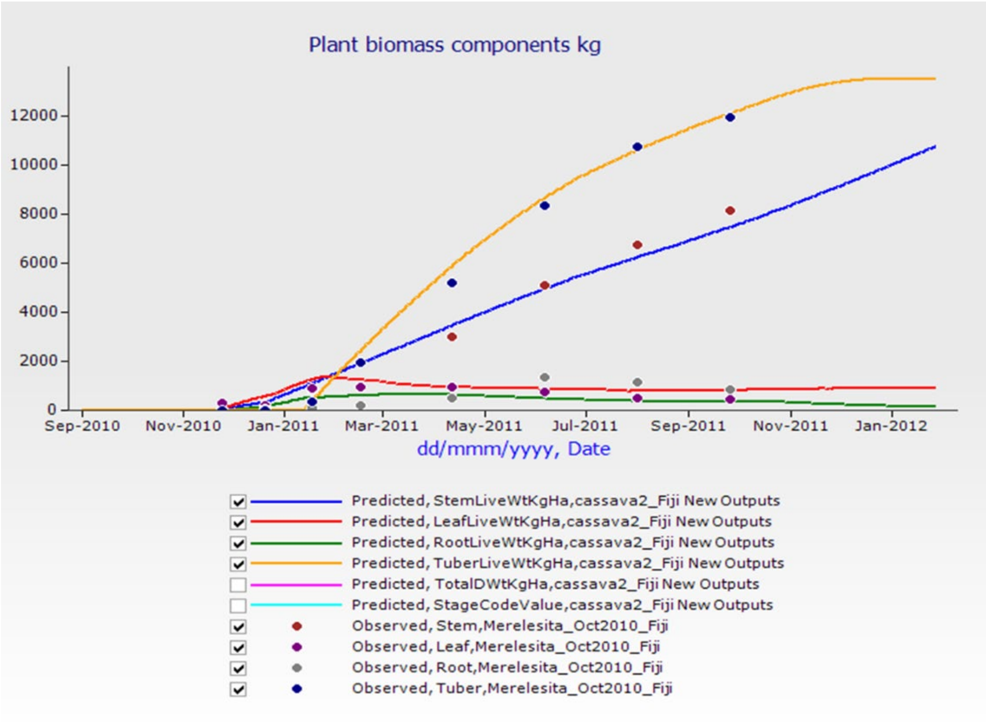


Figure 13. Partial validation of both tuber and leaf plus petiole biomass accumulation for the Merelesita cassava crop grown in Fiji. The blue, grey and red dots represent observation made during destructive harvests and the continuous lines represent the daily values simulated by the APSIM Cassava module.

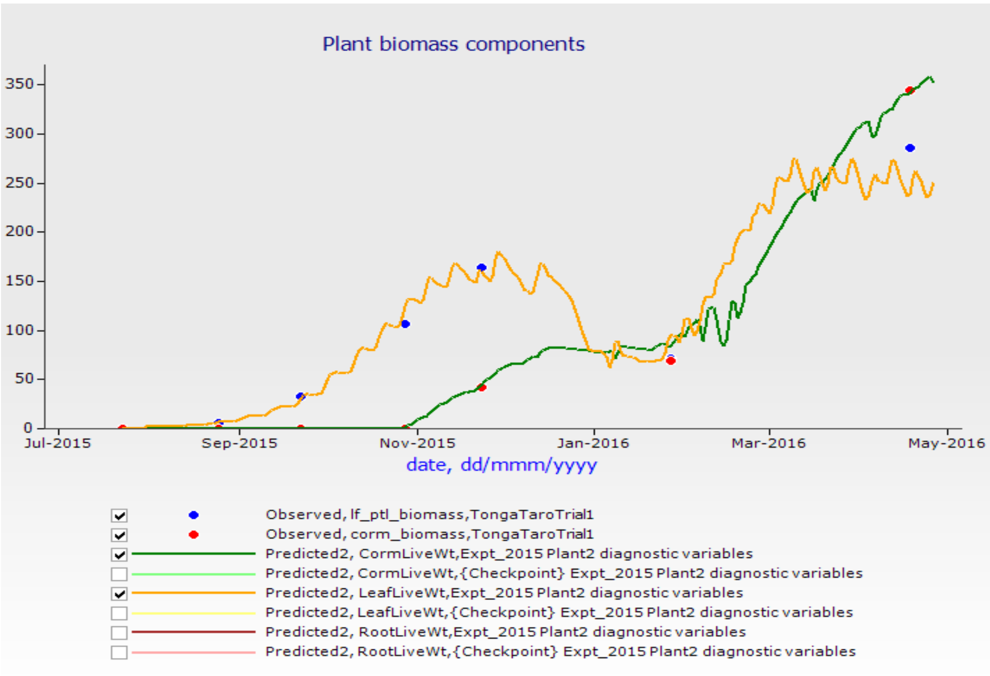


Figure 14. Partial validation of both corm and leaf plus petiole biomass accumulation for the Lauila taro crop grown in Tonga. The blue and red dots represent observation made during destructive harvests and the continuous lines represent the daily values simulated by the APSIM Taro module.

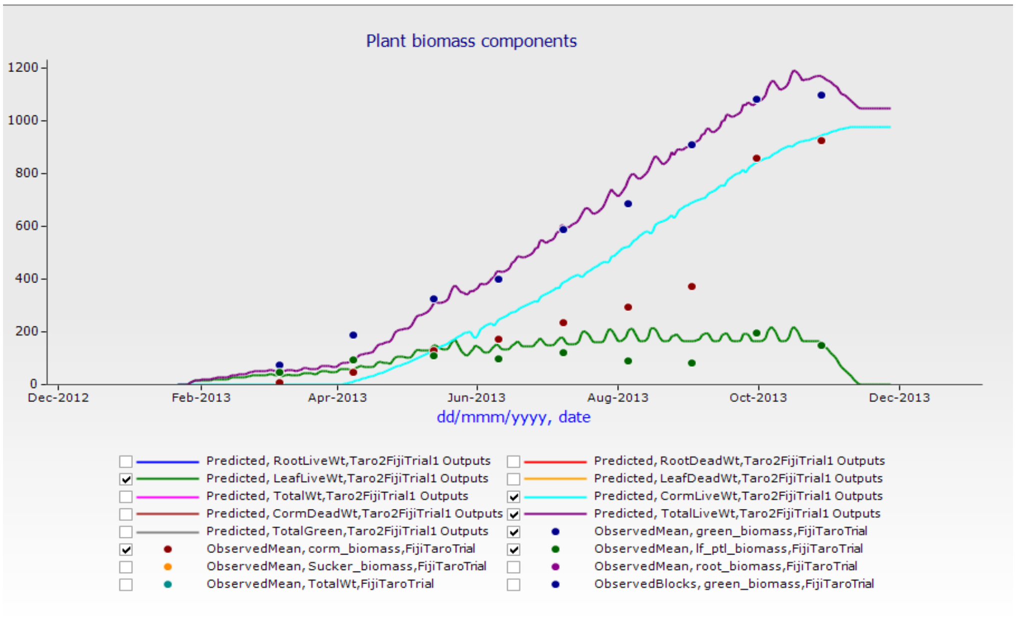


Figure 15. Partial validation of both corm and leaf plus petiole biomass accumulation for the Tausala taro crop grown in Fiji. The blue green and red dots represent observation made during destructive harvests and the continuous lines represent the daily values simulated by the APSIM Taro module.

Figure 15 highlights the agreement between the observed and predicted biomass accumulation for the Tausala taro crop grown in Fiji. The model tended to over-predict the growth of the corms and this was thought to be a function of over production of simulated leaves.

Figure 16a-d represents the comparison of observed and predicted leaf area at destructive harvest number three (H3) (Figure 13a) and destructive harvest number 5 (H5) from the taro trial at VARTC (Figure 16b). The correlation between both observed leaf area and modelled is between (0.99 and 0.98), representing a very good approximation of total plant leaf area by the APSIM Taro module. Capturing the leaf emergence and total leaf area are critical to the development of accurate corm production estimates, as the total leaf area determines the rate of biomass accumulation in the model. If this is captured well, the estimates of corm biomass will be accurate. Given the good agreement between the leaf emergence and total leaf area, we have some confidence that the corm production is well simulated.

Figures 16c and 16d represent the rate of leaf appearance and senescence based on observations of the number of leaves appearing (Figure 16c) and senescing (Figure 16d) against thermal time. The close correlation between thermal time and leaf appearance and senescence suggest that simple linear empirical relationships are robust when representing these features in the Taro module. The linear relationships have been incorporated into the model to control the rate of appearance and senescence.

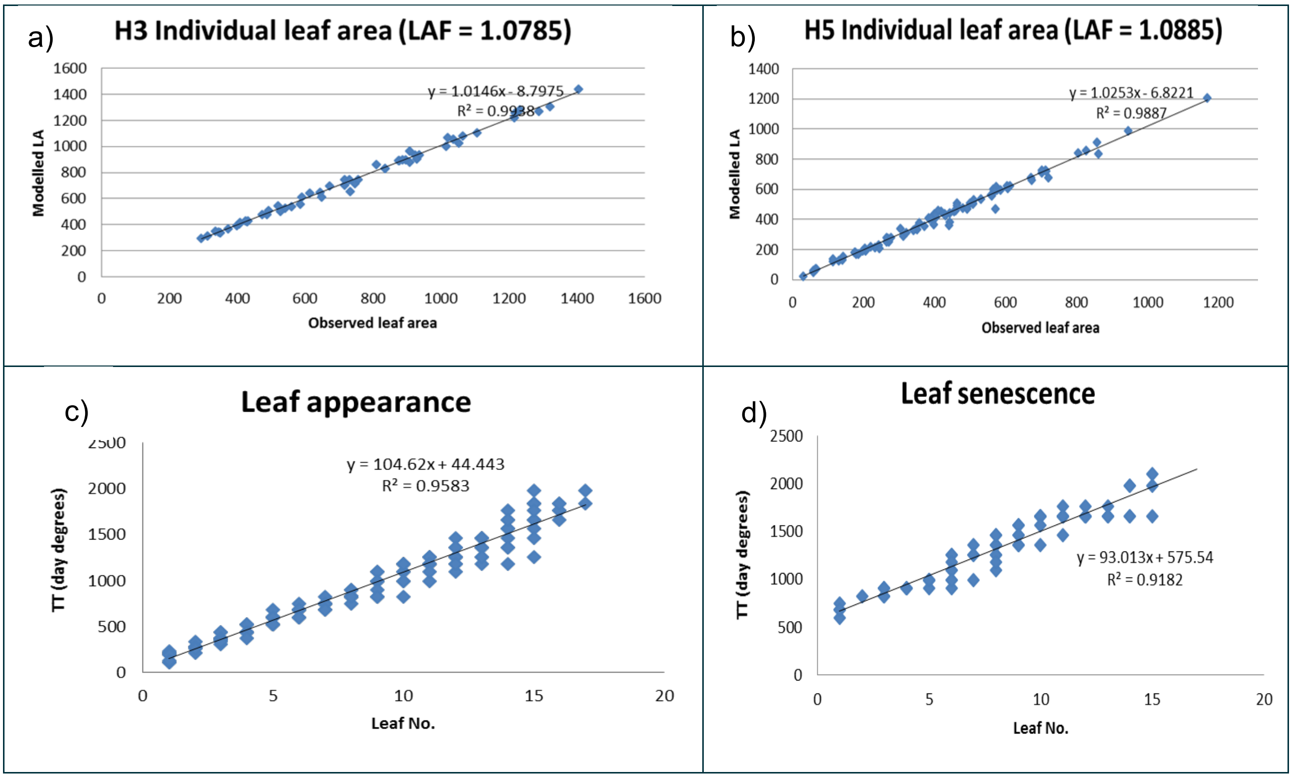


Figure 16. Comparison of observed versus simulated leaf areas from destructive harvests 3 (a) and 5 (b). Figures 16 c and d represent the correlation between thermal time and leaf appearance and senescence.

Due to the limited Lauila cultivar production data in Tonga, we attempted to validate the model corm yields against expert knowledge. We have done this by obtaining estimates of expected yields in tercile 1, 2 and 3 seasons and comparing these with the simulated corm yields for the period 1980 to 2015.

In a tercile 3 rainfall season Lauila yields are estimated to be between 17 and 23 t/ha, whilst during tercile 2 rainfall seasons corm yields are estimated at between 10 and 11.9 t/ha. During tercile 1 rainfall season production at the Tinopai farm is estimated to be between 3 and 5.9 t/ha (Figure 17).

The long-term simulation of the APSIM Taro module shows good variation across the different annual rainfall terciles, with low corm production associated with tercile 1 rainfall seasons and high corm production associated with tercile 3 rainfall seasons.

The Taro module tends to simulate both the “poor” and “average” growing seasons better than the “good” growing season production values. Corm production estimates are below those estimated for good “growing” seasons by between 2.5 and 8 t/ha. This is thought to be a function of two factors, namely the accuracy of the yield estimates from the experts consulted and the conversion from fresh weight (as observed in the field) to dry weight (as produced by the model). Conversion factors range from 0.2 to as high as 0.45 so our use of a mid-range conversion of 0.3 might account for the simulated yields being lower than the estimated yields in a high rainfall year.

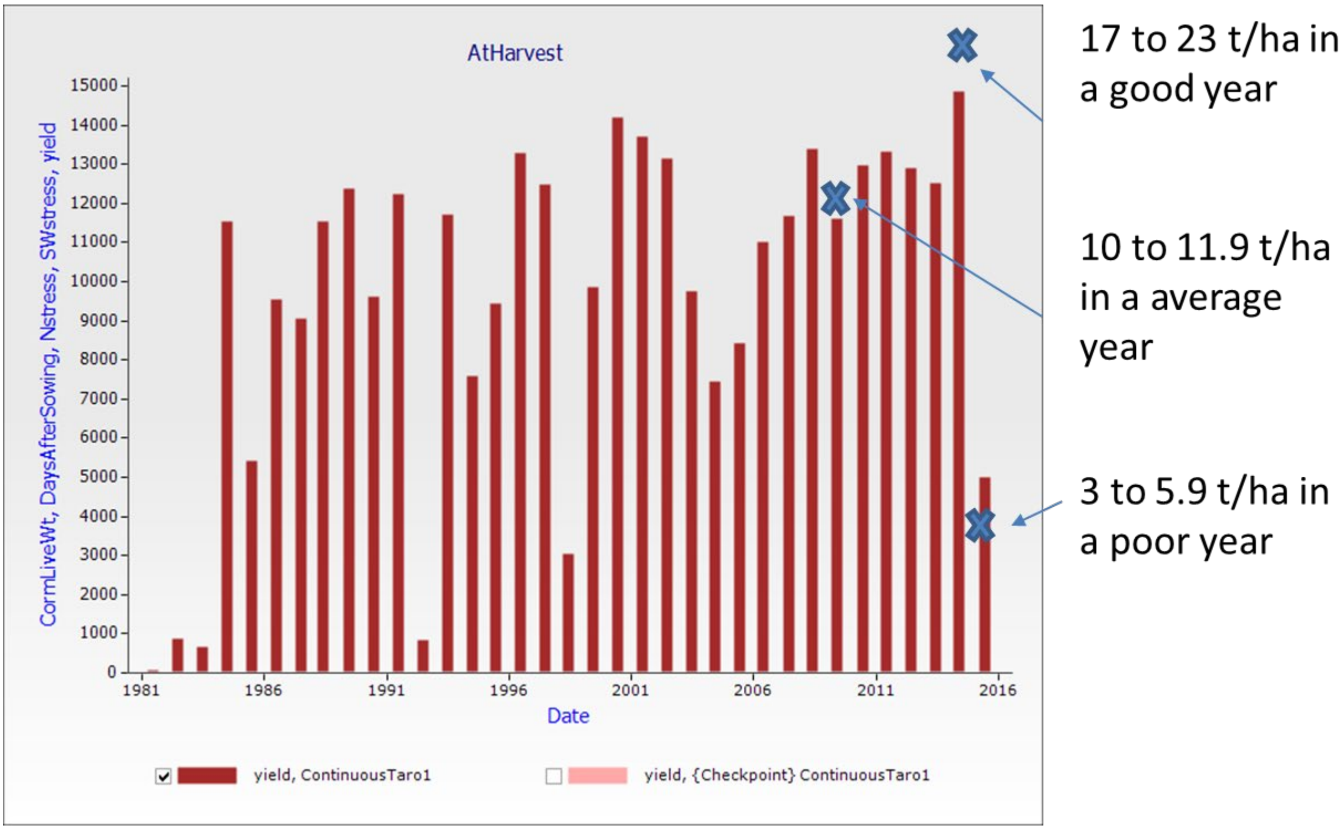


Figure 17. Long-term simulation of taro yields for the period 1980 to 2015. The blue crosses represent yield estimates from Tinopai farm for tercile 1 (“poor”), 2 (“average”) and 3 (“good”) rainfall seasons.

7.2 Climate change impacts and adaptation options for taro production

7.2.1 Baseline scenarios

‘Baseline’ management scenarios were configured in APSIM (Holzworth et al., 2014) to reflect typical, current taro management at separate locations in Tonga, Vanuatu and Fiji (Table 4). Due to some uncertainty regarding the parameterisation of the Fijian variety ‘Tausala’, the variety ‘Tarapatan’ was used in the simulations for both Fiji and Vanuatu. The variety ‘Lauila’ was used in the simulations for Tonga. Crops were planted at a density of 1 plant per m^2 within a defined site-specific three month window, triggered by a threshold rainfall total of 15mm over three days. If the cumulative rainfall trigger was not satisfied then planting was forced at the end of the window. In accordance with the typically low input nature of taro management in the Pacific, the baseline crops were rainfed with low N fertiliser inputs totalling 40 kg N/ha applied across two top-dress events (20 kg N/ha each) 60 and 90 days after planting. In order to remove inter-annual carryover effects, the levels of soil water, N and surface organic matter were reset at planting in each year of the simulation.

Table 4: Model configuration details for baseline scenarios at selected locations in Fiji, Vanuatu and Tonga.

	Location		
Management	**Koronivia Research Station near Suva, Fiji**	**VARTC, Vanuatu**	**Nishi Trading, Tonga**
Rainfall trigger (sow)	>15mm in 3 days	>15mm in 3 days	>15mm in 3 days
Sow window	Jun 1 - Aug 31 Aug 31: Must sow	Sep 1 - Nov 30 Nov 30: Must sow	Mar 1 - May 31 May 31: Must sow
N @ sowing	Nil	Nil	Nil
N topdress dates	N/A	N/A	N/A
Total N topdress (kgN/ha)	40kgN/ha	40kgN/ha	40kgN/ha
Reset N, H_2O, OM	Yes	Yes	Yes
Variety	Tarapatan	Tarapatan	Lauila
Density (plants/m^2)	1	1	1
Soil water @ sowing (%)	60	60	60
NO_3-N @ sowing (kgN/ha)	16	25	42
NH_4-N @ sowing (kgN/ha)	6	7	18

In order To capture seasonal climate variability effects, each baseline scenario was run over a 30 year time period from 1985 to 2015 using a combination of observed and generated long-term climate data sourced from representative climate observation sites. Site-specific summary plots for monthly rainfall and daily temperatures are shown in Figures 18 and 19.

Photo: preparation of taro trial at VARTC (Lunganville, Vanuatu).

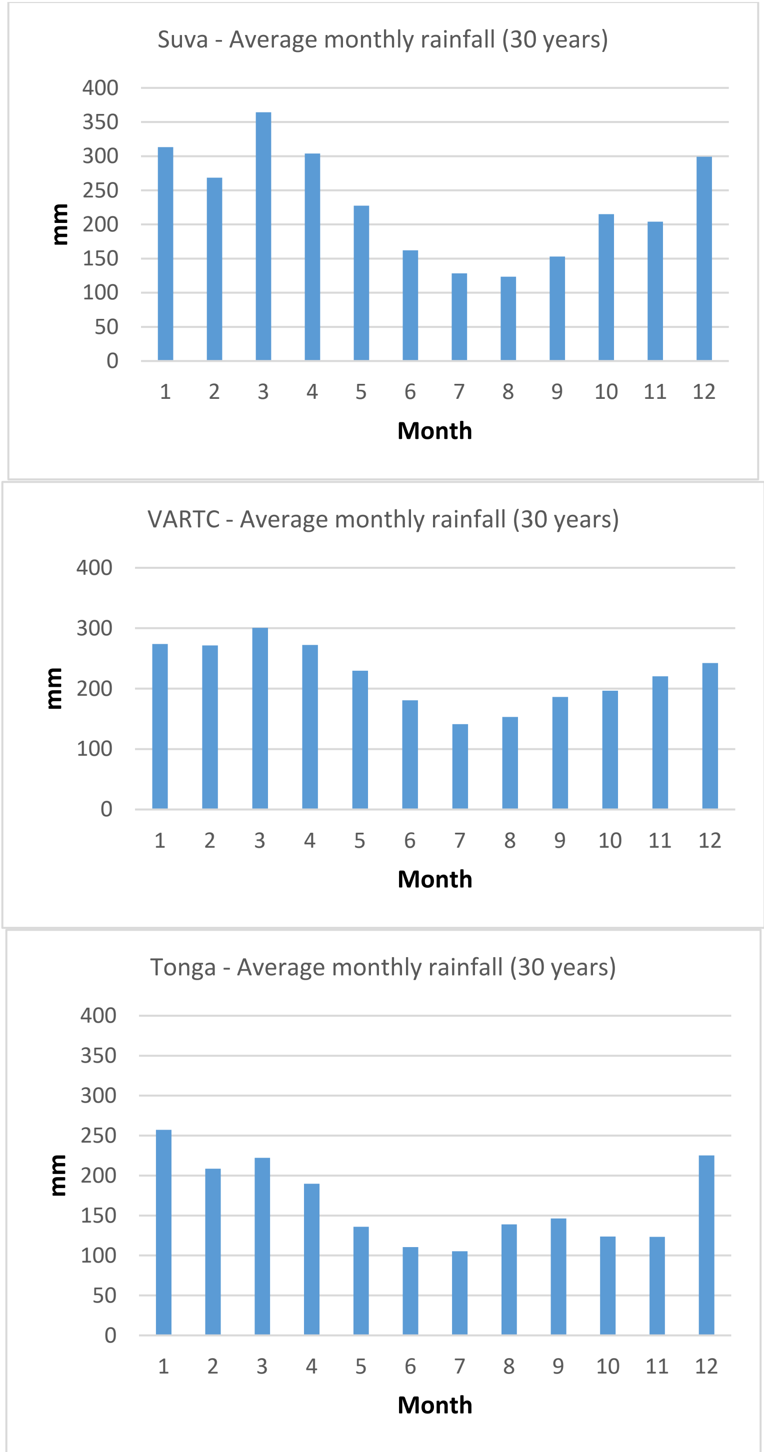


Figure 18. Average site-specific monthly rainfall at Suva, Vanuatu and Tonga (30 years).

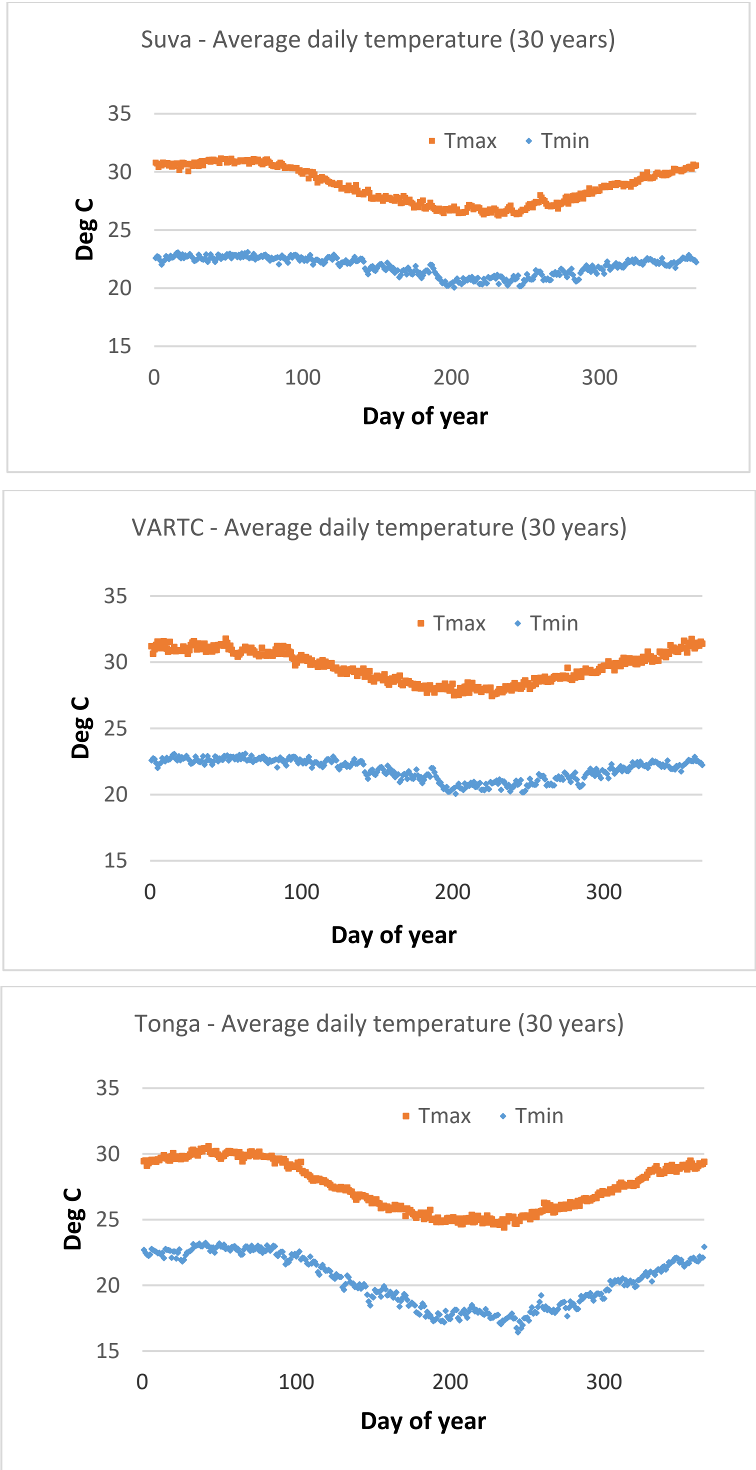


Figure 19. Average site-specific daily maximum and minimum temperatures (30 years) at Fiji, Vanuatu and Tonga.

Site-specific model settings for the key soil physical and chemical properties (Table 5) were derived from a variety of soil sampling procedures conducted in each region over the course of the project including: 1) regular destructive soil coring (i.e. mineral N, soil water content), 2) pre-planting soil pits (i.e. bulk density, organic matter content) and 3) rainout shelters (i.e. crop lower limit).

Table 5. Key site-specific soil chemical and physical properties.

Vanuatu								
Depth interval (cm)	**BD (g/cc)**	**DUL (mm/mm)**	**LL (mm/mm)**	**PAWC (mm)**	**Organic C %**	**NO3 (kg/ha)**	**NH4 (kg/ha)**	**pH**
0-15	0.86	0.53	0.23	45.3	2.8	10	3	7
15-30	0.84	0.56	0.31	36.6	2.4	6	2	7
30-60	0.86	0.51	0.37	42.3	2.4	4	1	7
60-90	0.78	0.53	0.37	48	2.4	2	0.5	7
90-120	0.85	0.59	0.42	51.9	2.1	1	0.5	7
120-150	0.89	0.59	0.43	48.3	1.2	1	0.2	7
150-180	0.82	0.55	0.40	45	0.7	1	0.1	7

Fiji								
Depth interval (cm)	**BD (g/cc)**	**DUL (mm/mm)**	**LL (mm/mm)**	**PAWC (mm)**	**Organic C %**	**NO3 (kg/ha)**	**NH4 (kg/ha)**	**pH**
0-15	1.14	0.47	0.29	26.3	1.0	1	1	7
15-30	1.24	0.43	0.29	21.2	0.9	2	1	7
30-60	1	0.51	0.29	67.2	0.9	3	1	7
60-90	1.05	0.50	0.29	59.1	0.9	4	1	7
90-120	1.01	0.51	0.3	33.6	0.8	3	1	7
120-150	1.01	0.51	0.31	3.6	0.5	3	1	7

Tonga								
Depth interval (cm)	**BD (g/cc)**	**DUL (mm/mm)**	**LL (mm/mm)**	**PAWC (mm)**	**Organic C %**	**NO3 (kg/ha)**	**NH4 (kg/ha)**	**pH**
0-15	0.92	0.6	0.25	52.5	2.9	21	10	6.2
15-30	0.81	0.6	0.3	45	2.3	6	2	6.2
30-60	0.77	0.55	0.33	66	2.4	4	2	6.2
60-90	0.76	0.45	0.35	30	2.7	3	1	6.2
90-120	0.79	0.45	0.36	27	0.5	5	2	6.2
120-150	1.03	0.45	0.38	21	0.4	2	1	6.2
150-180	0.98	0.45	0.39	18	0.4	1	0	6.2

7.2.2 Climate change scenarios

To explore the impact of climate change on taro production, a range of possible future temperature, rainfall and atmospheric CO_2 projections were imposed on the baseline scenarios. These projections were sourced from reputable climate and atmospheric models and cover the range of possible shifts in these climate variables in the Pacific region in the 2030-2050 period. The projections include temperature increases of up to 3°C, rainfall declines of up to 15%, and atmospheric CO_2 levels ranging between 420 and 500ppm.

The analysis was conducted using the climate change function within APSIM and involved a stepwise process beginning with consideration of shifts in individual climate variables before looking at simultaneous adjustments of more than one variable.

For the latter analysis, six potential combinations of temperature, rainfall and CO_2 were considered, chosen to cover the likely scope of future climate change: 1) +1°C temperature, -5% rainfall, 420ppm CO_2, 2) +2°C, -10% rainfall, 420ppm CO_2, 3) +3°C temperature, -15% rainfall, 420ppm CO_2, 4) +1°C temperature, -5% rainfall, 450ppm CO_2, 5) +2°C temperature, -10% rainfall, 500ppm CO_2, 6) +3°C temperature, -15% rainfall, 500ppm CO_2.

7.2.3 Adaptation scenarios

The final step in the analysis was to explore adaptation changes that might offset any potential negative impacts arising from climate change. The approach involved taking the most pessimistic climate change scenario (i.e. the projection that generated the biggest decline in yield, namely +3°C temperature, -15% rainfall, 420ppm CO_2) and exploring whether the associated yield decline (cf. baseline scenario) could be offset through adjustments in management settings including:

- changing the three month planting window
- introducing irrigation (i.e. irrigate 15mm whenever the rainfall total over the previous 4 days is less than 5mm and the period from the previous event is at least 14 days)
- doubling the N fertiliser rates from 40 kg N/ha to 80 kg N/ha, and
- increasing the planting density to 1.7 plants/m^2.

7.2.4 Taro Baseline Results

Figure 20 compares the annual taro yields across the three sites. The baseline yields in Tonga are typically lower and more variable than for the other two sites in response to the lower rainfall and temperatures (Figures 18 and 19). The high levels of organic matter (Table 5) and associated mineralisation rates account for the highest yields occurring in Vanuatu.

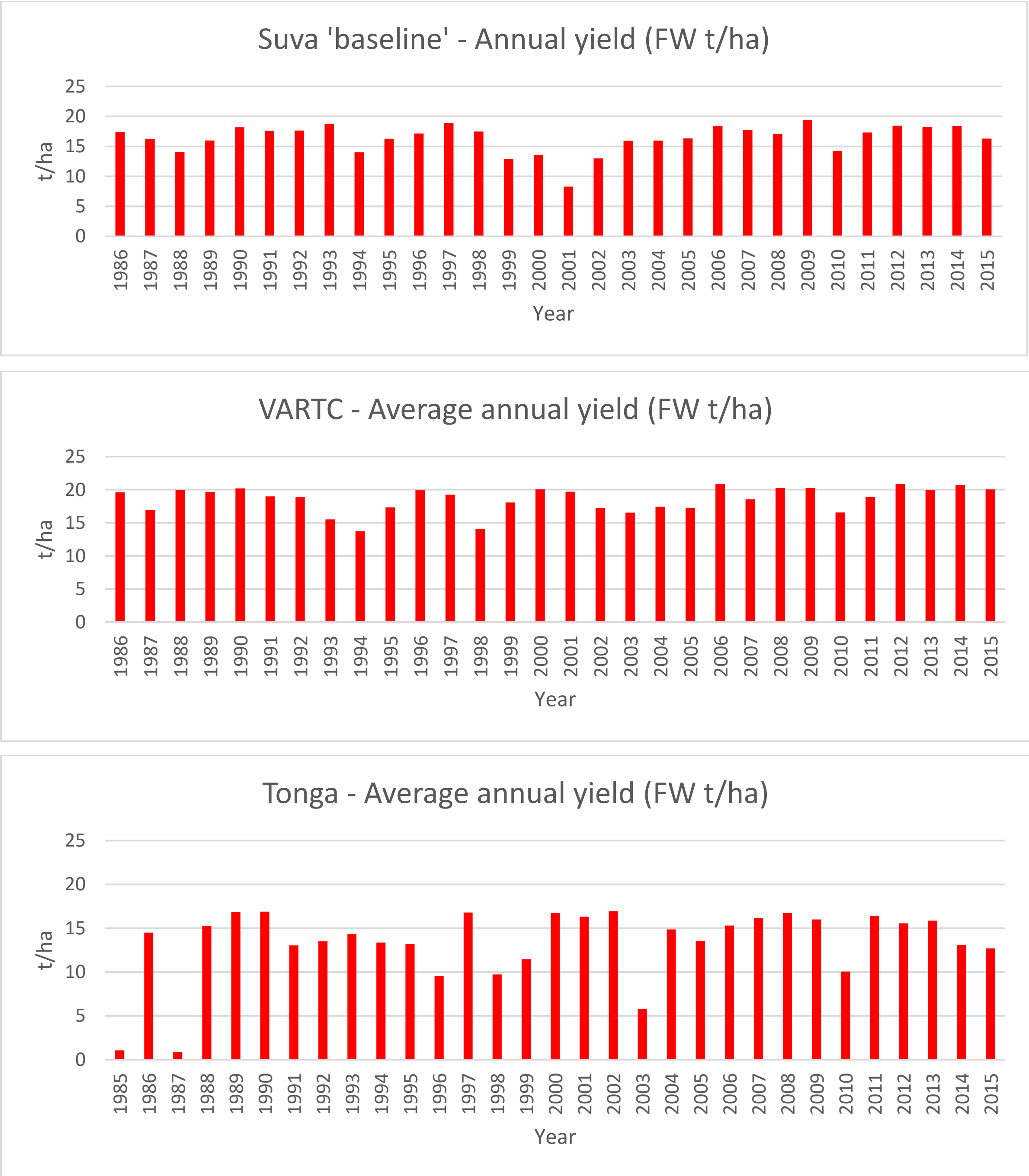


Figure 20. Annual site-specific yields for the baseline scenarios.

7.2.5 Taro response to future climate scenarios

Response to declines in future rainfall

The impact of future rainfall decline on yield was typically small across all sites and can be attributed to the high rainfall totals and intensity of individual rainfall events (Figure 21). As a consequence, much of the rainfall is ineffective and lost to the crop as either drainage or runoff. In Tonga, there is a stronger downward trend in yield with rainfall decline reflecting the lower rainfall at this site (i.e. long-term average of 1867mm cf. 2763mm and 1670 for Suva and Vanuatu respectively).

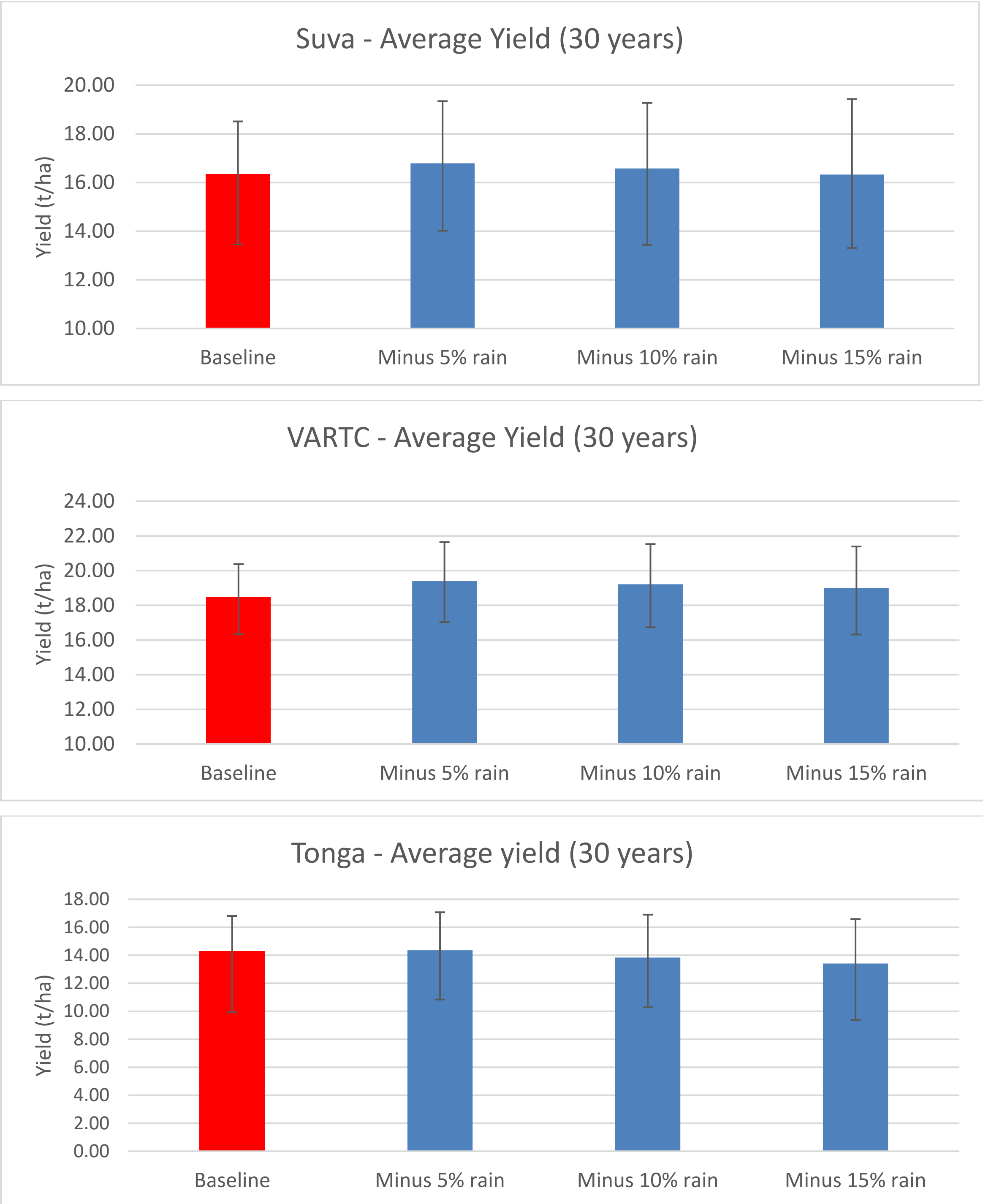


Figure 21. Site-specific average (30 years) yield for the baseline (red) and future rainfall decline (blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Response to increased future temperature

For Vanuatu and Fiji, yield was little affected by increases up to 2°C but there is a noticeable decline of 10-12% (cf. baseline) at 3°C (Figure 22). In Tonga, average yield is lower than the baseline scenario for all temperature increase scenarios but lowest for the 3°C projection.

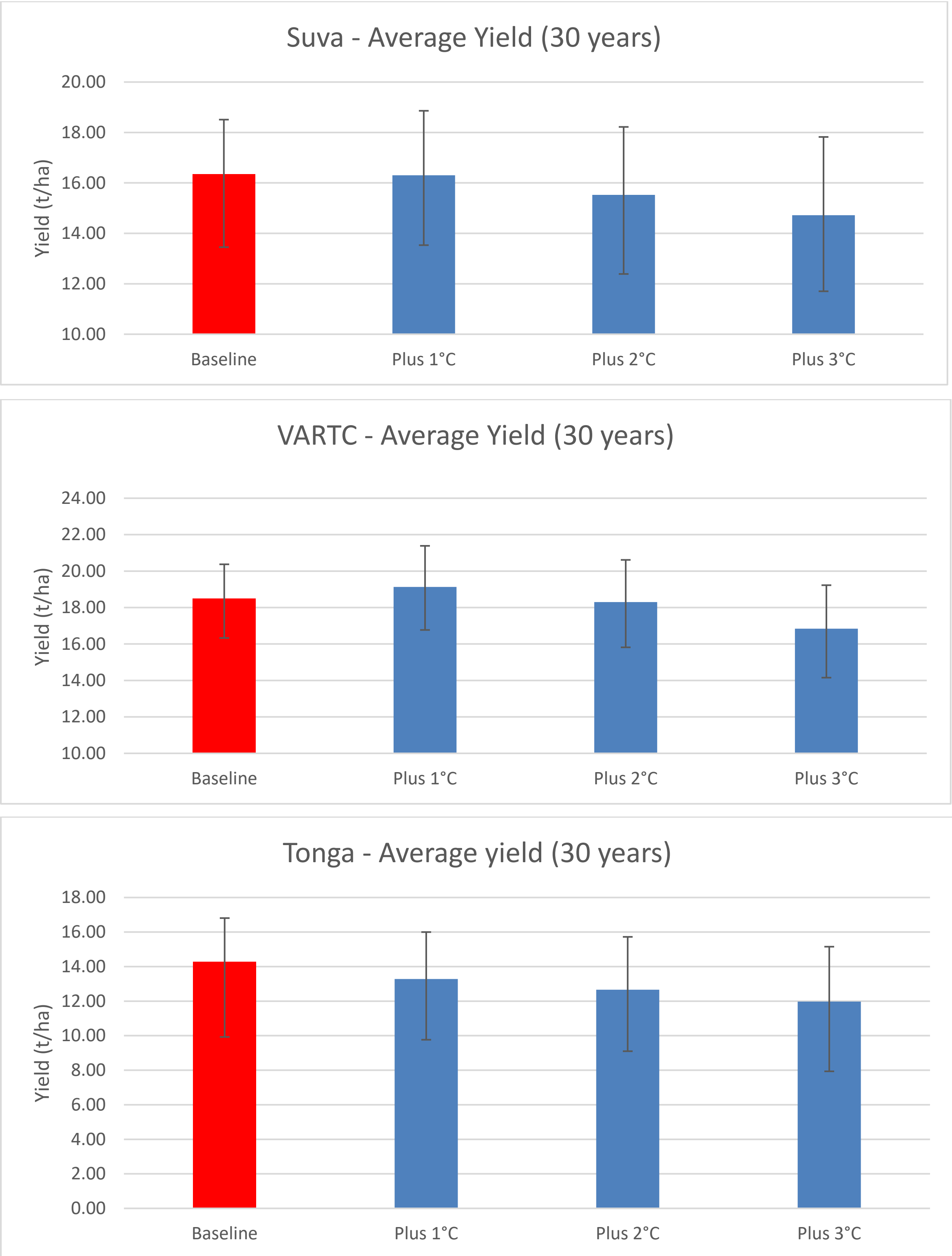


Figure 22. Site-specific average (30 years) yield for the baseline (red) and future temperature increase (blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

The yield decline with temperature occurred in response to the crop spending more time above optimum growing temperatures (i.e. slowing growth), and to a speeding up of crop maturity and a subsequent shortening of the corm filling period (Figure 23).

For every degree increase in future temperature, crop maturity was advanced by about two weeks (Figure 23). This might be expected to have profound effects on the future cropping calendar/sequence, market access, other crop management practices and cultivar selection (i.e. potential for later maturing types).

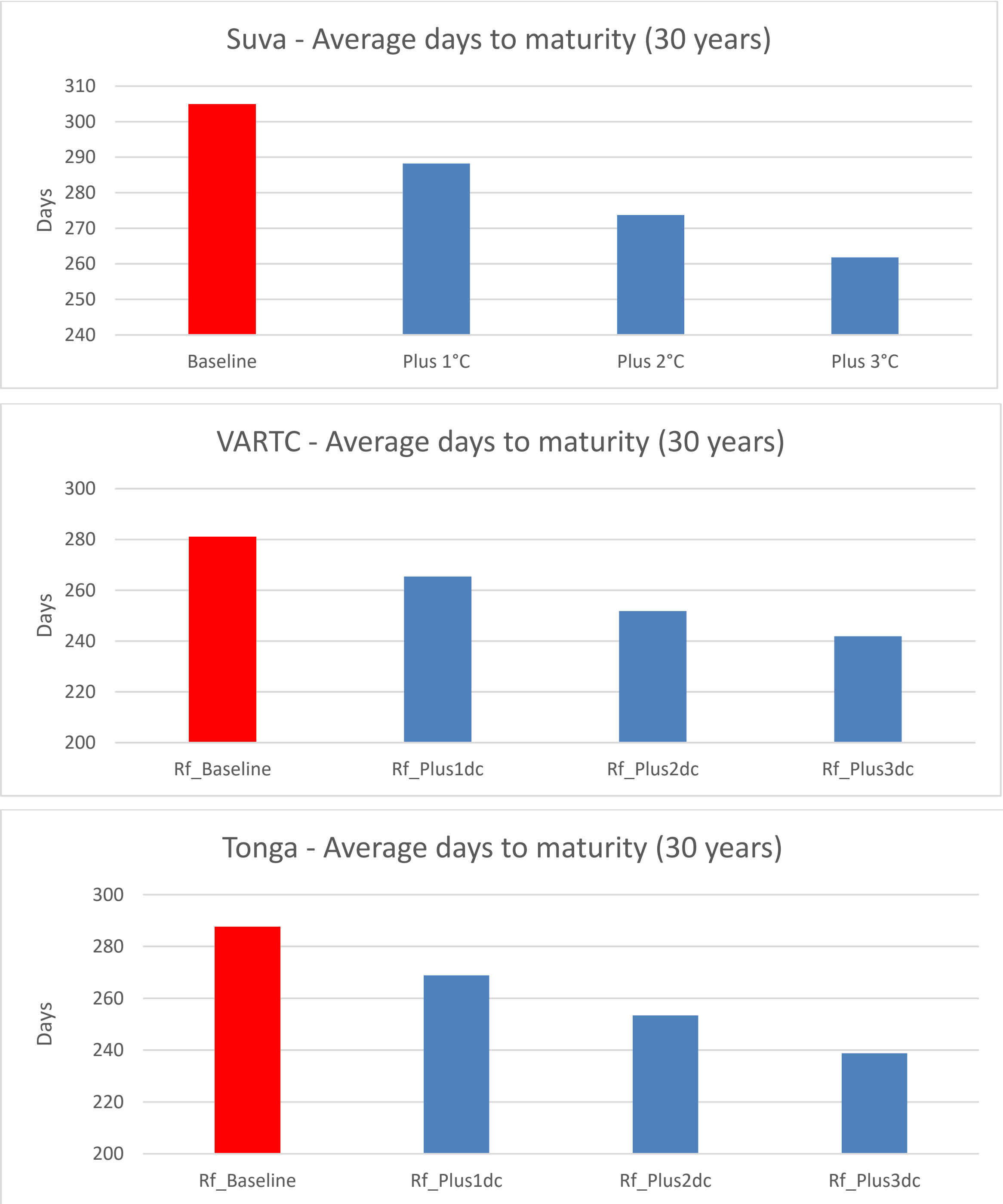


Figure 23. Site-specific average (30 years) days to maturity for the baseline (red) and future temperature increase (blue) scenarios.

In reality, taro is often harvested in advance of corm/physiological maturity in order to satisfy specific market demands or to avoid disease. In contrast to crops allowed to reach full maturity, temperature gains in these circumstances will result in a longer corm filling period due to the earlier commencement of corm filling (coupled with fixed harvest date) and higher yields (Figure 24).

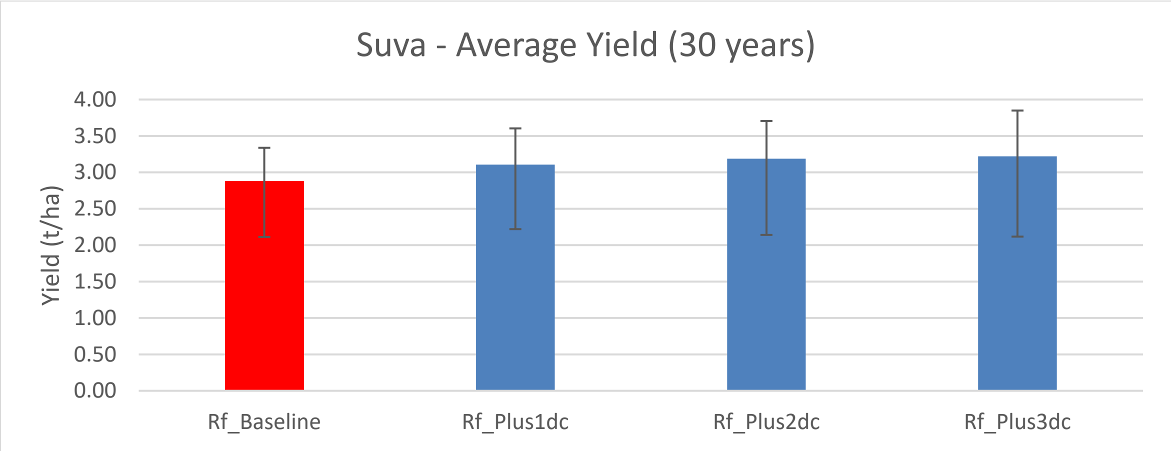


Figure 24. Average (30 years) yield at Suva for the baseline (red) and future temperature increase (blue) scenarios in which harvesting occurs at a fixed six months after planting.

Response to increased future CO_2

Across all sites, yield increased with increasing atmospheric CO_2 concentration (Figure 25). This reflects the typical ‘CO_2 fertilisation’ response of C3 crops such as taro and is in response to gains in water, N and RUE. Note that the CO_2 routines that are currently built into the model are generic in nature. The trial work of Ros Gleadow at Monash University (Section 7.4) into the effects of elevated CO_2 on taro growth and development is yet to be fully incorporated into the APSIM Taro model.

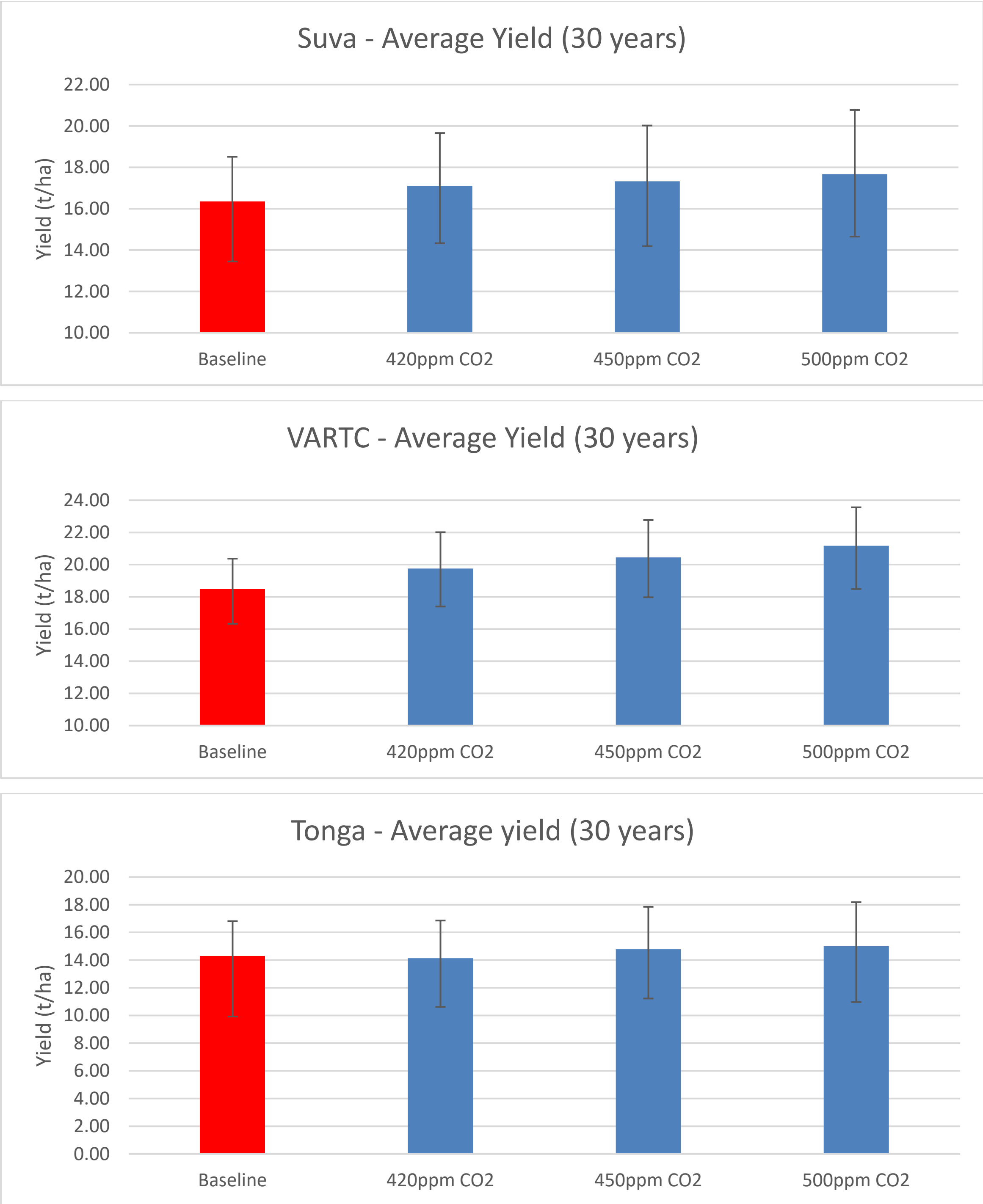


Figure 25. Site-specific average (30 years) yields for the baseline (red) and CO_2 increase (blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Response to combined scenarios of temperature, rainfall and CO_2

The results presented above represent simulated changes in taro yields in response to changes in individual climate variables. In reality, these climate and atmospheric variables change concurrently and Figure 26 shows the impact of six different climate variable combinations on yield. These combinations generate a range of responses, from yields that are below, to those that are above or comparable to the baseline scenario. The lowest yield was associated with the largest shifts in rainfall and temperature (-15% and +3°C) coupled with the lowest CO_2 concentration of 420ppm. Conversely, the highest yield was associated with the highest CO_2 concentrations (500ppm) and small/modest declines in rainfall (5%) and increases in temperature (1°C).

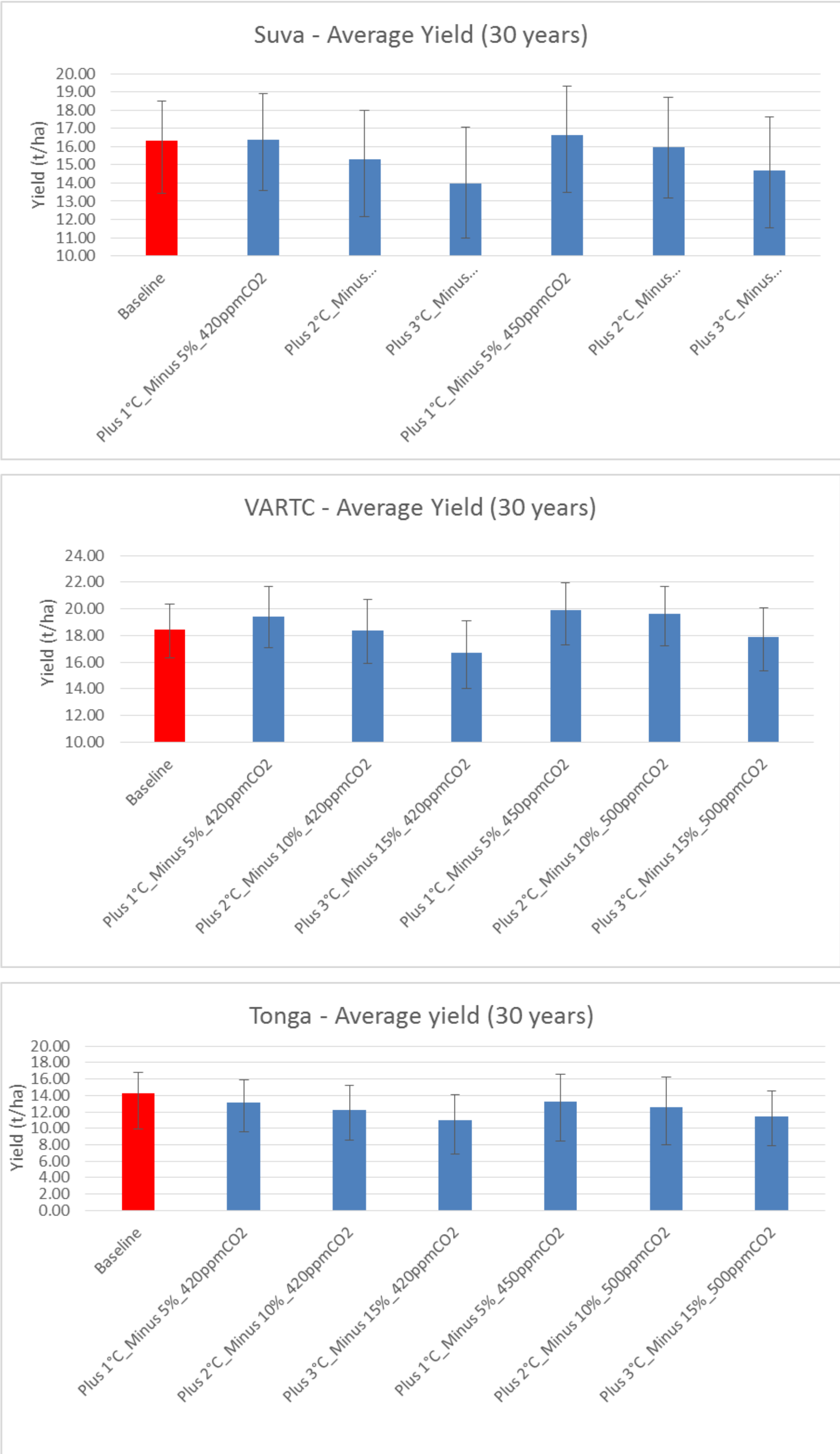


Figure 26. Site-specific average (30 years) yields for the baseline (red) and combined variable (blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

The yield of taro under baseline (historical) climates and in response to step-wise and combined changes in climates at Suva, VARTC and Tonga, are summarised in Table 6.

Table 6. Summary, site-specific average, 10th and 90th percentile yields for single climate variable change and mixed climate variable scenarios. Values represent fresh weights in tonnes per hectare (t/ha).

	Suva			VARTC			Tonga		
Treatment	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**
Baseline	16.3	13.5	18.5	18.5	16.3	20.4	14.3	9.9	16.8
Minus 5% rain	16.8	14.0	19.3	19.4	17.0	21.6	14.4	10.8	17.1
Minus 10% rain	16.6	13.4	19.3	19.2	16.7	21.5	13.8	10.3	16.9
Minus 15% rain	16.3	13.3	19.4	19.0	16.3	21.4	13.4	9.4	16.6
Plus 1°C	16.3	13.2	19.0	19.1	16.5	21.2	13.3	8.5	16.6
Plus 2°C	15.5	12.7	18.3	18.3	15.9	20.4	12.7	8.0	16.3
Plus 3°C	14.7	11.6	17.7	16.8	14.3	19.0	12.0	8.4	15.2
420ppm CO_2	17.1	14.2	19.4	19.8	16.5	21.9	14.1	9.3	17.4
450ppm CO_2	17.3	14.3	19.7	20.5	18.1	22.5	14.8	10.6	17.6
500ppm CO_2	17.7	14.7	20.2	21.2	18.7	23.3	15.0	10.8	17.8
+1°C_-5%_420ppmCO_2	16.4	13.1	19.2	19.4	16.6	21.5	13.1	8.0	16.5
+2°C_-10%_420ppmCO_2	15.3	11.9	18.1	18.4	15.7	20.7	12.2	6.7	16.1
+3°C_-15%_420ppmCO_2	14.0	10.2	17.5	16.7	13.8	19.2	10.9	6.2	15.3
+1°C_-5%_450ppmCO_2	16.6	13.2	19.6	19.9	17.0	22.0	13.3	7.8	16.7
+2°C_-10%_500ppmCO_2	16.0	12.7	18.8	19.6	16.8	22.1	12.6	6.7	16.7
+3°C_-15%_500ppmCO_2	14.7	10.8	18.3	17.9	14.8	20.5	11.4	6.8	15.7

7.2.6 Taro adaptation options

Extra N fertiliser

Current taro production in the Pacific typically involves low inputs of fertiliser, usually applied in small amounts by hand either at sowing or as a topdressing 2-3 months after planting. These small fertiliser inputs are based on a belief that fertiliser is expensive and unlikely to generate a decent return on investment. This perception no doubt relates to the deep, uniform and inherently fertile, organic matter rich characteristics of the native volcanic soils.

This response is borne out in the model results on the volcanic soils of Vanuatu and Tonga where yield is essentially unresponsive to the doubling of fertiliser under both the current and future climates (Figure 27).

In contrast, there is a modest increase in yield on the alluvial soil in Fiji which has much lower organic matter levels (Table 5).

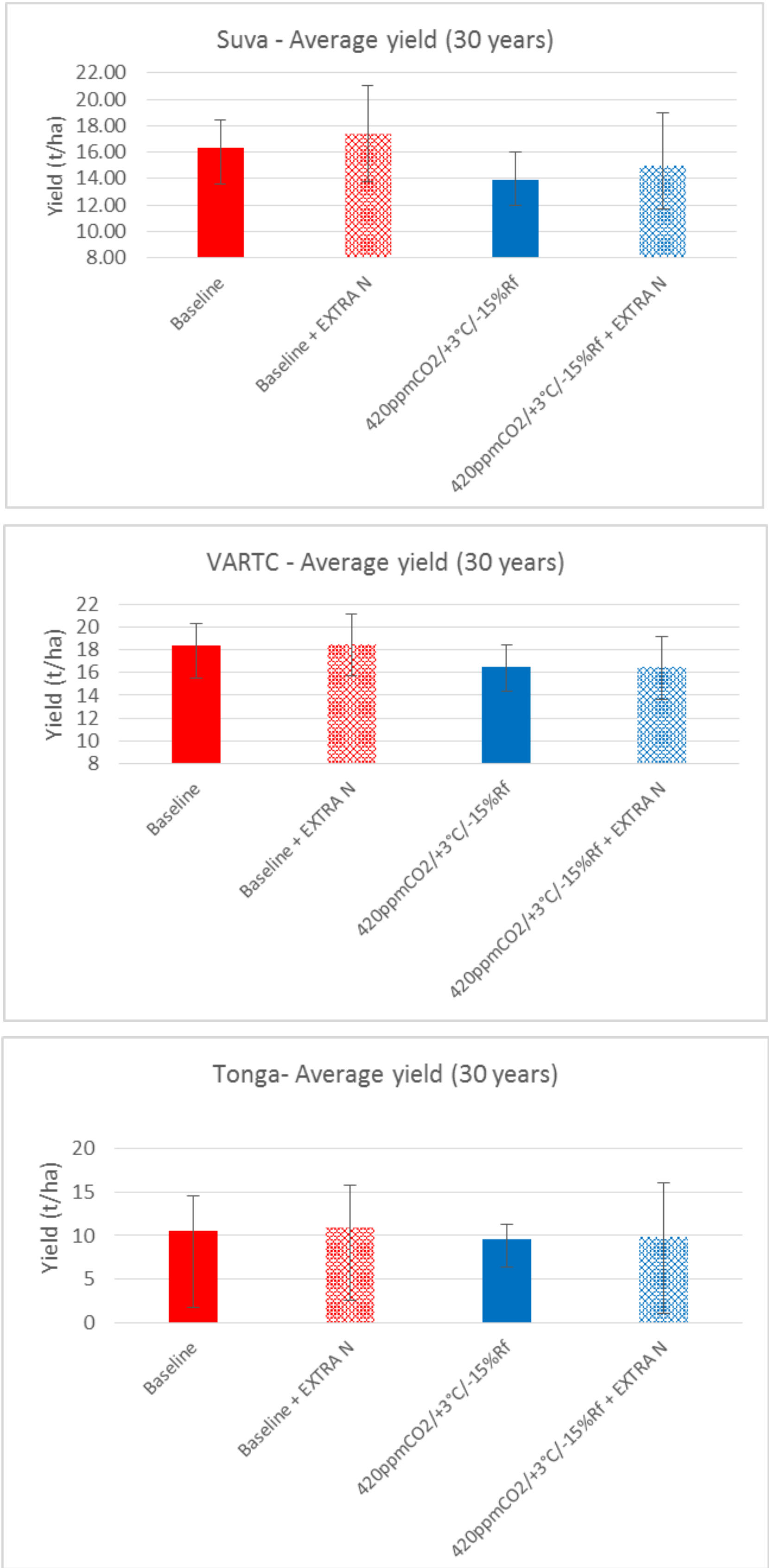


Figure 27. Site-specific average (30 years) yields for the baseline (red), baseline plus extra N (hatched red), climate change (blue), climate change plus extra N (hatched blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Introduction of irrigation

Irrigation of taro across the three regions is rare among smallholder producers but is starting to be adopted in larger commercial operations to supplement natural rainfall, especially in the lower rainfall climate of Tonga.

The model results indicate substantial gains from the use of irrigation across all sites both under the current and future climate conditions (Figure 28). In the case of Fiji and Vanuatu, irrigated yields under the future climate are almost comparable to rainfed yields under the current climate. In Tonga, the irrigated future climate yields exceed current climate rainfed yields.

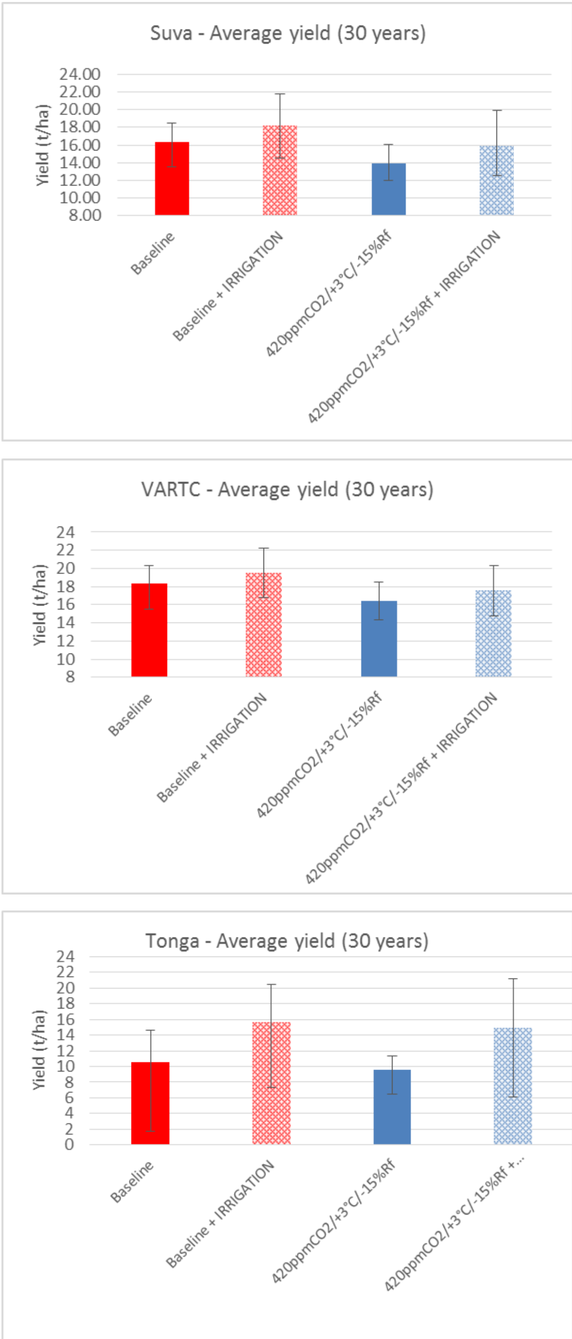


Figure 28. Site-specific average (30 years) yields for the baseline (red), baseline plus irrigation (hatched red), climate change (blue), climate change plus irrigation (hatched blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Irrigation and extra N fertiliser

The addition of extra N fertiliser to the irrigated scenarios further increases the yield potential relative to the baseline scenario (Figure 29).

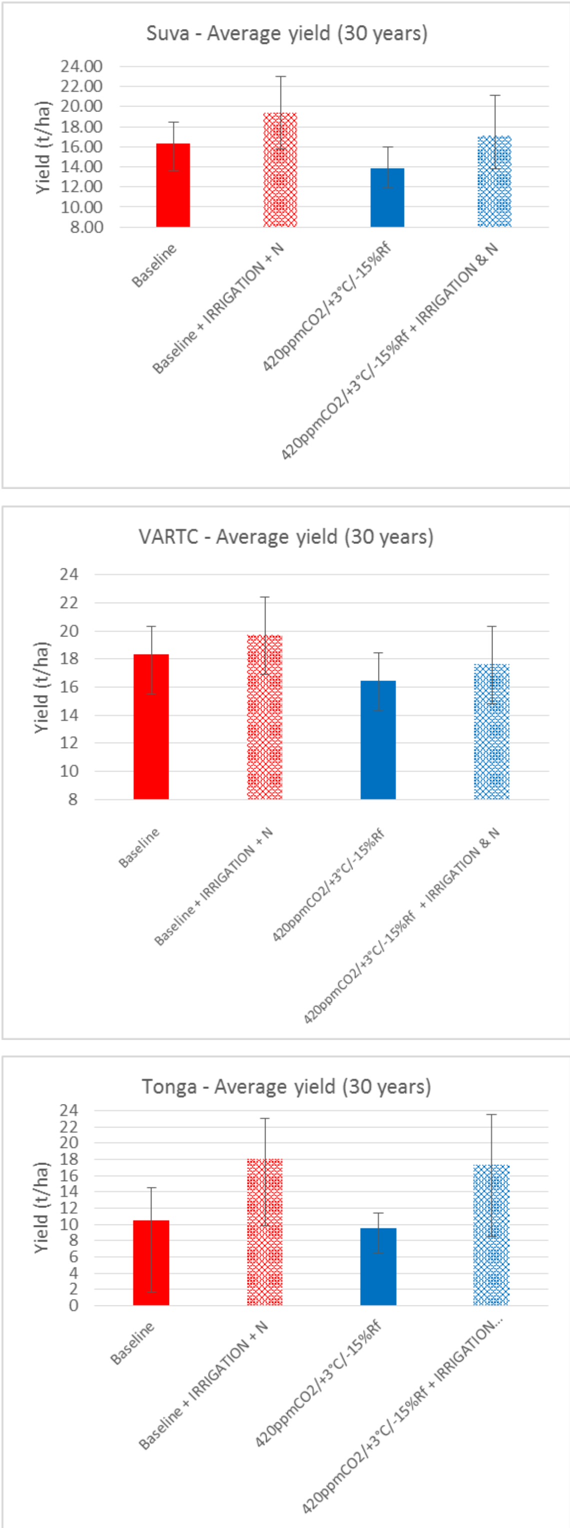


Figure 29. Site-specific average (30 years) yields for the baseline (red), baseline plus irrigation and N (hatched red), climate change (blue), climate change plus irrigation and N (hatched blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Modified planting window

Aside from a small increase with a shift to a September to November planting window in Fiji, all other alternate planting windows resulted in yield declines under the future climate (Figure 30).

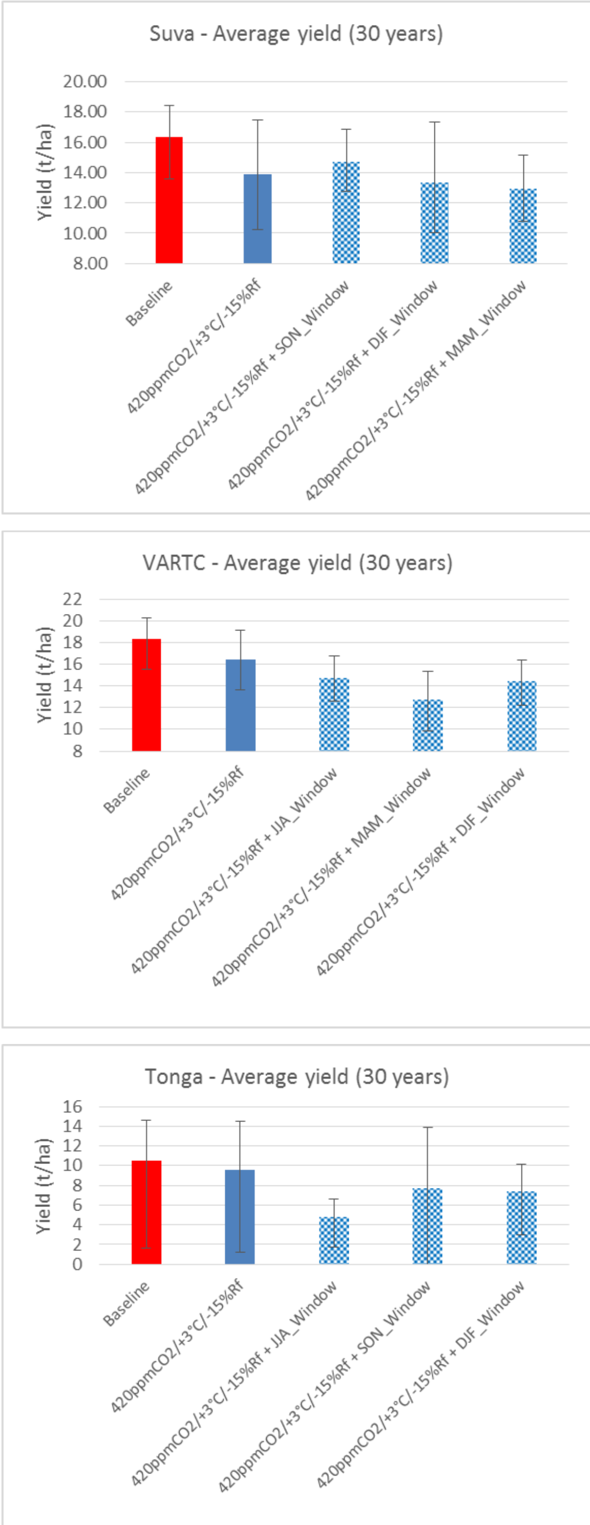


Figure 30. Site-specific average (30 years) yields for the baseline (red), climate change (blue), climate with modified planting window (hatched blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

Increased plant density

The response to increasing plant density is variable across the three sites according to the amount of available resources (Figure 31). In the case of Vanuatu, the higher mineralisation rates coupled with high rainfall can support a higher plant population resulting in higher overall yields. In Tonga, there is a yield penalty associated with higher plant density presumably due to restrictions associated with lower rainfall at this site. Yields were unresponsive to higher plant density in Fiji.

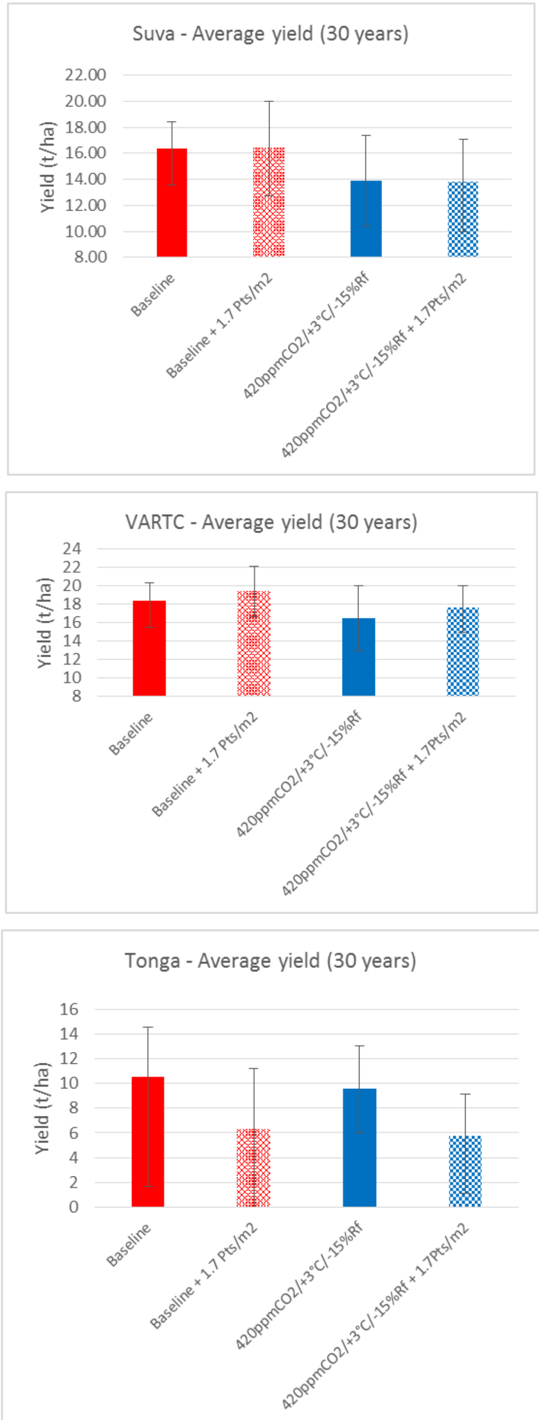


Figure 31. Site-specific average (30 years) yields for the baseline (red), baseline with increased density (hatched red), climate change (blue), climate change with increased density (hatched blue) scenarios. The whiskers show the 90th and 10th percentile yields across the 30 year simulation period.

As noted above, the increase in temperature leads to earlier crop maturity and a shorter period of corm filling. One obvious response would be to shift to using later maturing cultivars to offset the yield reduction. Conversely, earlier maturation may open up new market opportunities or allow beneficial changes to the crop rotation/mix.

Changes in taro yield in response to the adaptation scenarios applied to the baseline and future climate scenarios are summarised in Table 7.

Table 7. Summary, site-specific average, 10th and 90th percentile yields for climate change adaptation scenarios.

	Suva			VARTC			Tonga		
Scenario	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**	**Average**	**10th**	**90th**
Baseline	16.4	13.6	18.4	18.4	15.5	20.3	10.5	1.7	14.6
Baseline + IRRIGATION	18.2	16.2	20.2	19.6	16.7	20.8	15.6	12.2	16.8
Baseline + EXTRA N	17.4	14.7	19.6	18.5	15.6	20.4	10.9	1.4	15.8
Baseline + IRRIGATION + N	19.4	17.6	20.2	19.7	16.7	20.9	18.1	12.8	18.9
Baseline + 1.7 Pts/m2	16.4	13.7	18.4	19.4	16.7	21.0	6.3	1.3	9.8
420ppmCO_2/+3°C/ -15%Rf	13.9	10.2	17.5	16.5	13.7	19.2	9.6	1.3	14.5
420ppmCO_2/+3°C/ -15%Rf + IRRIGATION	15.9	14.0	18.1	17.6	15.5	19.6	15.0	11.8	16.7
420ppmCO_2/+3°C/ -15%Rf + EXTRA N	15.0	11.7	19.0	16.5	13.7	19.2	9.9	1.0	16.0
420ppmCO_2/+3°C/ -15%Rf + IRRIGATION & N	17.1	15.0	19.3	17.7	15.5	19.6	17.4	13.0	20.1
420ppmCO_2/+3°C/ -15%Rf + SON_Window	14.7	12.5	16.9	14.7	8.0	19.8	4.8	0.8	10.4
420ppmCO2/+3°C/ -15%Rf + DJF_Window	13.4	11.5	14.8	12.7	9.2	17.0	7.7	1.5	12.7
420ppmCO_2/+3°C/ -15%Rf + MAM_Window	12.9	9.9	15.4	14.4	12.7	16.2	7.4	1.5	11.9
420ppmCO_2/+3°C/ -15%Rf + 1.7Pts/m2	13.8	10.0	17.1	17.6	15.0	20.0	5.8	1.1	9.1

7.3 Climate change impacts and adaptation options for cassava production

The effect of climate change upon cassava production in Fiji is investigated in this study through a simulation approach. This analysis closely follows the approach adopted for simulating the effect of climate change on taro (Section 7.2), and uses the prototype Cassava crop module in APSIM to:

1) explore the potential impact of projected climate change scenarios on cassava production, and
2) investigate a range of alternative management practices that might assist farmers to offset any negative consequences arising from climate change.

Unlike the multi-variety and multi-site analysis conducted for taro (Section 7.2), this analysis is restricted to a single cassava variety in Fiji, because reliable field trials for calibration of the cassava prototype were limited to this location (near Suva). However, the influence of different climates upon the single cassava variety simulated has been investigated in this analysis by the addition of a second, contrasting climate from Fiji (at Nadi).

7.3.1 Baseline scenarios

Representative local ('baseline') cassava management was characterised for cassava production in the Suva region of Fiji (Table 8), following consultation with a local collaborators. Crops were planted at a density of 2 plants per m² within a three month window, triggered by a threshold rainfall total of 15mm over three days. If the cumulative rainfall trigger was not satisfied then planting was forced at the end of the window.

Table 8: Model configuration details for baseline and climate change adaptation scenarios used for all locations simulated

Management practice	Baseline scenario	Adaptation scenario
Crop management		
Planting window	1 March – 31 May	1 July – 30 September
Prerequisite rainfall before planting	>15mm in 3 days; if rainfall requirement not met then cassava is sown on the last day of the planting window	>15mm in 3 days; if rainfall requirement not met then cassava is sown on the last day of the planting window
Variety	Merelesita	Merelesita
Density (plants/m²)	2	3
Crop duration (months)	9	12
N fertiliser		
Applied at planting	Nil	Nil
Applied at 4 and 8 weeks after planting	10 kg urea-N per application	22.5 kg urea-N per application
Irrigation		
Frequency of application	Nil (rainfed)	Where rainfall in the preceding 14 days is less than 5 mm, apply 15 mm of irrigation
Initial soil properties		
Soil water at planting (%)	60	60
Profile soil mineral N as nitrate-N present at planting (kg NO_3-N/ha)	20	20
Profile soil mineral N as ammonium-N present at planting (kg NH_4-N/ha)	5	5
Simulation resets		
Reset soil N, soil water and surface organic matter	At planting	At planting

In accordance with the typically low input nature of cassava management in the Pacific, the baseline crops were rainfed with low N fertiliser inputs totalling 20 kg N/ha applied across two top dress events (10 kg urea-N/ha each) at four and eight weeks after planting.

In order to focus on yield responses to changes in management within each year, the inter-annual carryover effects from change in of soil water, N and surface organic matter were removed by resetting these factors at planting in each year of the simulation.

Cassava production was simulated in response to weather data measured at the Koronivia Research Station near Suva, Fiji (referred to as the 'Suva' location). This site is the same as the Suva site described for the analysis done on taro (Section 7.2). The climate data for both the Suva and Nadi sites are contained in Figure 32 for convenience. The Suva location represented a relatively wet location within Fiji, so simulations were repeated using climate data for a second site with lower average annual rainfall of ~two-thirds that of Suva, at Nadi (Figure 32). To capture seasonal climate variability effects, each baseline scenario was run over a 32 year (Suva) or 27 year (Nadi) time period. When scenarios were simulated using the Suva or Nadi climates, climate information was the only input that changed and all other management and soil properties were used consistently between locations.

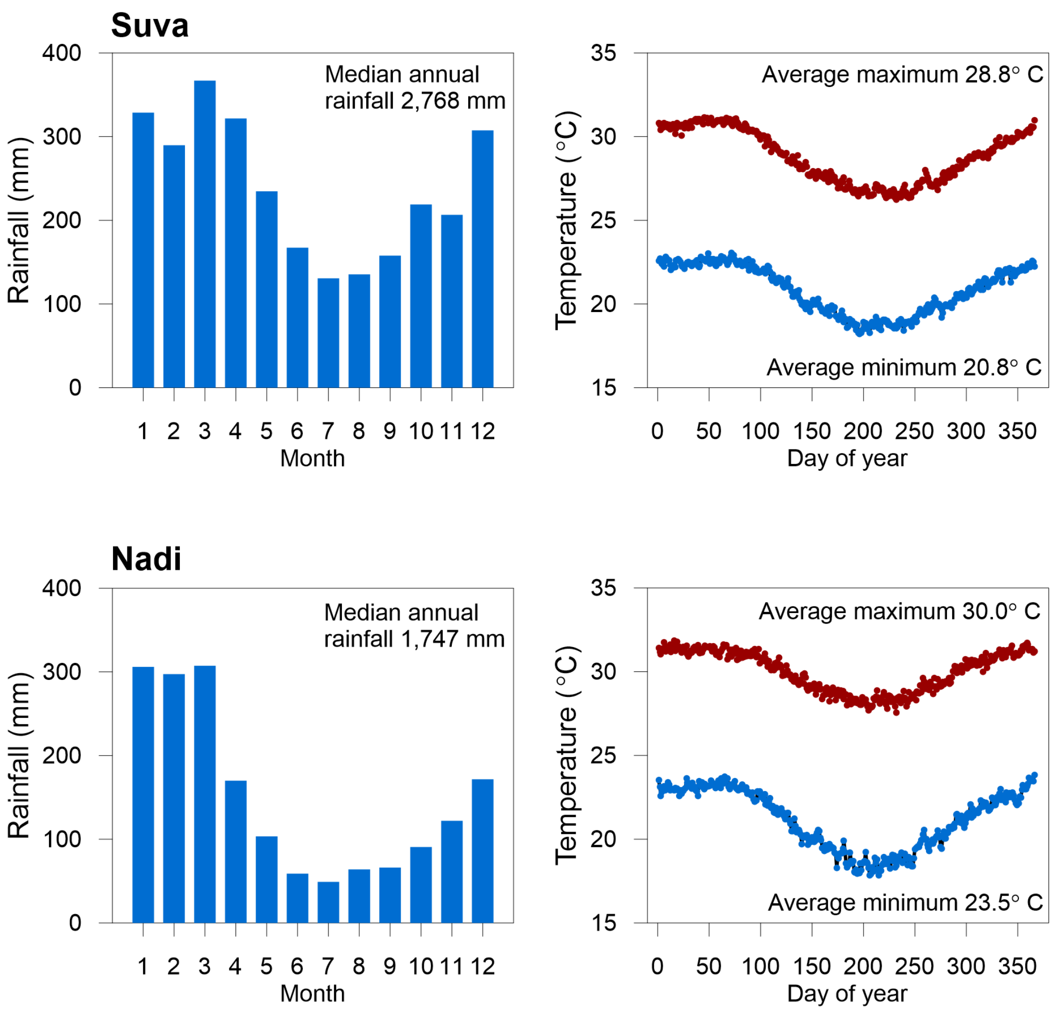


Figure 32. Average monthly rainfall totals and average daily minimum and maximum temperatures at Suva (1985-2016) and Nadi (1983-2009), Fiji.

Key physical and chemical soil properties that were used to parameterise the Cassava model at Suva (Table 9). All scenarios simulated at both Suva and Nadi use the Suva soil properties.

Table 9: Key site-specific soil chemical and physical properties at the Koronivia Research Station, Suva and used for all simulations with the cassava prototype at all locations

Depth interval	BD	DUL	LL	PAWC	Organic C	NO_3	NH4	pH
(cm)	(g/cc)	(mm/mm)	(mm/mm)	(mm)	(%)	(kg/ha)	(kg/ha)	
0-15	1.14	0.47	0.29	26.3	1.0	3.0	1.0	7.5
15-30	1.24	0.43	0.29	21.2	0.9	3.0	1.0	7.5
30-60	1.0	0.51	0.29	67.2	0.9	4.0	1.0	7.5
60-90	1.05	0.50	0.29	59.1	0.9	4.0	1.0	7.5
90-120	1.01	0.51	0.3	33.6	0.8	3.0	0.5	7.5
120-150	1.01	0.51	0.31	3.6	0.5	3.0	0.5	7.5

7.3.2 Climate change scenarios

To explore the impact of climate change on cassava yields, a range of possible future temperature, rainfall and atmospheric CO_2 projections were imposed on the baseline scenarios. These projections were made relative to historical temperature and rainfall (Figure 32) and a baseline CO_2 concentration of 400 ppm. The climate projections used were the same as those described for taro (Section 7.2.2).

7.3.3 Adaptation scenarios

Adaptation scenarios were developed that had potential to improve cassava yields under historic climates and in response to the climate change. The scenarios included variations in the management of N fertiliser, planting window, planting density, crop duration and the addition of irrigation (Table 10). For simplicity, the simulated yield response of cassava to the adaptation scenarios is restricted to the baseline and the most yield-limiting climate change scenario.

7.3.4 Cassava Baseline results

The range of simulated annual cassava yields was similar at Suva and Nadi, from 9 to 23 t/ha at Suva and from 9 to 24 t/ha at Nadi (Figure 33). However, yield variability was reduced for the higher rainfall location of Suva, resulting in an average yield at Suva of 21 t/ha (standard deviation 2.7 t/ha) compared to 19 t/ha (standard deviation 3.9 t/ha) at Nadi.

At both locations, low yields of 9-12 t/ha occurred in low rainfall years that received 46-69 % of median rainfall (the year 1999 at Suva, and years 1987, 1998 and 1999 at Nadi).

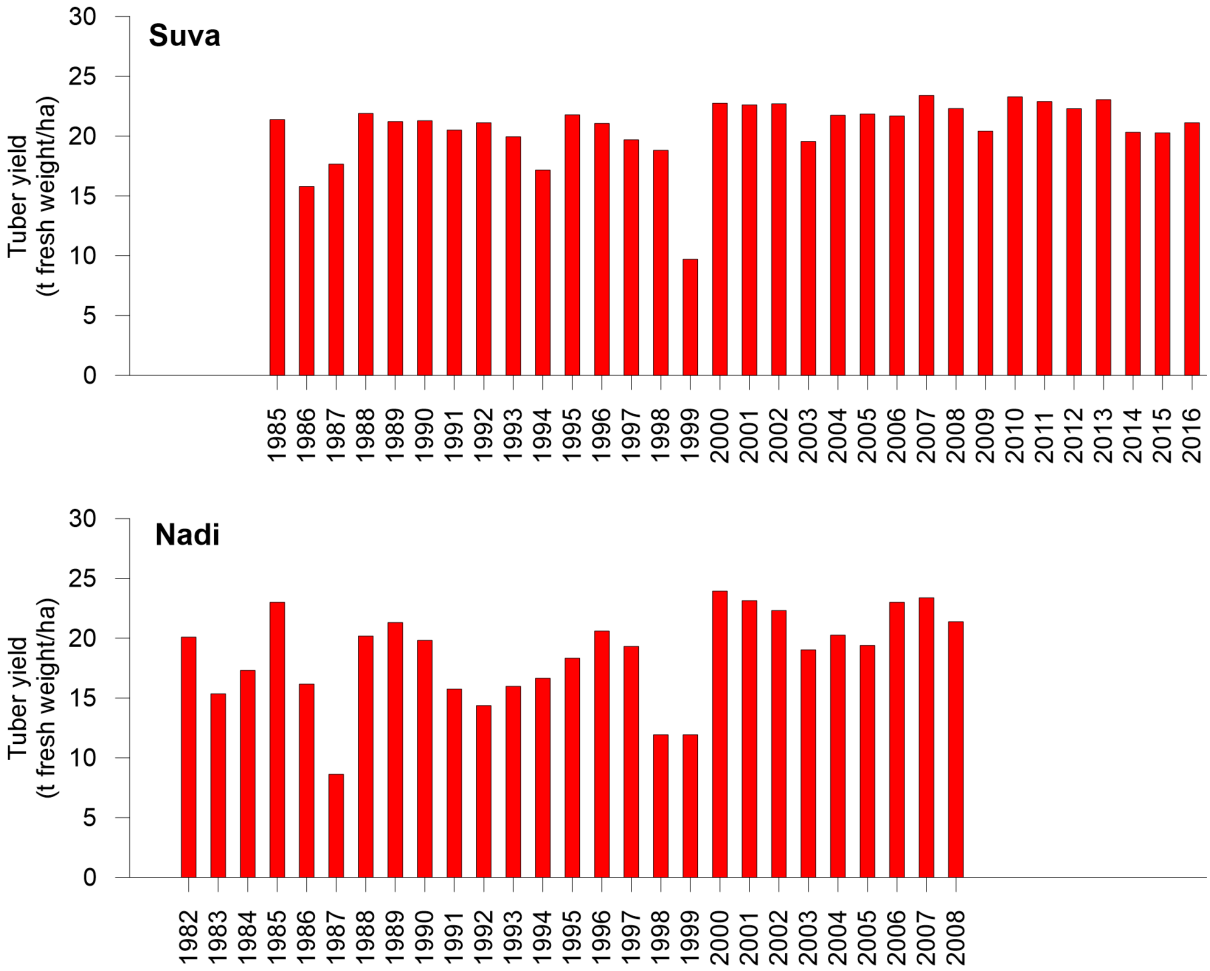


Figure 33. Simulated annual cassava yield at Suva and Nadi for the baseline scenarios

7.3.5 Cassava response to future climate scenarios

Response to declines in future rainfall

There was essentially no effect of projected decreases in rainfall of up to -15% upon the average or range of simulated cassava yields for Suva or Nadi (< 1 t/ha Figure 34). Projected rainfall amounts therefore remained adequate for crops to attain the same average yield within baseline temperature and CO_2 concentrations at each location.

Different cassava varieties can be harvested at a range timescales from 5 and 24 months. The 9 month maturation period for the cassava variety used here is likely to provide some opportunity for the crop to rover after drought stress. Cassava varieties that have a shorter maturation period may be more sensitive to declines in rainfall, but this could not be tested at this time.

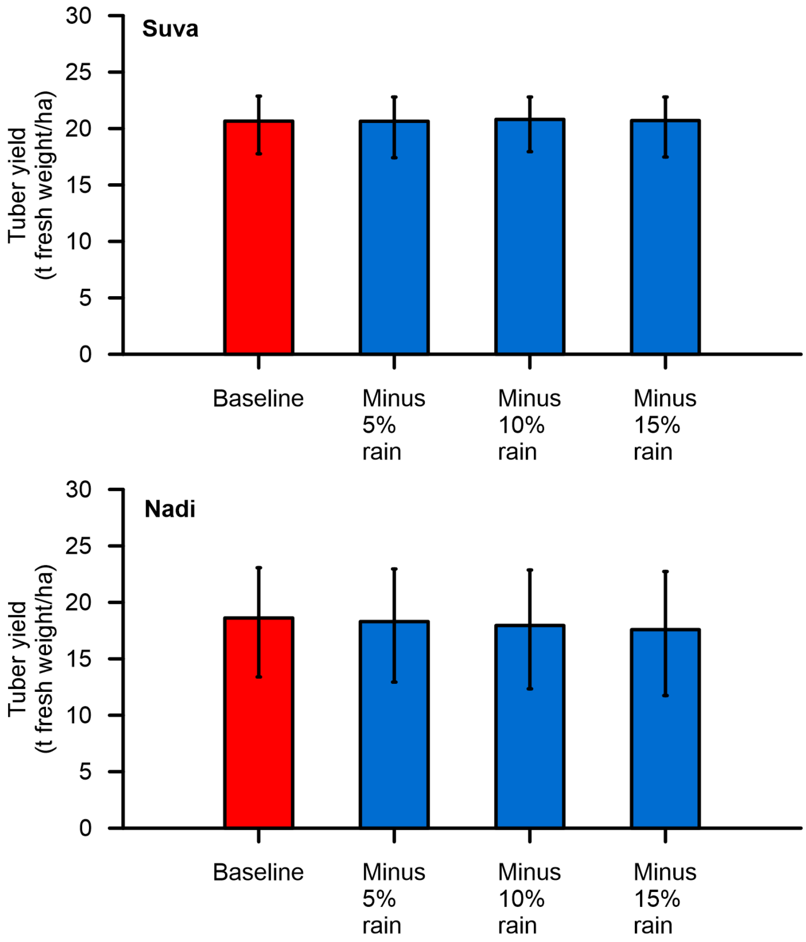


Figure 34. Average cassava yield simulated at Suva and Nadi for the baseline (red) and future rainfall decline (blue) scenarios. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Response to increased future temperature

Average cassava yields increased by 1.7, 1.2 and 1.1 t/ha at Suva, and by 0.9, 1.2 and 0.4 t/ha at Nadi, in response to increases in temperature of 1, 2 and 3°C respectively (Figure 35). The lowest yield values (obtained in the drought years of 1999 at Suva and in 1987, 1998 and 1999 at Nadi) increased by around 1 t/ha in response to the overall increase in temperature (e.g. from 9.7 t/ha for the baseline to 10.8 t/ha for a +3°C temperature increase at Suva in 1999).

Under conditions where rainfall was not limited, the largest baseline yield at Suva (23.4 t/ha) increased by up to 3.5 t/ha under a +3°C temperature increase. However, the largest baseline yield at Nadi increased by < 1 t/ha in response to a +3°C temperature increase, as this location is water limited.

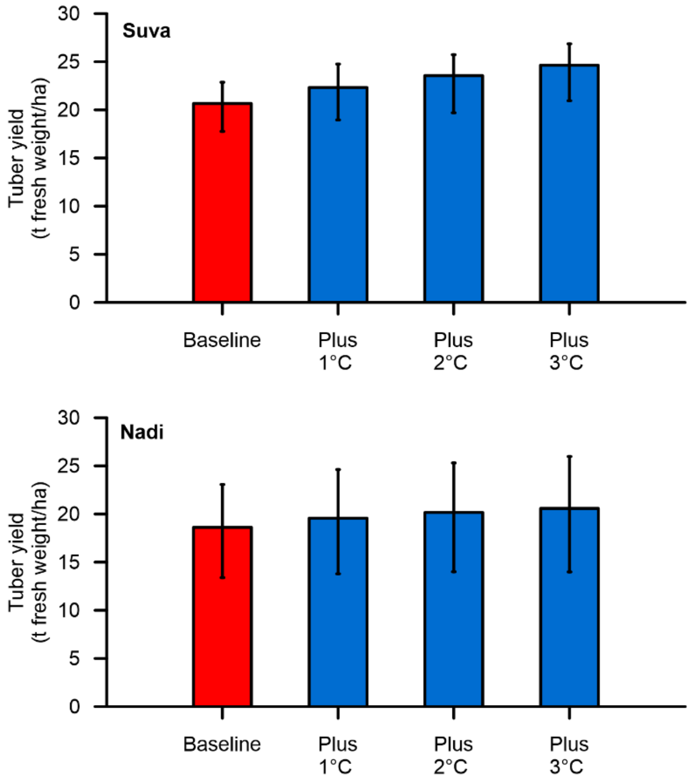


Figure 35. Average cassava yield simulated at Suva and Nadi for the baseline (red) and future temperature increase (blue) scenarios. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

The increase in cassava yield in response to increased temperatures resulted from an increased rate of progression of the cassava crop through successive developmental phases and a longer period spent in the tuber development phase (Figure 36).

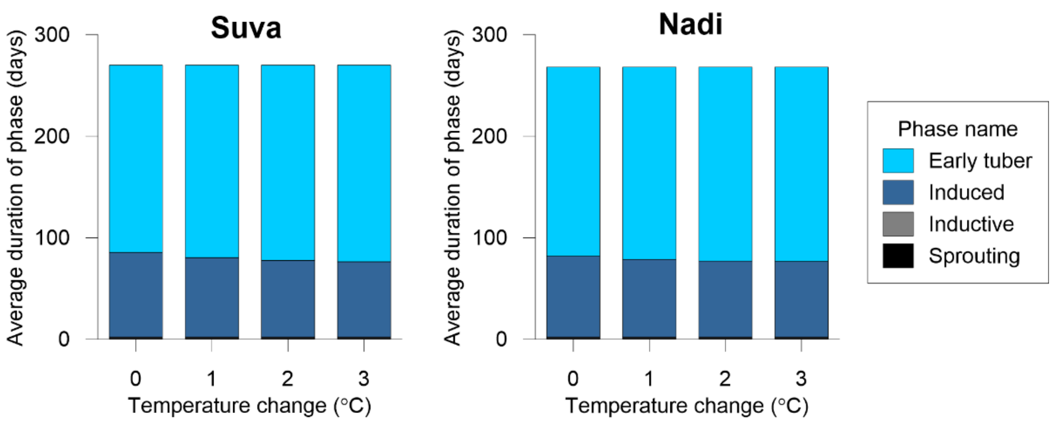


Figure 36. Average duration for cassava crops within the sprouting, inductive, induced and early tuber crop phases simulated at Suva and Nadi in response to projected increases in temperature of 1-3°C. The duration of the sprouting and inductive crop phases average a single day each. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively.

The greatest yield response occurred in response to a 1°C increase in temperature, resulting in an additional five days in tuber development at Suva and an additional three days in tuber development at Nadi. For an average temperature increase of 3°C, the length of tuber development increased on average by nine and five days for Suva and Nadi, respectively. These results contrast to those of taro because cassava did not reach maturity during the simulation phase; it thus continued to accumulate tuber biomass rather than reach an earlier maturity in response to the increase in temperature. The simulated increase in yield of cassava in response to increased temperature could therefore be substantially less or result in a decrease in yield for short-duration varieties (depending on the time of harvesting).

Response to increased future CO_2

There was essentially no yield response to increases in CO_2 concentrations for cassava at Suva or Nadi (Figure 37). The cassava prototype includes generic crop responses to increases in CO_2 reflecting a typical 'CO_2 fertilisation' response for a C3 crop. However, other work (Section 7.4) has found that cassava yields increase in response to increased CO_2 concentrations. These responses have yet to be fully incorporated into the APSIM cassava prototype, and thus the model requires further development before it can accurately represent the response of yield to change in CO_2 concentrations.

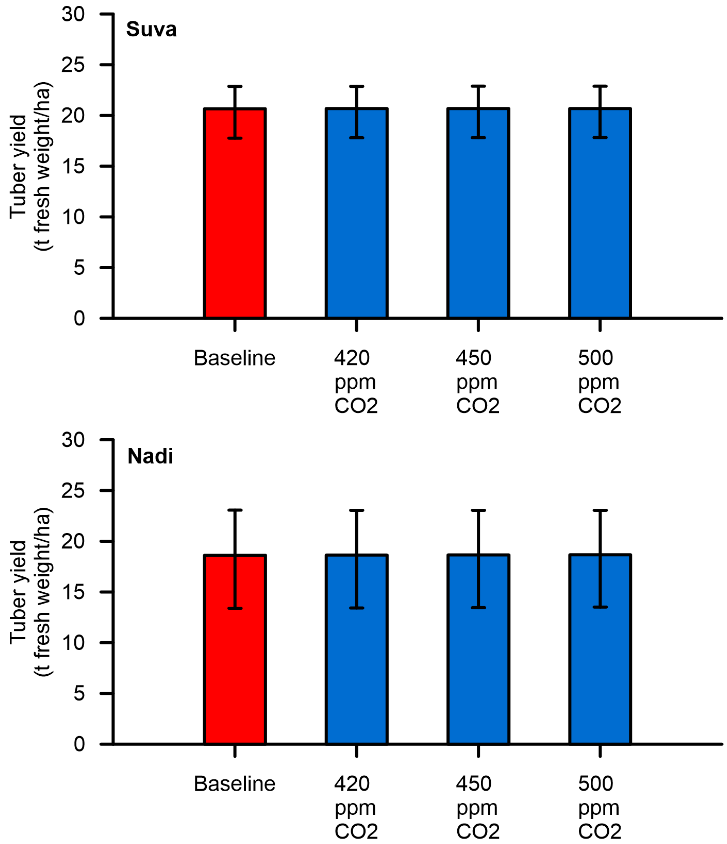


Figure 37. Average cassava yield simulated at Suva and Nadi for the baseline (red) and future CO_2 increase (blue) scenarios. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Response to combined scenarios of temperature, rainfall and CO_2

Cassava yields increased in response to all simulated combinations of rainfall, temperature and CO_2 concentrations at Suva (Figure 38). These increases were dominated by the crop response to increased temperature, consistent with the response to this factor when simulated in isolation from other changes in climate (Figure 32). Changes in rainfall and CO_2 concentration are likely to have had little effect on yield in the integrated scenarios at Suva, given crop responses to these factors in isolation (Figures 31 and 37). The future climate combinations had little effect on average yield at Nadi (Figure 38). For this drier location, the potential increase in yield from increased temperatures (Figure 35) was mitigated by loss of production resulting from decreases in rainfall.

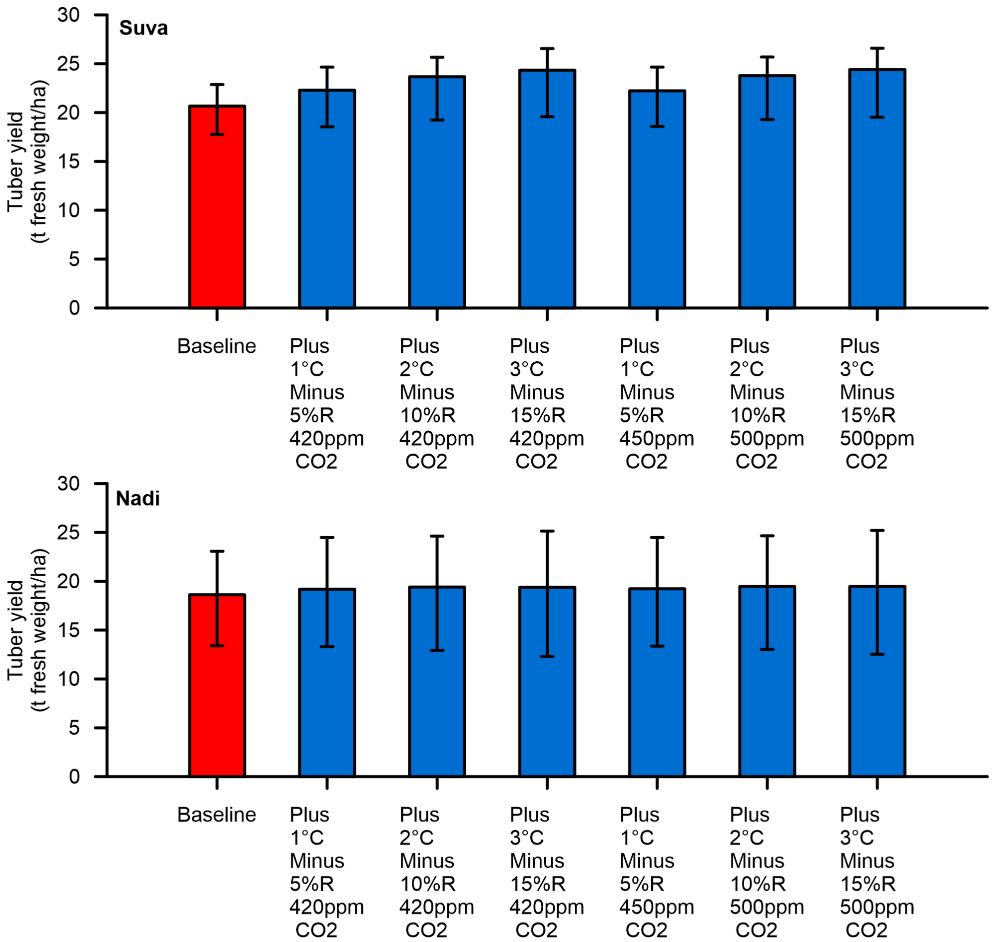


Figure 38. Average cassava yield simulated at Suva and Nadi for the baseline (red) and combined future changes in temperature, rainfall (R) and concentrations of CO_2 in combination (blue) scenarios. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

The response of cassava tuber yield to the individual and combined effects of climate factors at Suva and Nadi is summarised in Table 10. Yields at both locations were unchanged relative to the baseline in response to changes in CO_2 concentrations, and there was a small (~0.1 t/ha) decline in yield for crops grown in response to a 5% decline in rainfall simulated in isolation. For all other scenarios (i.e. those associated with an increase in temperature), average yield increased relative to the baseline value by up to 4 t/ha at Suva and by up to 2 t/ha at Nadi.

The effect of adaptation scenarios on cassava yields is simulated for (a) baseline management, and (b) the most yield-limiting future climate scenario. For (a), adaption scenarios that increase baseline yields based on historical climate records indicate practices with potential to be adopted immediately to improve current yields.

Adaptation scenarios that improve future yields in (b) indicate practices that may be adopted in future to adapt to climate change. For the purposes of (b), the most yield-limiting climate combination selected for this comparison was the +1°C_-5%_420ppmCO_2 combination.

7.3.6 Cassava adaption options

Extra N fertiliser

Cassava production can involve low inputs of N fertiliser, usually applied in small amounts by hand either at sowing or as a top-dressing 2-3 months after planting. For this adaptation simulation, the rate of N fertiliser was approximately doubled to 45 kg N/ha (Table 8). When combined with the amount of 25 kg N/ha soil mineral N provided through model resets at planting (Table 8), the total mineral N from combined sources approached N fertiliser rates recommended by the Fijian Ministry of Agriculture (Poasa Nauluvula, pers. comm., 26/5/2017).

This increase in N fertiliser rate had essentially no effect on cassava yield in either the baseline or most climate-limiting future scenario at either location (<1 t/ha; Figure 39). However, for soils with lower organic carbon than used in this study (Table 8) and in real conditions without resets in which organic carbon rundown could occur, then it is possible that additional N fertiliser could generate an increase in yield.

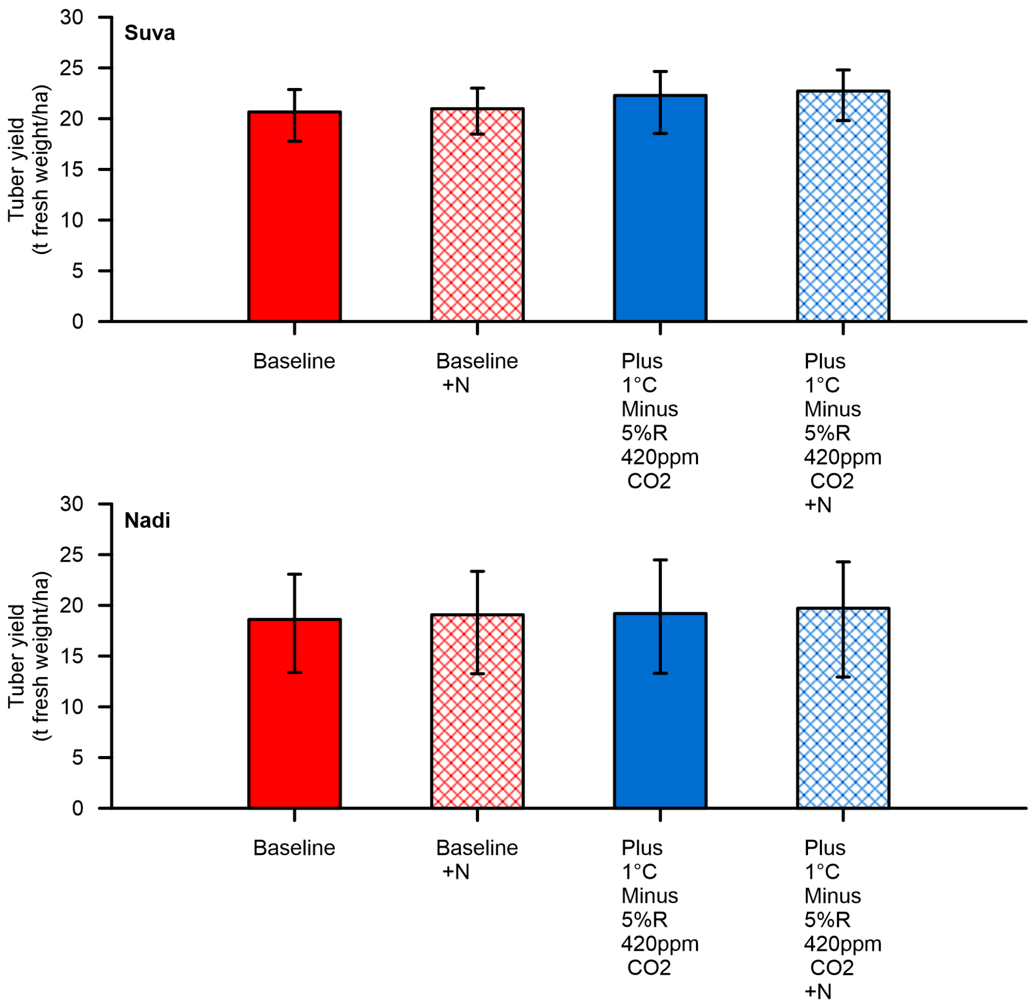


Figure 39. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with additional N fertiliser adaptation scenario (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with additional N fertiliser (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Introduction of irrigation

Irrigation of cassava had essentially no effect on average cassava yield at Suva in either the baseline or most climate-limiting future scenario (<1 t/ha; Figure 40), although it reduced the range of yields between the 10th and 90th deciles by ~3 t/ha.

This result was consistent with the absence of any effects on cassava yield of reducing the amount of rainfall at Suva (Figure 31), indicating that adequate rainfall is received at Suva on average under current and future climate projections. However, for the drier location at Nadi, the irrigation adaptation option improved average cassava yield in both the baseline and most climate-limiting climate scenario (Figure 40). Cassava yields increased in response to irrigation by ~3 t/ha in both the baseline and the future scenario, and reduced the range of yields between the 10th and 90th percentiles by ~6 t/ha.

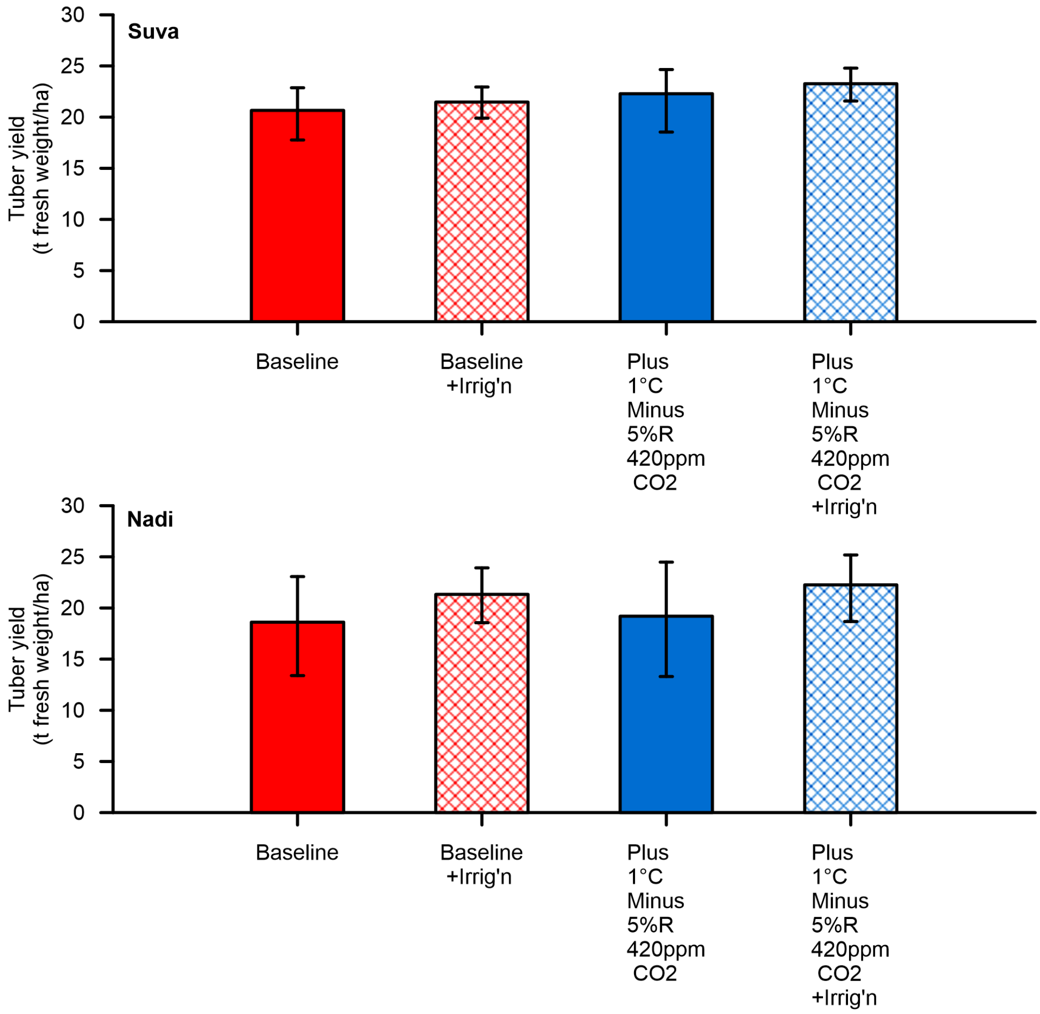


Figure 40. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with irrigation adaptation scenario (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with irrigation (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Irrigation and extra N fertiliser

The application of extra N fertiliser and irrigation in combination had little (≤1 t/ha) effect on cassava yields at Suva in either the baseline or most climate-limiting future scenario (Figure 41), consistent with the absence of a response to these management practices applied in isolation (Figures 39 and 40). This outcome differed at Nadi, where a response to both additional N fertiliser and irrigation occurred, resulting in an increase in average yield and decrease in yield variability (Figure 41).

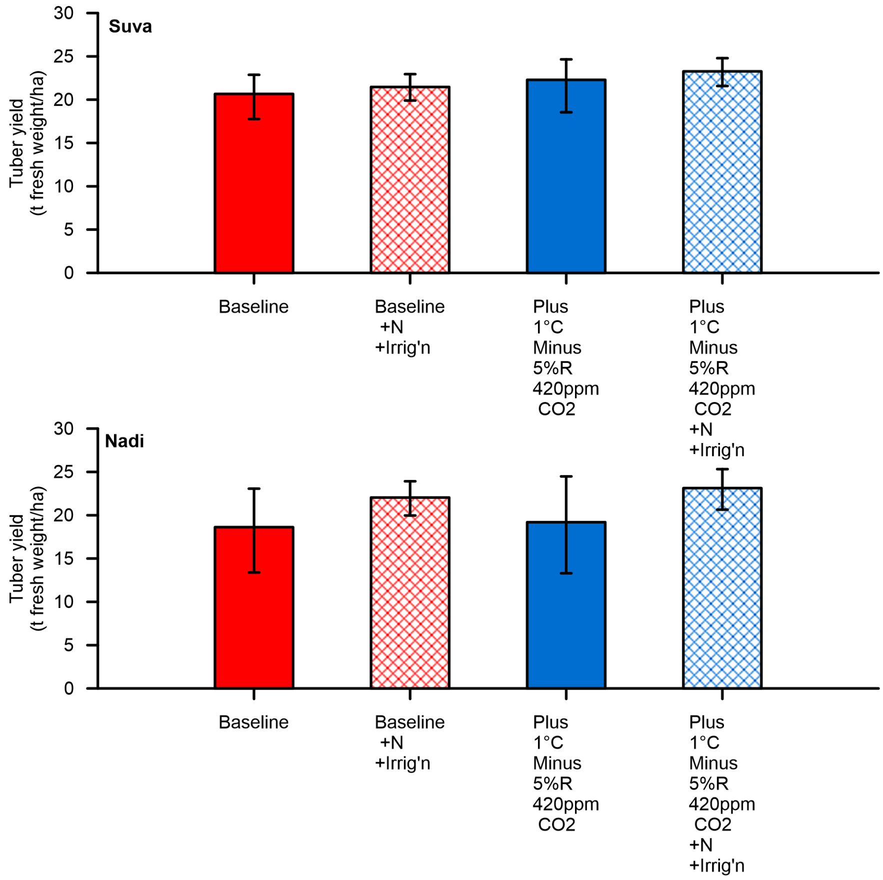


Figure 41. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with additional N fertiliser plus irrigation adaptation scenario (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with additional N fertiliser plus irrigation (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Modified planting window

The yield of cassava crops in both the baseline and most climate-limiting future scenario increased, and the variability of yields decreased, at both Suva and Nadi in response to a change in planting window from March-May to July-September (Figure 42). The July-September planting occurred at the beginning of the wetter time of year (Figure 32), providing the crop with better opportunity for establishment and also an increased likelihood of receiving higher in-crop rainfall than from the baseline planting window.

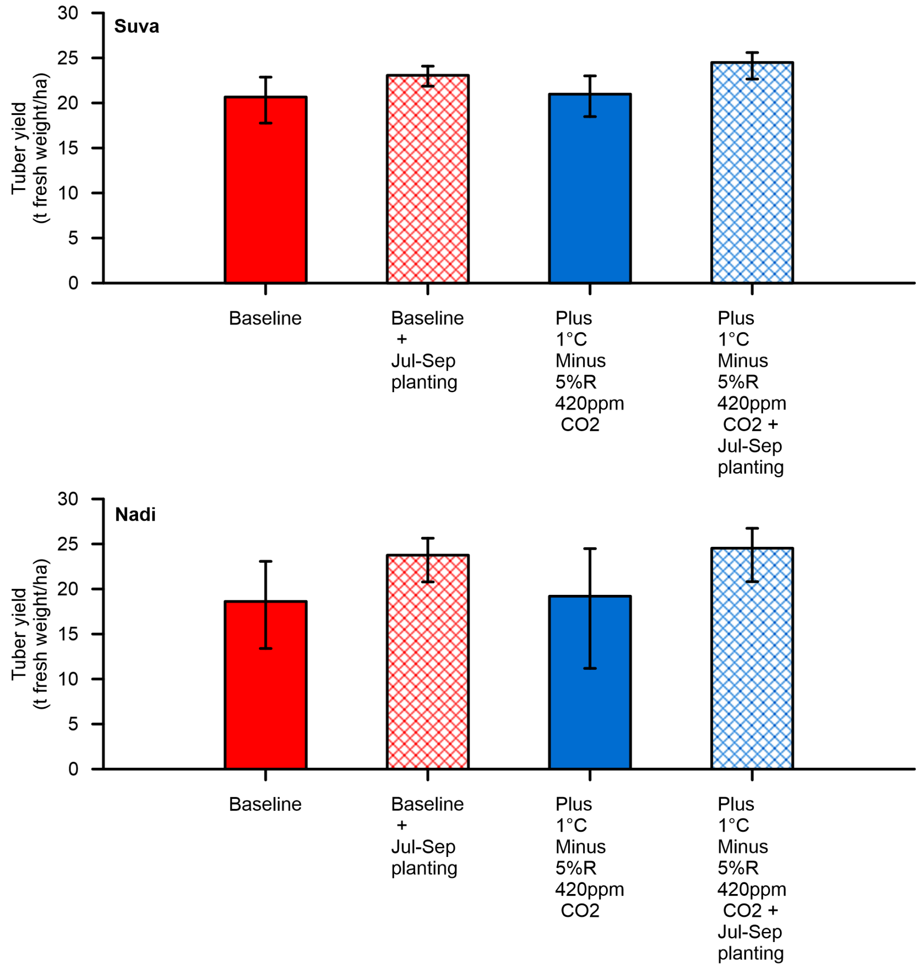


Figure 42. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with different planting window (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with different planting window (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Increased plant density

The yield of cassava crops in both the baseline and most yield-limiting future climate scenarios at Suva and Nadi improved in response to an increase in planting density from 2 to 3 plants/m^2 (Figure 43).

The increase in yield could be associated with a decrease in tuber size as plants become more crowded, which may have implications for the marketability of tubers. However, the effect of planting density on tuber size was not able to be simulated in the current cassava prototype because individual tuber size is not available as a model output.

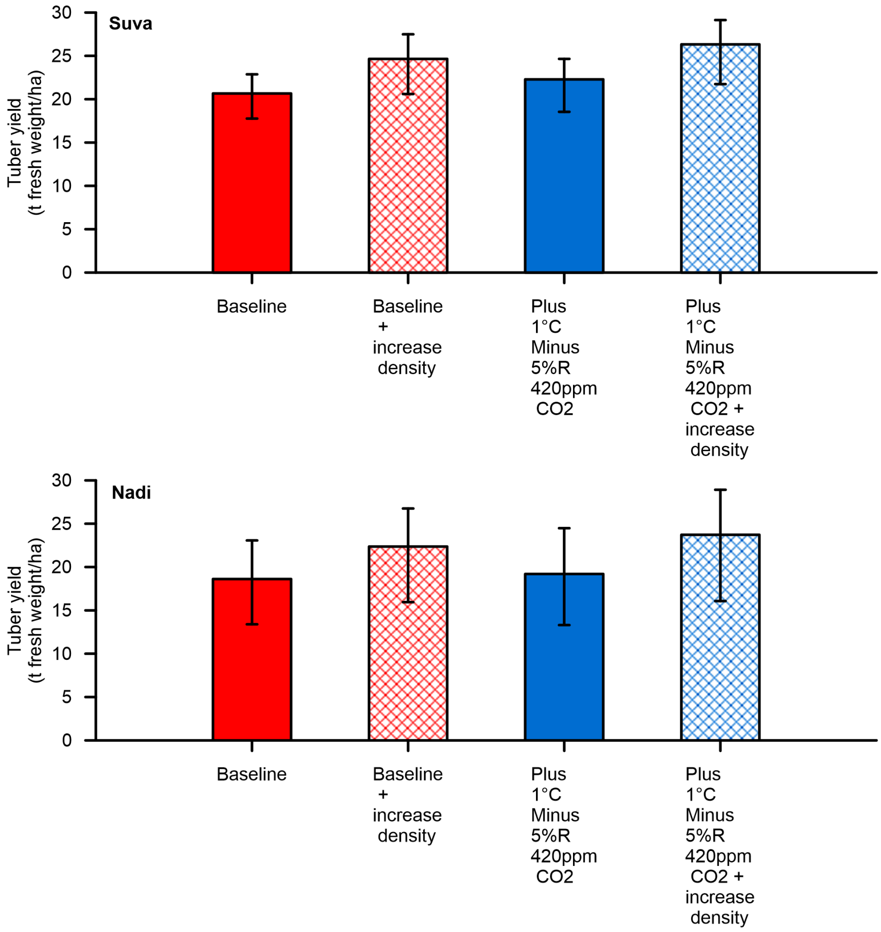


Figure 43. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with increased planting density (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with increased planting density (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

Extended crop duration

The yield of cassava crops increased at both Suva and Nadi in response to an increase in crop duration from nine to twelve months (Figure 44).

This outcome is likely to be variety-specific. For example, the simulated cassava variety in this study reached maturity at ~640 days after sowing, and so extending the crop duration from nine to twelve months led to a greater period spent in tuber development.

However, cassava is a perennial plant and different cassava varieties can be harvested from between five months and two years of age, as well as being harvested during tuber elongation (depending on need).

It is therefore unlikely that cassava yields would increase in response to an increase in crop duration for varieties that mature rapidly (i.e. at or before nine months after planting in this study).

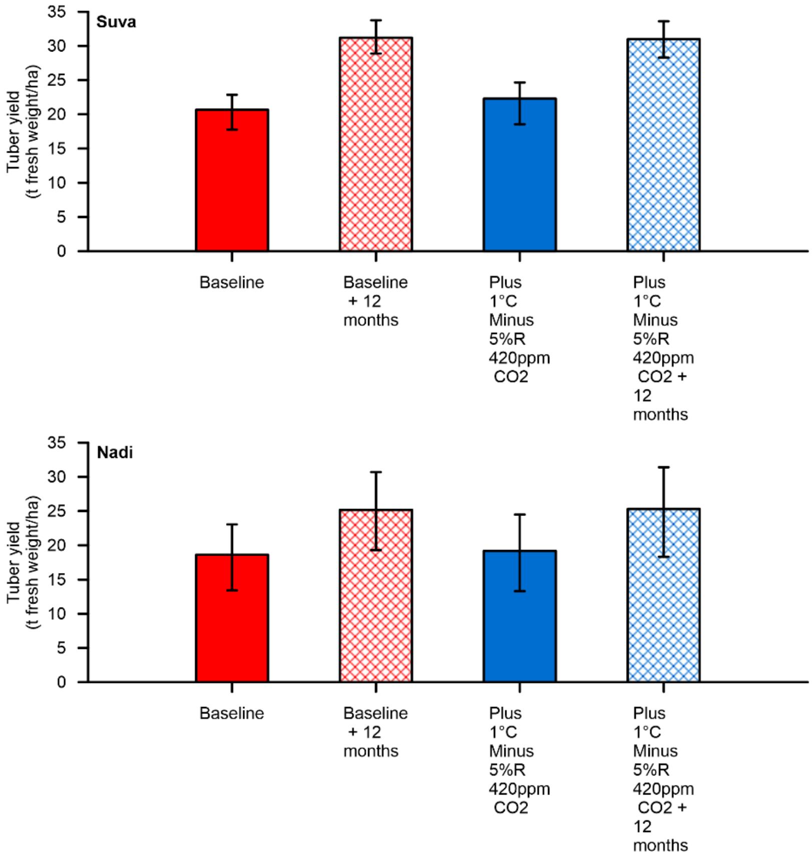


Figure 44. Average cassava yield simulated at Suva and Nadi for the baseline (red), baseline with increased crop duration (hatched red), most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2; blue), and most yield-limiting future climate with increased crop duration (hatched blue). Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively. Error bars depict the 90th and 10th percentile yields.

In summary, the average cassava yield increased in response to all adaptation options relative to yields simulated in both the baseline and most yield-limiting future climate scenarios (Table 10). The potential for increased yields to occur was greater at Suva (≤ 10.5 t/ha) than at the drier location of Nadi (≤ 6.6 t/ha).

The largest increase in yield occurred in response to the adaptation option of increasing the crop duration from nine to twelve months at both locations. For this option, yield variability (indicated by the range in values between the 10th and 90th percentile yields) remained similar to that for yields without adaptation management, but the 10th percentile yield also increased. This practice represents an adaptation option that could be adopted now and under future climates, depending on the time to maturity of the variety grown (unsuited to fast-maturing varieties).

A smaller increase in average yield of between <1 t/ha and up to 4-5 t/ha occurred for cassava crops grown using the other adaptation options. For both locations, the variability in yields decreased when the amount of water available to crops was increased by either applying irrigation or by planting at the beginning of the wet season using a window from July-September.

Table 10: Average, 10th decile and 90th deciles, and range between the 10th and 90th decile yields of cassava crops subjected to the baseline and most yield-limiting future climate (+1°C, -5% rainfall, 420 ppm CO_2) in response to adaptation scenarios at Suva and Nadi. Yields are simulated for a 32 and 27 year period at Suva and Nadi, respectively.

	Cassava yield (t/ha)							
	Suva				Nadi			
Scenario	**Avg**	**10th**	**90th**	**Range**	**Avg**	**10th**	**90th**	**Range**
Baseline scenario with historical climate + adaptation options								
Baseline	20.7	17.8	22.9	5.1	18.6	13.4	23.1	9.7
+ irrigation	21.5	19.9	22.9	3.0	21.3	18.6	23.9	5.3
+ extra N fertiliser	21.0	18.5	23.0	4.5	19.1	13.3	23.4	10.1
+ irrigation + N fertiliser	21.5	19.9	22.9	3.0	22.0	20.0	23.9	3.9
+ Jul-Sept planting window	23.1	21.9	24.1	2.2	23.7	20.8	25.6	4.8
+ 3 plants/m2	24.6	20.6	27.5	6.9	22.4	16.0	26.7	10.7
+ harvest at 12 months	31.2	28.9	33.7	4.8	25.2	19.3	30.7	11.4
Most yield-limiting future climate scenario (+1°C, -5% rainfall, 420 ppm CO_2) + adaptation options								
+1°C, -5% rainfall, 420 ppm CO_2	22.3	18.5	24.6	6.1	19.2	13.3	24.5	11.2
+ irrigation	23.3	21.6	24.8	3.2	22.3	18.7	25.2	6.5
+ extra N fertiliser	22.7	19.8	24.8	5.0	19.7	12.9	24.3	11.4
+ irrigation + N fertiliser	23.3	21.6	24.8	3.2	23.1	20.6	25.3	4.7
+ Jul-Sept planting window	24.5	22.7	25.6	2.9	24.5	20.8	26.7	5.9
+ 3 plants/m2	26.3	21.7	29.1	7.4	23.7	16.1	28.9	12.8
+ harvest at 12 months	31.0	28.3	33.6	5.3	25.3	18.3	31.4	13.1

Photo: Mature taro crop at Nishi Trading trial, Tonga.

7.4 CO_2 experimental results

7.4.1 Phenology

Taro and cassava were monitored weekly. Over the 137 days leading up to the first destructive harvest, there were observable differences between species, time point and CO_2 treatments. The height (Figure 45) of cassava plants was significantly increased in the 700ppm and 900ppm growth chambers towards the end of the study (Day 116, 130), and on day 55. Cassava plants grown at 400ppm and 500ppm were a similar height. Taro plants did not show significant height changes ($p>0.05$) at any points, but did have shorter petioles throughout the study ($p<0.05$).

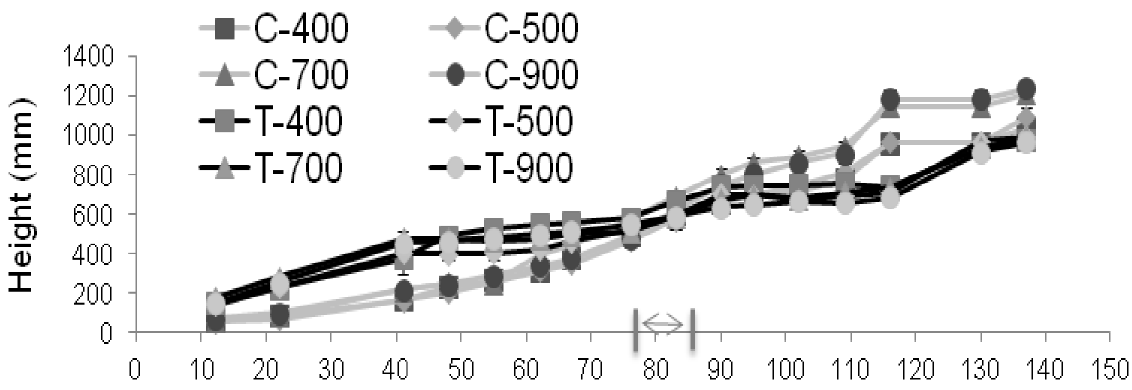


Figure 45. Height (mm) data collected from day 12-137, of taro (black line) and cassava (grey line) measured in four treatment concentrations of CO_2 (400, 500, 700 and 900ppm), error bars applied to each line as ± standard error.

Cassava plants had more leaves than taro throughout the study ($p>0.001$), with 54 leaves overall when measured at day 137, compared to taro plants that had 16 leaves overall. Cassava plants grown at eCO_2 had significantly fewer leaves on day 48 ($p=0.0035$) and 55 ($p<0.001$) but were otherwise not affected by eCO_2 concentration. The number of leaves (Figure 46) was not influenced by eCO_2 in taro plants ($p>0.05$) at any time points.

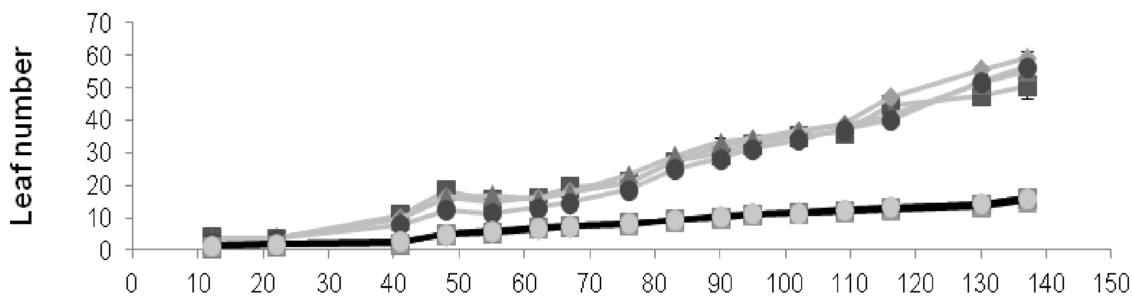


Figure 46. Leaf Number data collected from day 12-137, of taro (black line) and cassava (grey line) measured in four treatment concentrations of CO_2 (400, 500, 700 and 900ppm), error bars applied to each line as ± standard error.

Taro plants had significantly decreased leaf area (length x width) at many time points (Day 109-130), in eCO_2 chambers 500 and 900ppm, and were significantly higher in the 700ppm room earlier in the study (Day 41-55) (Figure 47). The estimated leaf area of cassava was similar across CO_2 treatments throughout the study.

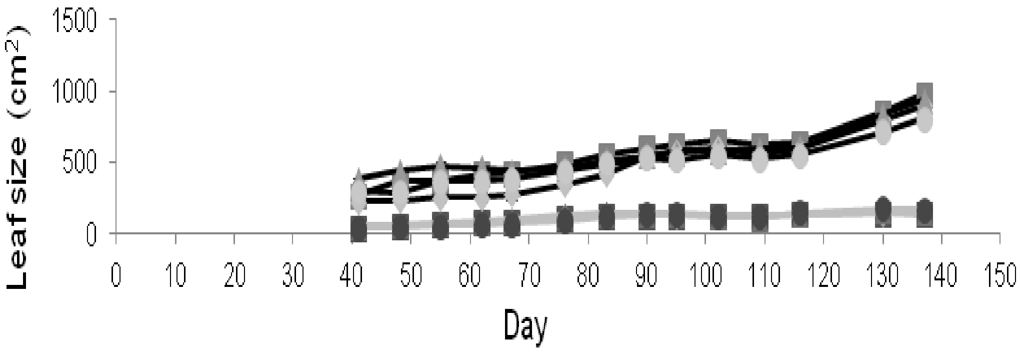


Figure 47. Leaf Number data collected from day 12-137, of taro (black line) and cassava (grey line) measured in four treatment concentrations of CO_2 (400, 500, 700 and 900ppm), error bars applied to each line as ± standard error.

7.4.2 Biomass accumulation and partitioning

Cassava and taro plants were harvested and divided into the various tissue types and weighed. A few key points are illustrated in the following figures. A more complete data set is available as an Excel spread sheet, on request. There is an increase in total biomass with increasing CO_2 concentration in both cassava and taro. In cassava, most of this increase is from 400 to 500 ppm (Figure 48). For tuber mass, this is largely associated with an increase in tuber number, consistent with previous studies (e.g. Rosenthal et. al., 2012). For taro, there is a stepwise increase in total mass, corm number and corm mass with each increase in CO_2. The proportion of mass in the main plant is not significantly different in plants from the different atmospheric CO_2 treatments.

Photo: Destructive harvest of taro at VARTC.

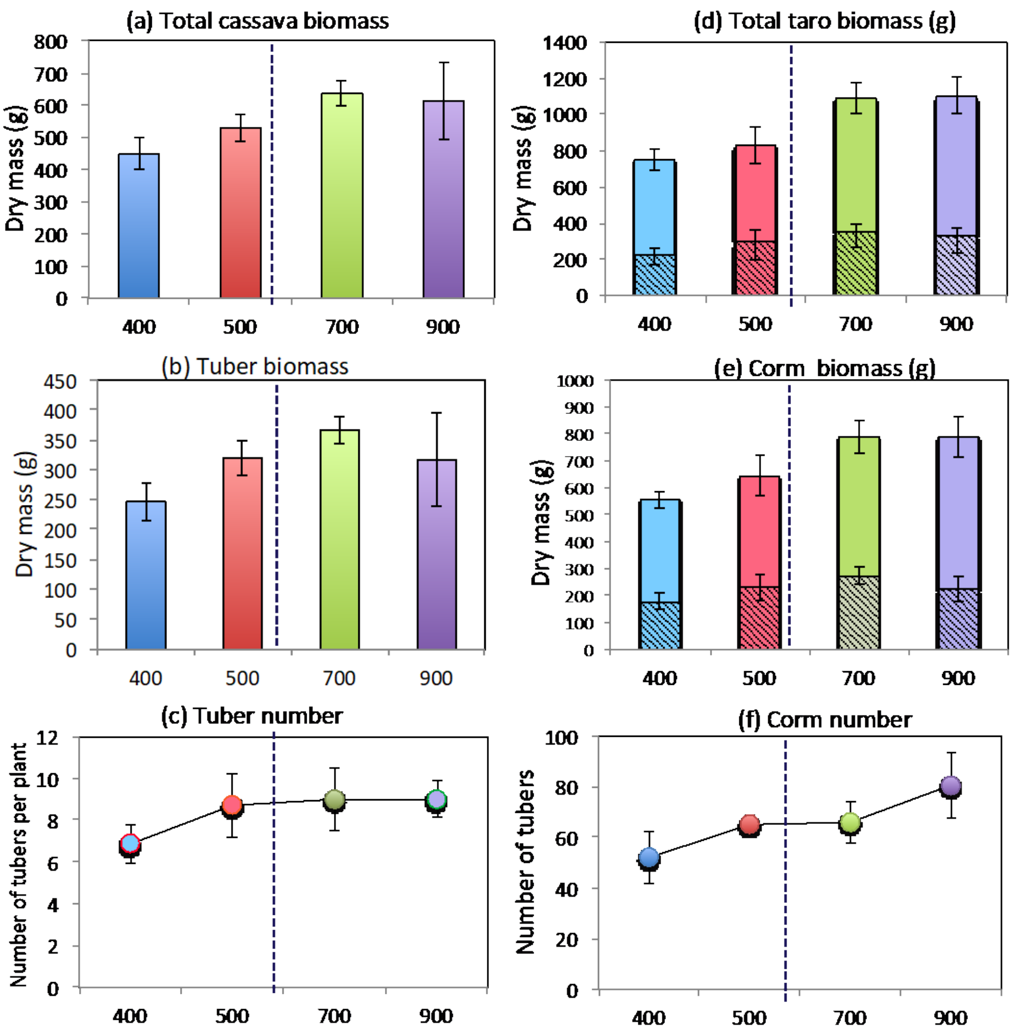


Figure 48. Key biomass and growth data from the elevated CO_2 experiment for cassava (left) and taro (right). The dashed line represents the sort of CO_2 concentration that is may be reached in the next 50 years. Most of the stimulation in growth is at these moderate concentration changes,

7.4.3 Photosynthetic rates of CO_2 experiment as an indicator CO_2 fertilisation.

The photosynthetic rate was measured in cassava and taro leaves the week prior to the final harvest, when plants were approximately 6 months and 8 months old, respectively using a Li-Cor 6400 Portable Photosynthesis Analyser (Figure 49).

Photosynthesis was measured at the CO_2 concentration that the plants were growing in (growth CO2 viz 400, 500, 700 and 900 ppm CO_2) and shows the promotion of photosynthesis at the various levels of CO_2. Photosynthesis was also measured at a common CO_2 (400 ppm). Comparing the photosynthetic rate in today's air is a measure of the photosynthetic capacity of the system and gives information on the capacity of the photosynthetic apparatus to make use of the higher levels of CO_2 in the future.

Many studies have shown that some plants reduce their investment in photosynthetic machinery and redirect resources to other activities, such as cyanide production (e.g. Gleadow et al., 1998; Gleadow et al., 2009) but this may not be always the case for cassava (Rosenthal, Gleadow et al,. 2012).

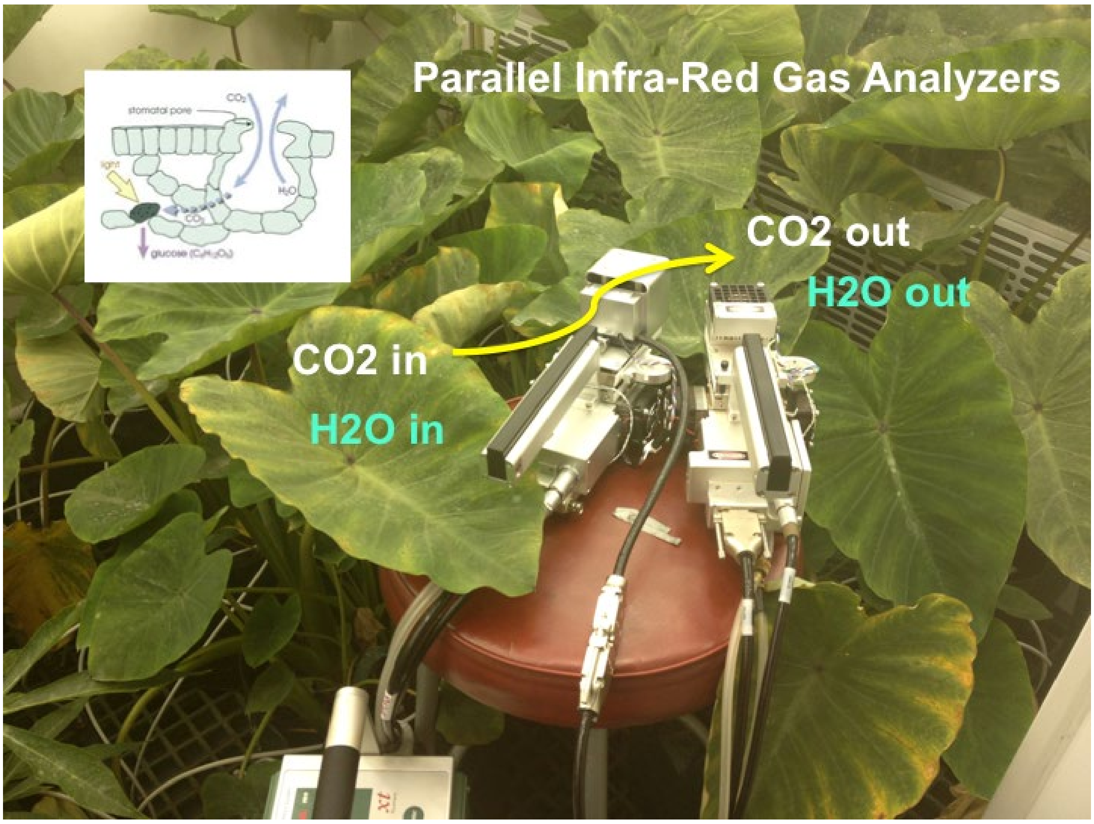


Figure 49. Two Li-Cor 6400 machines measuring photosynthetic rates on a taro leaf. A chamber is placed over the leaf. The concentration of CO2 and is measured in a flow of air entering and leaving the leaf. The change in both is used to calculate the photosynthetic rate, the rate of transpiration and the stomatal aperture using known algorithms. Normally only one machine was used, but in this case the equipment was being calibrated. Insert shows the normal flow of air in and out of a stomatal pore.

7.4.4 Gas exchange of plants grown at elevated: photosynthesis and transpiration

Plants grown at higher CO_2 concentrations overall had higher rates of photosynthesis (Figure 50) and lower transpiration rates (Figure 51). The results indicate that the most gains from CO_2 fertilisation will come in the next 30-50 years, after which the effects of rising CO_2 will be more modest. The very high concentrations of CO_2 used here (700 and 900 ppm) are beyond what can reasonably expected if the current plans for moderating carbon emissions are met. They are, however, important for useful understanding the mechanisms governing plant responses and for modelling plant behaviour as they ensure any conclusions are interpolations, not extrapolations.

The photosynthetic responses observed here for cassava are consistent with other studies on cassava (e.g. Rosenthal *et. al*., 2012). There are no equivalent data available for comparison for taro, as this is to our knowledge the first experiment of its type. For cassava, the most benefit in terms of higher photosynthetic rates was from 400 to 500ppm, with no further increase in rates at 700 or 900ppm, when measured at growth CO_2 (Figure 50a). For taro there was a progressive increase in photosynthetic rate at growth CO_2 concentrations from 400, 500, 700 and 900 ppm (Figure 50b). Taro did not show the decrease in photosynthetic rates when measured at a common (today's) CO_2 concentration that was seen cassava (Figure 50c, d). There was a small decrease at 900 ppm, indicating that taro will have the capacity to utilize the increasing levels of CO_2 with a higher sensitivity to CO_2 fertilisation.

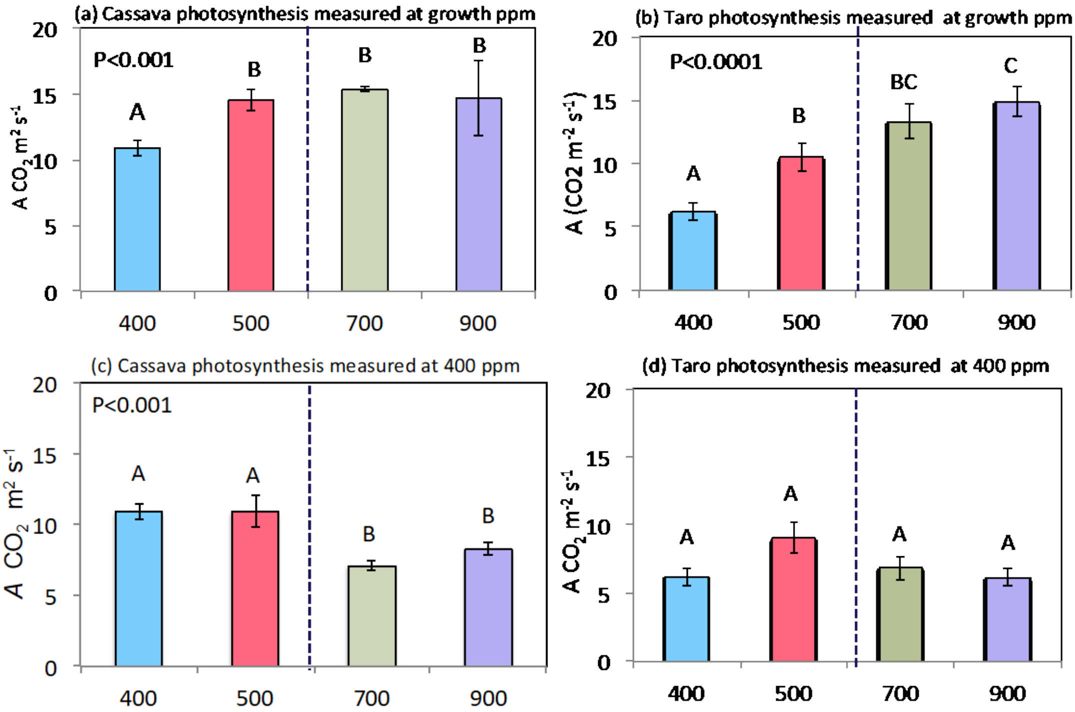


Figure 50. Photosynthetic rates (A, CO_2 Assimilation) for 6 month old cassava and taro growing the CO_2 experiment. Bars to the left of the line represent photosynthesis in today's air and at 500 ppm, a target that will be reached around 2050 with status quo emissions. (a) and (b) Photosynthetic rate of plants grown and measured at 400, 500, 700 and 900 ppm CO_2; (c) and (d) Photosynthetic rates of plants grown at various CO_2 concentrations but measured at a common concentration of 400ppm. This is a measure of acclimation, i.e. a decrease means that the plants have downsized their photosynthesis system. Bars with the same letter are not significantly different at the 95% level. Values are the mean of 6 replicates ± 1SE.

We measured transpiration rates (T), the rate of water loss, and stomatal conductance (gs) because stomata are known to be sensitive to CO_2, closing when CO_2 concentrations are high and opening when CO_2 is low. This commonly leads to an observed increase in water use efficiency (i.e. the amount of carbon fixed per water lost) in plants grown at elevated CO_2. The data for cassava mirrored the other gas exchange data, i.e. there was no significant effect from 400 to 500 ppm (average= 0.253 ± 0.012) but stomatal conductance was significantly lower at the extreme conditions of 700 and 900 ppm (average 0.127 ± 0.019). The positive side of this effect is that transpiration is also significantly lower in the 700 and 900 plants (Figure 51), with the net result that cassava plants use less water to achieve the same amount of biomass (i.e. they are more water efficient). We detected no significant difference in stomatal conductance in taro, with an average of 0.093 ± 0.014 mol H_20 m^{-2} s^{-1} and only a moderate reduction in transpiration. This makes sense, given that taro is a swamp plant and not well adapted to dry conditions.

In conclusion, taro showed a greater photosynthetic response to higher CO_2 levels, but that cassava had the greatest response in terms of increased water use efficiency. Thus, if water is limited, these data suggest that cassava is likely to perform better at high CO_2, but if there is ample water, then taro would be the better choice.

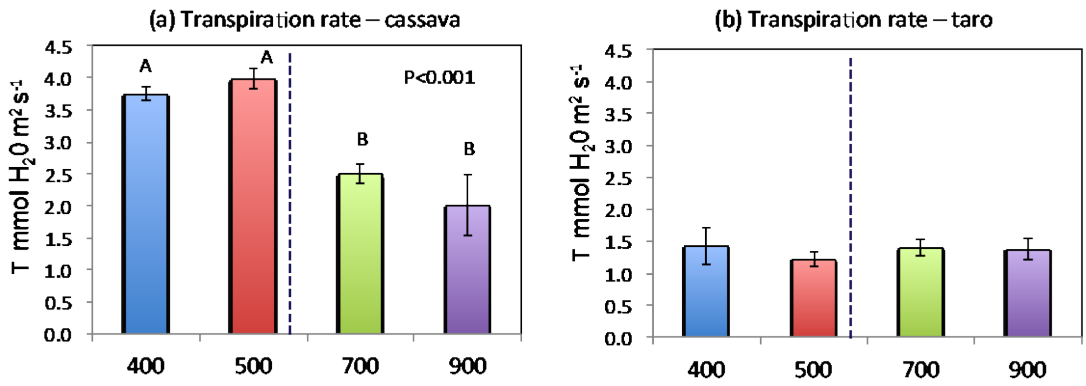


Figure 51. Rate of transpiration (T, water lost) for 6 month old (a) cassava and (b) taro growing the CO_2 experiment. Dotted lines are positioned at 550 ppm CO2, a level likely to be reached given current emission scenarios. Bars with the same letter are not significantly different at the 95% level. Values are the mean of 6 replicates ± 1SE.

7.4.5 Anti-nutrient analysis for cassava (cyanogens) and taro (Oxalic acid)

Linamarin levels in cassava were measured using the evolved cyanide method, sometimes referred to as the cyanide potential (HCNp). There was no significant difference in HCNp in cassava plants grown in the different atmospheres, apart from a small, non-significant decrease in HCNp in the leaves at 700 and 900 (Figure 52). This confirms work by Gleadow and others in free-air CO_2 experiments that HCN on a per mass basis does not change in tubers and leaves (Rosenthal *et. al.*, 2012) and for tubers reported in Gleadow *et. al.* (2009) and consistent with studies of other cyanogenic species. The variety of taro grown in this experiment was not cyanogenic.

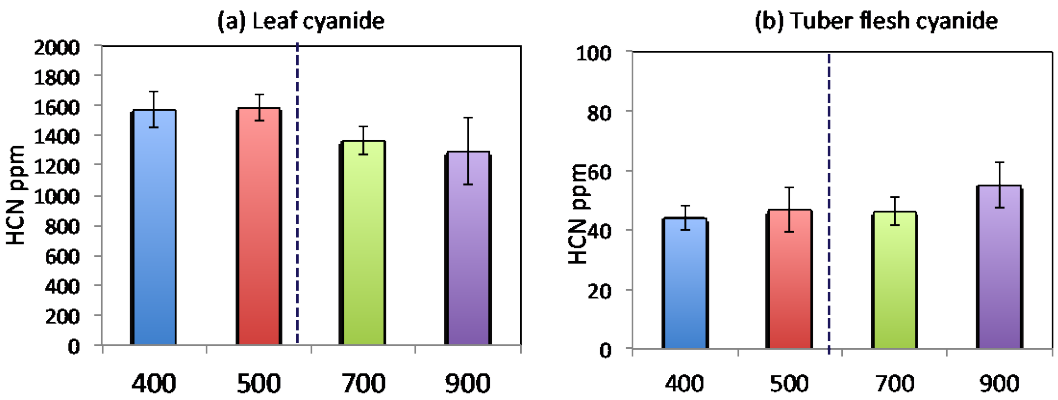


Figure 52. Concentration of hydrogen cyanide in the leaves (a) and tubers (b) of measured 6 month old cassava plants grown in the elevated the CO_2 experiment. Dotted lines represent 550 ppm CO2, a level likely to be reached given current emission scenarios. Values are the mean of 7 replicates ± 1SE.

Oxalic acid occurs naturally in all plants, but in taro it forms into needle like shards of calcium oxalate that can irritate the throat and sometimes interact with other proteins to initiate an allergic reaction and throat swelling. We found a highly significant decrease in oxalic acid with increasing CO_2 (Figure 53). This means that taro may become more palatable in future. This is the first time oxalic acid has been measured on taro growing in a controlled environment experiment.

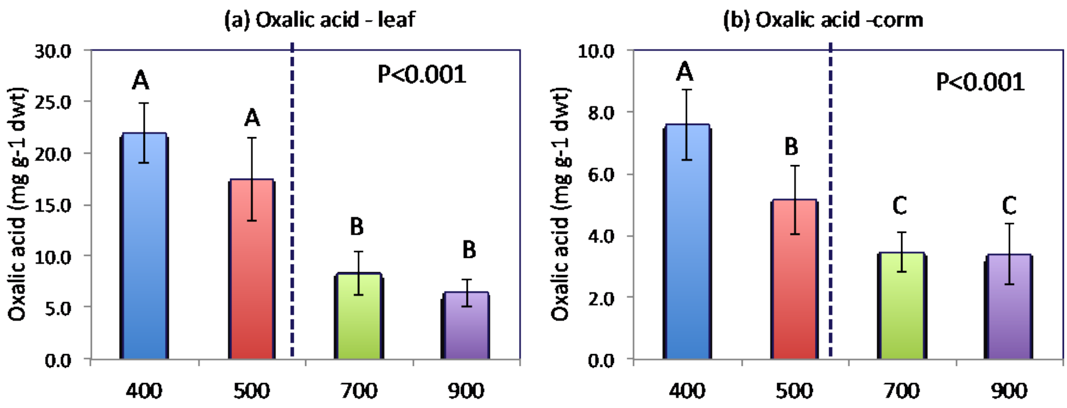


Figure 53. Concentration of oxalic acid in the fully expanded leaves (a) and corms (b) of the main plants of 6 month old taro grown in the elevated the CO_2 experiment. Values are the mean of 7 replicates ± 1SE. Means with the same letter are not significantly different.

7.4.6 Total N and allocation of N to cyanide in cassava

We measured total elemental N (% dry mass) as a proxy for protein in the fully expanded leaves and underground storage organs of cassava and taro. Leaves grown at ambient CO_2 had a N concentration of about 4% N, indicating that the plants were not N limited, but neither was the availability of N high (Reuter and Robinson 1997 Plant Analysis: An interpretation manual). Leaf N of cassava plants was reduced to 3.8%, 3.4% and 3.0% in the elevated CO_2 treatments 500, 700 and 900 ppm respectively (Figure 54a). Taro plants grown at 400 and 500 ppm had a foliar N concentration of, on average, 3.8%, which was significantly higher than the N level of plants grown at 700 and 900ppm of 3.4%. This is consistent with most studies of elevated CO_2-grown plants that show a small but significant decrease in leaf protein (Cavagnaro *et. al.,* 2011).

Taro corms contained 1.4% N at 400ppm, compared with 1.2%, 1.1% and 0.9% in plants grown at 500, 700 and 900ppm CO_2, respectively (Figure 54b). The N concentration of cassava tubers was 0.7% in all CO_2 treatments (400, 500, 700 and 900ppm). Despite noticeable lower concentrations of N in taro corm tissue, the effect of eCO_2 treatments (400, 500, 700 and 900ppm) on the N concentration of storage organs in cassava and taro was not significant (p=0.593).

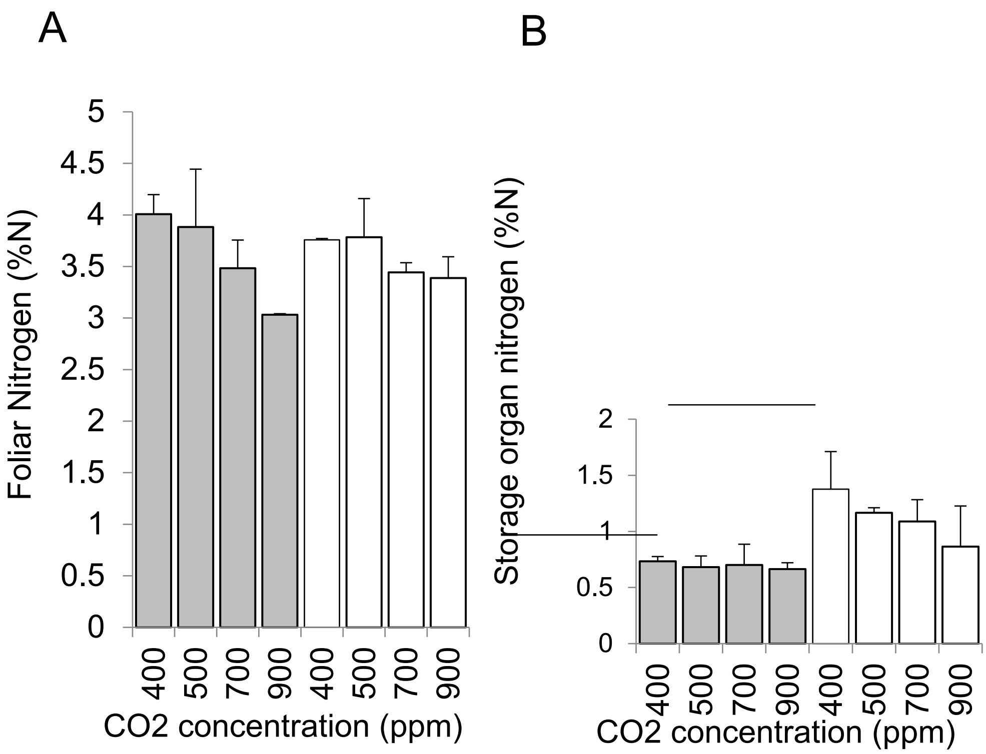


Figure 54. The N percentage (%) of expanded leaf (A) and tuber/corm (B) from cassava (grey) and taro (white) plants grown in four CO_2 concentrations (400, 500, 700 and 900ppm), each data point is the mean of 3 plants ± standard error.

7.4.7 Micro- and macronutrient analysis for elevated CO_2-grown plants

Millions of people worldwide suffer from micronutrient deficiencies, yet little is known about how the concentration of these important elements will be impacted on by elevated CO_2. (See Cavagnaro *et. al*., 2011 for review). This study analysed micronutrient concentration in cassava and taro at elevated CO_2 for the first time. Figure 55 shows the results for Zinc (Zn) and Iron (Fe), two of the most important in terms of human nutrition. We found that there was minimal change in concentration in the leaves with increasing CO_2.

It is noteworthy that the concentrations of both these micronutrients were lower in taro leaves compared with cassava leaves. For tubers, the concentration of Fe in cassava tubers was about twice as high in plants grown at ambient CO_2 as were grown at 500-900 ppm. There was also a significant, although small, decrease in Zinc concentration in cassava tubers with increasing CO_2. Taro corms had so little Fe that it was not possible to make a comparison between the differing growth conditions. By contrast, Zn concentrations were higher in taro corms than in cassava tubers. Moreover Zn concentration did decline with increasing CO_2. There are a number of other interesting changes in the other micro- and macronutrients, which can be found in the full four tables (Tables 11 to 14). We draw attention to the low sodium concentration in cassava. This is consistent with our salinity study (Gleadow *et. al.,* 2016) that showed cassava was very salt sensitive.

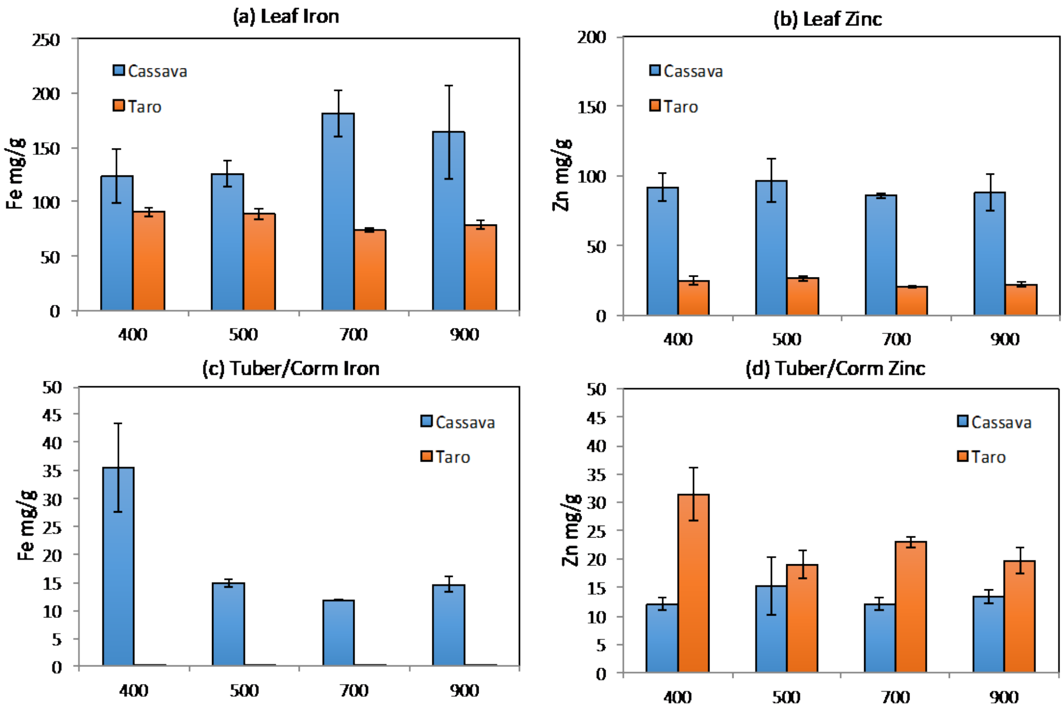


Figure 55.Comparison of Iron (Fe) and Zinc (Zn) concentrations in leaves (a,b) and underground storage organs (c,d) of cassava and taro grown at four different concentrations of CO_2. Values are the mean of seven plants ± 1SE. A full nutrient analysis is given in the following tables.

Table 11: Nutrient analysis of **cassava leaves** grown at four levels of CO_2. Values are the mean of 6 replicates ± 1SE. << indicates that the value was too low to determine.

NUTRIENT ANALYSIS: CASSAVA LEAVES								
	400	**SE**	**500**	**SE**	**700**	**SE**	**900**	**SE**
Macro-								
N %	4.16	0.13	4.00	0.10	3.76	0.09	3.58	0.19
P %	0.51	0.04	0.46	0.03	0.34	0.02	0.37	0.04
K %	2.74	0.12	2.66	0.08	2.30	0.11	2.48	0.06
S %	0.23	0.01	0.22	0.01	0.21	0.01	0.21	0.01
C %	45.97	0.14	45.65	0.30	45.93	0.35	45.29	0.38
Ca %	1.63	0.10	1.41	0.10	1.41	0.09	1.78	0.13
Mg %	0.25	0.01	0.24	0.01	0.24	0.01	0.30	0.03
Na %	<<	<<	0.01	<<	<<	<<	<<	<<
Micro-								
Cu mg/kg	4.90	0.57	6.32	0.81	4.39	0.30	3.93	0.40
Zn mg/kg	91.55	9.96	96.49	15.57	65.98	1.82	87.90	12.87
Mn mg/kg	93.87	10.77	120.02	10.56	114.04	3.32	119.93	8.26
Fe mg/kg	123.40	24.39	125.81	11.67	191.09	22.10	164.21	43.19
B mg/kg	58.13	2.38	51.60	2.75	73.45	9.03	101.86	7.27
Mo mg/kg	0.35	0.05	0.39	0.04	0.66	0.13	0.62	0.13
Co mg/kg	0.10	0.00	0.12	0.01	0.11	0.00	0.14	0.00
Si mg/kg	893.26	77.09	618.43	24.32	703.93	62.53	955.38	49.73
Ratios-								
N:S x	17.95	0.25	17.79	0.24	17.51	0.25	17.27	0.55
N:P	8.40	0.47	8.88	0.59	11.21	0.53	10.06	0.70
N:K	1.53	0.07	1.51	0.07	1.66	0.10	1.45	0.08
C:N	11.12	0.36	11.45	0.28	12.26	0.24	12.86	0.70
Crude Protein mg/g	25.99	0.84	25.00	0.65	23.47	0.55	22.40	1.20

Table 12: Nutrient analysis of **Taro leaves** grown at four levels of CO_2. Values are the mean of 6 replicates ± 1SE. << indicates that the value was too low to determine

NUTRIENT ANALYSIS: TARO LEAVES								
	400	SE	500	SE	700	SE	900	SE
Macro-								
N %	3.83	0.34	4.42	0.18	3.45	0.09	3.56	0.11
P %	0.28	0.02	0.31	0.01	0.28	0.01	0.27	0.01
K %	2.65	0.17	2.93	0.10	2.42	0.10	2.37	0.12
S %	0.49	0.06	0.67	0.16	0.42	0.04	0.65	0.06
C %	45.83	0.59	46.77	0.34	45.00	0.38	45.52	0.33
Ca %	1.11	0.20	1.48	0.18	1.35	0.07	1.53	0.12
Mg %	0.29	0.03	0.29	0.02	0.29	0.02	0.27	0.02
Na %	0.17	0.04	0.08	0.01	0.11	0.03	0.28	0.04
Micro-								
Cu mg/kg	7.89	1.02	7.43	0.72	5.83	0.61	12.00	1.54
Zn mg/kg	24.56	3.05	26.57	2.00	20.17	0.73	21.67	1.38
Mn mg/kg	69.22	9.34	80.86	7.09	70.17	4.81	77.67	5.07
Fe mg/kg	90.50	4.59	88.71	4.85	74.00	2.53	78.83	3.98
B mg/kg	94.00	10.43	111.57	8.88	77.00	8.66	79.00	10.46
Co mg/kg	<<	<<	<<	<<	<<	<<	<<	<<
Mo mg/kg	2.02	0.46	1.91	0.52	3.18	0.94	2.23	0.34
Si mg/kg	426.88	38.63	389.14	19.70	308.17	40.92	411.17	26.55
Ratios								
N:S 6.6	8.66	0.61	7.89	0.89	8.37	0.60	5.75	0.53
N:P 15	11.84	1.55	14.41	0.70	12.38	0.26	13.27	0.64
N:K 1.5	1.33	0.09	1.53	0.10	1.43	0.08	1.53	0.09
C:N 10	16.61	3.44	10.66	0.37	13.08	0.24	12.85	0.28
Crude Protein 28.5	21.62	2.68	28.20	1.13	21.55	0.59	22.23	0.68

Table 13. Nutrient analysis of **cassava tubers** grown at four levels of CO_2. Values are the mean of 6 replicates ± 1SE. << indicates that the value was too low to determine.

NUTRIENT ANALYSIS: CASSAVA TUBERS (flesh)								
Tuber	400	SE	500	SE	700	SE	900	SE
Macro								
N %	0.70	0.04	0.72	0.03	0.68	0.03	0.65	0.01
P %	0.21	0.01	0.20	0.01	0.20	0.01	0.19	0.00
K %	1.14	0.04	1.17	0.03	1.25	0.03	1.20	0.06
S %	0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.00
C %	42.04	0.13	42.23	0.10	42.23	0.12	42.02	0.21
Ca %	0.18	0.01	0.17	0.01	0.18	0.01	0.19	0.01
Mg %	0.08	0.00	0.09	0.00	0.09	0.00	0.09	0.01
Na %	0.07	0.01	0.06	0.00	0.06	0.00	0.06	0.00
Micro-								
Cu mg/kg	2.30	0.37	9.98	7.18	3.80	1.30	5.12	1.98
Zn mg/kg	12.06	1.18	15.28	5.17	12.04	1.16	13.40	1.21
Mn mg/kg	2.40	0.20	2.46	0.18	2.28	0.08	2.42	0.17
Fe mg/kg	35.54	7.95	14.89	0.73	11.78	0.00	14.60	1.40
B mg/kg	2.52	0.07	2.45	0.06	2.80	0.07	2.73	0.21
Mo mg/kg	<<	<<	<<	<<	<<	<<	<<	<<
Co mg/kg	<<	<<	<<	<<	<<	<<	<<	<<
Si mg/kg	318.37	6.46	319.03	3.83	316.17	5.63	319.15	7.07
Ratios								
N:S 6.6	12.04	0.63	12.99	0.39	11.37	0.44	11.99	0.71
N:P 15	3.32	0.17	3.61	0.11	3.38	0.07	3.50	0.08
N:K 1.5	0.61	0.03	0.62	0.02	0.54	0.03	0.55	0.02
C:N 10	61.32	3.05	59.09	2.23	63.10	2.47	64.40	1.57
Crude Protein 28.5	4.36	0.24	4.51	0.20	4.22	0.17	4.09	0.09

Table 14: Nutrient analysis of **taro corms** grown at four levels of CO_2. Values are the mean of 6 replicates ± 1SE. << indicates that the value was too low to determine.

NUTRIENT ANALYSIS: TARO CORMS (flesh)								
	400	se	500	se	700	se	900	se
Macro								
N %	1.19	0.06	1.02	0.08	0.83	0.06	0.81	0.06
P %	0.29	0.01	0.28	0.03	0.22	0.02	0.21	0.02
K %	1.26	0.06	1.13	0.08	0.96	0.07	1.10	0.13
S %	0.13	0.01	0.12	0.01	0.10	0.01	0.11	0.00
C %	43.69	0.89	42.99	0.50	43.45	0.60	42.25	0.58
Ca %	0.06	0.00	0.05	0.00	0.05	0.00	0.05	0.00
Mg %	0.16	0.01	0.14	0.01	0.15	0.00	0.13	0.01
Na %	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.01
Micro								
Cu mg/kg	12.33	5.78	2.00	0.45	2.40	0.40	1.75	0.25
Zn mg/kg	31.33	4.60	19.00	2.41	23.00	1.05	19.75	2.32
Mn mg/kg	4.00	0.37	3.17	0.40	3.00	0.32	2.25	0.25
Fe mg/kg	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
B mg/kg	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Mo mg/kg	0.57	0.08	0.45	0.06	0.46	0.07	0.45	0.03
Co mg/kg	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Si mg/kg	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Ratios								
N:S 6.6	8.73	0.78	9.28	0.42	9.48	0.47	8.25	0.34
N:P 15	4.03	0.05	3.85	0.20	4.12	0.25	4.28	0.21
N:K 1.5	0.88	0.03	0.93	0.06	0.96	0.07	0.85	0.10
C:N 10	40.38	3.97	42.00	3.11	49.12	1.97	49.63	3.13
Crude Protein 28.5	7.13	0.59	6.96	0.50	5.68	0.22	5.50	0.25

7.5 Taro Nutrient experimental results

An analysis of the above ground responses reveals a complex correlation between N and above ground biomass. For plant height, total leaf area and leaf number observations, taro grown under N concentrations of 2.5 mM, 5. mM and 10.0 mM values increased consistently as nutrient concentrations increased i.e. a positive correlation between above ground biomass and nutrient concentrations. However at the highest concentrations above ground biomass accumulation was lower than at the nutrient concentrations, suggesting that 15 mM is above the optimum for taro under the conditions used here. More variation between treatments was observed in plant height and total leaf area than with leaf number, suggesting a more direct response between leaf number and nutrient concentration (Figure 56).

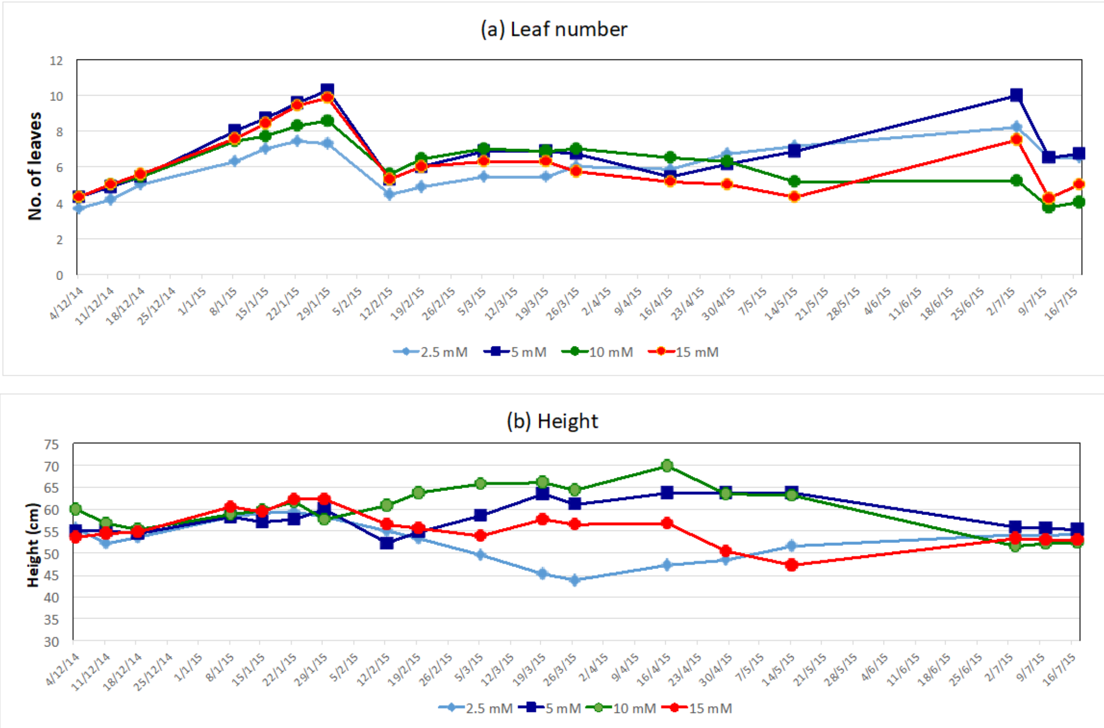


Figure. 56 Phenological development of taro plants grown with fertiliser containing four different concentrations of nitrate. Number of leaves over time of taro plants grown at four different concentrations of nitrate.

Plants were harvested when 8 months old, at the time when plants are normally harvested in the field. Examples of the plants are shown in Figure 57. Data for growth for harvest in April are presented in Figure 58. All the results indicate optimum growth is 10.0 mM N. It is possible that the high growth at 15 mM led to early maturation and thus plants were past the optimum for biomass production (Figure 58).

Figure 57. Photos of taro from each of four treatments at June 2015. From left to right: 2.5 mM 5 mM 10 mM and15 mM N treatments. Note that the height remain similar but there is an increase in leaf area and the number of suckers in plants grown at the higher levels of N.

There are several points to make from the taro growth trial:

- The low/limited N treatment group (2.5 mM) has by far the most extensive root system and moderate corm development.
- The 5 mM treatment group showed similar trends in root system growth to 2.5 mM but not to the same extent. Corms were slightly larger.
- The 10 mM plants had relatively small root system allocation but large corms.
- The high nutrient treatment (15 mM) treatments had smaller root systems.
- Corm size in the 15 mM treatment was similar to that of the 10mM treatment.
- Sucker development depended on nutrient levels and was highest in plants from the mid nutrient levels. Plants grown at very low (2.5 mM) had fewer suckers, with slightly more suckers visible on the 5 mM grown plants. Plants grown at 10 mM and 15 mM had the most suckers.

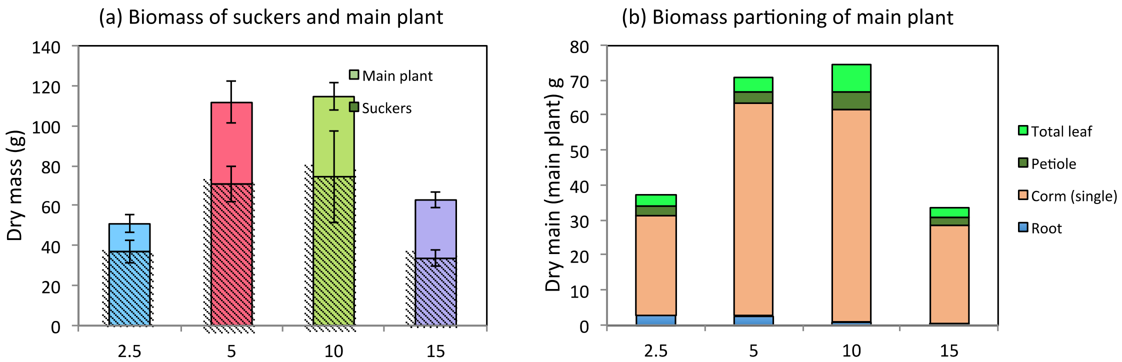


Figure 58. Biomass and partitioning of taro grown at 2.5, 5 and 10 mM NO_3 levels of N after 7 months (a) Total dry mass, separated into suckers and corm, with corm number; (b) Partitioning between the different plant parts of the main plant.

These observations are consistent with what is known about the response of plants to soil nutrients. At low nutrients, plants allocate more energy to producing roots which effectively increases the ability to take up nutrients and mitigating the effect of low N on overall plant growth. Plants grown at very high N generally allocate less resources to roots (i.e. reduced N harvesting from the soil) and also typically do not allocate resources to storage organs. Plants grown at high N supply were smaller. This may be due to the balance between nitrate and ammonia in the nutrient solution. This needs to be further investigated by growing plants under different types of N, including urea which is used in commercial operations.

7.6 Cassava salinity trial

This work was done by Amelia Pegg for her Honours project in 2014. It has been published in the highly regarded international *Journal of Experimental Botany* (Gleadow et al., 2016). The description below is an excerpt from that paper.

Cassava has the ability to cope with a wide-range of environmental stresses and continues to produce tubers under poor growing conditions, yet little is known about how it responds to salt stress. Its classification as “moderately sensitive” by the FAO is based on three early studies (Anon, 1976; Hawker and Smith, 1982; Indira, 1978). More recently, (Carretero et al., 2008), in a study of pre-tuberous plants, found large effects on growth at 68mM NaCl and only 30% survival at the highest concentration (136.8 mM NaCl). Even less is known about the impact of salinity on the nutritional value of cassava.

The aim of this study was, therefore, to determine the effect that salinity had on biomass and nutritional composition at two different life stages of cassava. In the first experiment we tested the tolerance of established plants, with well-developed tubers, to a wide range of sodium chloride solutions. The second experiment involved a detailed study on young clonally propagated plantlets through to tuber initiation. Photosynthetic parameters, growth indices, mineral nutrient composition and cyanogenic glucoside concentration were determined and used to estimate the impact of salinity on plant production and nutritional value.

For Experiment 1: The effect of salt on cassava plants (cv MAus7) with established tuberous roots (‘tubers’, hereafter) was tested. Cassava (one plant per pot) was grown in 8L pots for 8 months (June 2013-January 2014) and then treated with four different concentrations of sodium chloride for 4 weeks (0, 50, 100 or 150mM NaCl) for 28 days. Plants were destructively harvested after 28 days.

For Experiment 2: Longer-term effects of salt on plants prior to tuber initiation were tested. Young plants were established from cuttings (Jan 2014) and transplanted after 2 months (approx. 15 cm tall, 3 leaves) into 2L pots and watered with a commercial full nutrient solution for two weeks. Plants were then watered with three different concentrations of salt, (0, 40 and 80mM NaCl (N=10) for 70 days. Harvesting protocols and other calculations are described in the paper and were consistent with the protocols for all other experiments.

Experiment 1: Effect of range of salt concentrations on established cassava plants

Above ground biomass decreased with increasing salinity and was significantly lower in plants grown at 100mM and 150mM NaCl (Figure 59A) compared to controls. Root:shoot ratio was higher as a consequence of increased salinity, driven by the difference in above ground biomass, as there was no significant difference in tuber biomass between treatments (Figure 58B,C). Leaf area of plants decreased as salinity level increased, primarily through plants shedding leaves with significant differences detected between control and 100mM, control and 150mM, and 50 and 150mM NaCl treatment groups (Figure 59D).

The HCNp in the leaves decreased with increasing salt concentration (Fig. 58E). In the tubers, HCNp initially increased and was significantly higher at 50mM and 100mM NaCl ($F_{3,22} = 6.46$, p=0.006 and 0.015, respectively). At the highest salt treatment the HCNp decreased in the tubers but there was no significant difference compared to any other treatment.

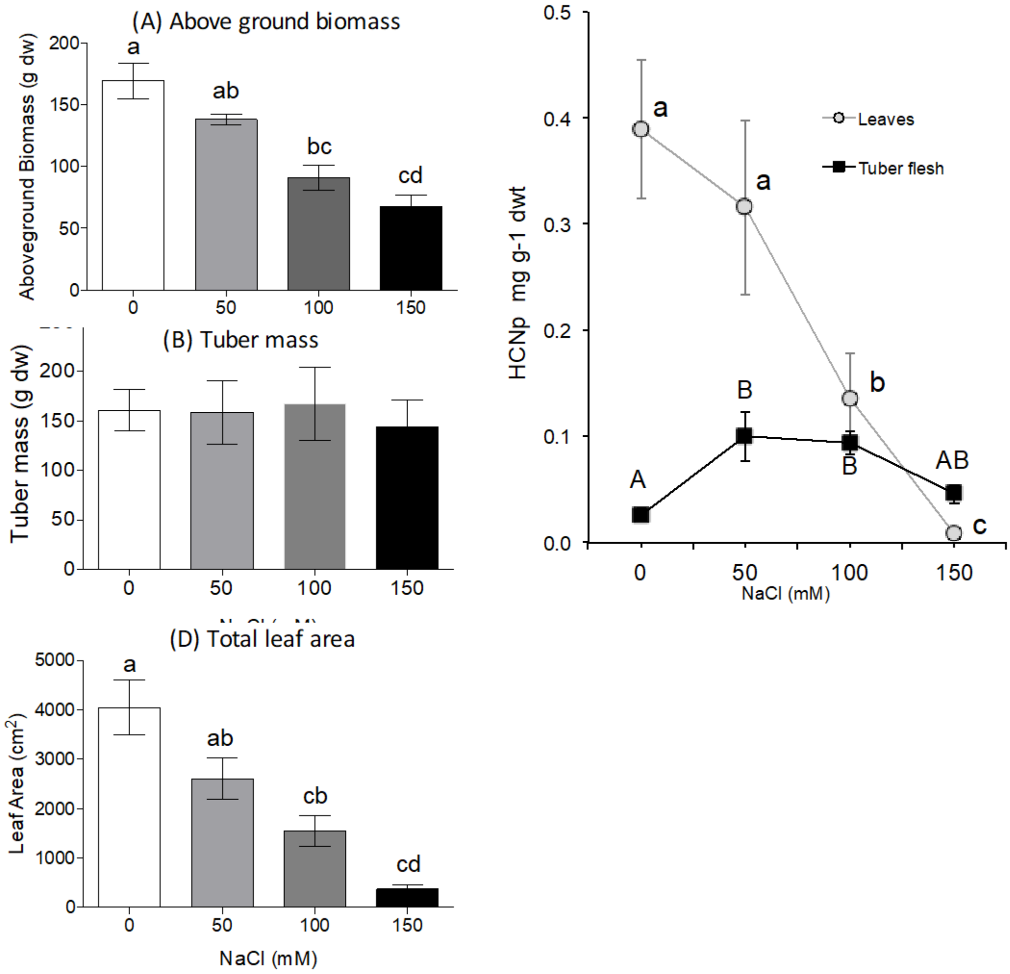


Figure 59. Biomass and growth measurements and tissue hydrogen cyanide potential (HCNp) of 6 month-old cassava plants grown at 0, 50, 100 and 150mM NaCl for 28 days (Experiment 1; N=7 for each treatment). Means (±SE) with different letters are significantly differences at p<0.05 (from Gleadow et al., 2016)

Experiment 2: Long-term effects of salinity on young cassava plants and tuber initiation

The number of leaves present on each plant was recorded once a week for the duration of the study. After five weeks, plants in the 80mM NaCl group began to lose leaves at a steady rate, whereas, plants in control and 40mM NaCl groups had steady increases in their number of leaves over the course of the experiment (Figure 60). Total biomass was highest in plants grown without salt. There was no significant difference in the RGR between plants grown at 0mM and 40mM NaCl, but there was a significant decrease in plants at 80mM salt (Figure 61).

HCNp was highest in the leaves of plants grown at 40mM plants, with lower levels in control plants and those grown at 80 mM NaCl. Statistical tests on HCNp were unable to be performed for tubers grown at 80mM NaCl as only one plant grown at this salt level contained tuberous roots.

There were significant differences in concentrations of key nutrients and trace elements between treatments (Figure 61). The most striking difference is seen in the concentration of sodium. Plants at 80mM NaCl had much higher amounts of sodium in their leaves (1.80%) compared to control (0.01%) and 40mM (0.02%) plants.

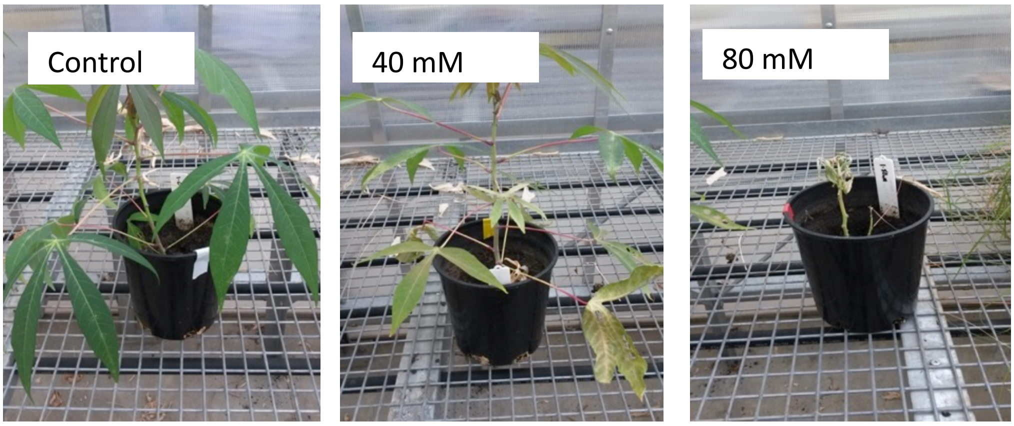


Figure 60. Examples of the young cassava cuttings growing in moderately low concentrations of sodium chloride.

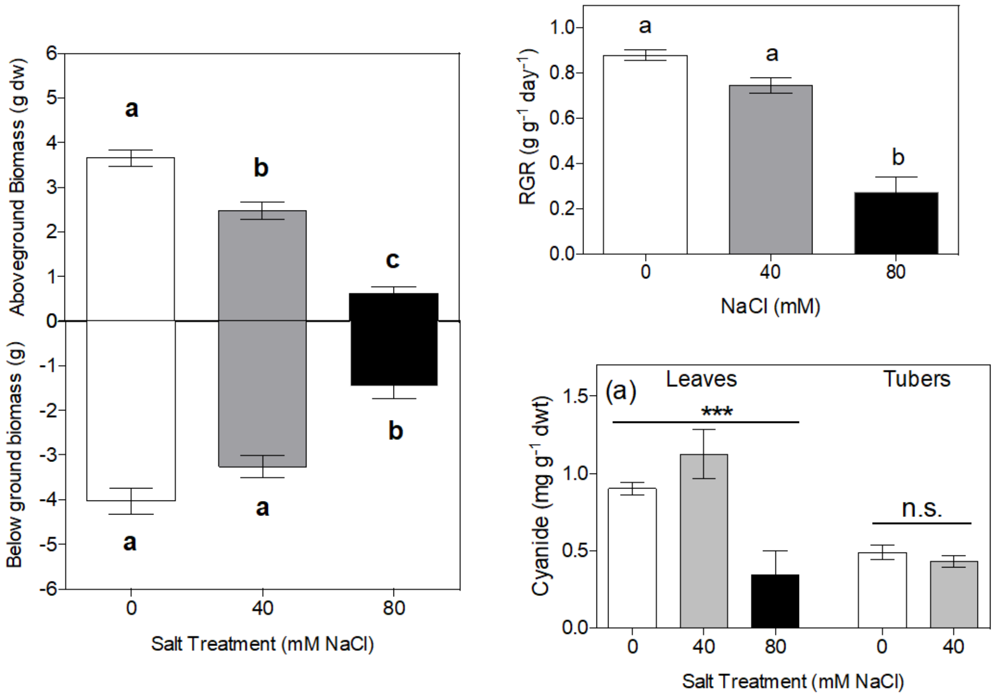


Figure 61. Size, growth rate and HCNp (cyanide potential) of cassava plants grown for 9 weeks with nutrient solutions containing different concentrations of salt (0, 40, 80 mM NaCl (Experiment 2; N=10 for each treatment) (diagrams from Gleadow et al., 2016).

The impact of salinity on growth and nutritional value (i.e. the cyanogenic glucoside and micronutrient concentrations) depended on the age of the plant. Older plants that had already developed tubers were more salt tolerant than younger, pre-tuberous plants in terms of survival and growth. The key effect of salinity on cassava was a reduction in biomass, leaf area and photosynthetic rate. There was an increase in HCNp in the leaves of young cassava plants under moderate stress (Figure 61) but in the leaves of mature cassava plants, HCNp decreased step-wise with increases in salinity (Figure 59). The age-effected differences may be related to: (a) the propensity for cassava to shed leaves in response to abiotic stress, (b) the relatively high costs involved in excluding sodium; and (c) relatively higher investment by younger plants in leaves compared to older plants.

We found tuberous plants were able to tolerate fairly high concentrations of salt, up to 150mM NaCl (Figure 59). In contrast, growth and survival of pre-tuberous plants was severely retarded at 80mM NaCl, with only one plant developing a tuber (Figure 61). These results are broadly consistent with earlier studies that report severe stunting and death of cassava plants between 50 and 135 mM, depending on variety, length of treatment and soil environment, with older plants and those with mycorrhizae generally being more tolerant (Carretero et al., 2008; Hawker and Smith, 1982; Indira, 1978).

Evidence that cassava is able to tolerate low-moderate concentrations of salt comes from the ionic composition of the tissues. Foliar sodium concentration was the same at 40 mM NaCl as in plants grown under control conditions, indicating that survival is from ionic exclusion, rather than tissue tolerance. This ability to exclude sodium breaks down at the higher concentrations with a 100-fold increase in foliar sodium in plants grown at 80mM. This type of response is typical of plants that are sensitive to salt. Salt-tolerant species, by contrast, are able to tolerate quite high concentrations of tissue salt (Munns and Gillman, 2015). Some plants cope with excess available Na by accumulating K as a balancing cation and may influence K+ uptake (Mattius, 2014; Munns and Gillman, 2015). We found no evidence for a change in ionic balance in salt-stressed cassava in the leaves. However, in the tubers there was a significant increase in both Na and K with salt stress.

We conclude cassava to be sensitive to low-moderate concentrations of salt, particularly at early stages of development and, therefore, that cassava is not suitable for planting in regions contaminated with even relatively low levels of salt. In coastal areas, impacts may be minimized by irrigating with less saline water, or during periods of high rainfall to allow time for plants to become established before they are exposed to higher concentrations of salt. Given that alternative tuberous crops such as sweet potatoes are even more salt sensitive than cassava (Shannon and Grieve, 1999), breeding for more salt tolerant varieties is necessary if cassava is to continue to expand its role as a staple in a future, more saline world.

7.7 Taro salinity trial

This experiment was done by Georgia Lloyd for her Honours project in 2017. Taro is often the species of choice in areas where there is coastal flooding. Given the sensitivity of cassava to salt (see section above) we wanted to see if taro was more tolerant and might be a suitable alternative in areas subject to coastal flooding. Studies on taro cuttings in Fiji indicated that it was, in fact, very salt tolerant. The aim of this study was, therefore, to determine the effect that salinity had on biomass and nutritional composition at taro.

Taro suckers (*Colocasia esculenta* cv Samoan Pink) were purchased as described for the taro N trial (above). Suckers were planted into 12 L pots and after three months were allocated to 5 salt treatments (0, 50, 100, 150 or 200mM NaCl; N=18) and watered with their respective salt solution three times a week for 11 weeks. Pots were flushed with water once per week to prevent the build-up of salt.

Throughout the study, weekly measurements of plant height, leaf number and leaf area were taken. Before harvest, photosynthetic parameters (photosynthetic rate, transpiration, conductance and internal CO_2 concentration) were measured using a Li-COR 6400 portable photosynthesis meter and light-adapted chlorophyll fluorescence (Fv/Fm) using a Pulse Amplitude Modulated (PAM) fluorometer.

Plants were destructively harvested and fresh and dry weights taken for each plant part separately (leaf, petiole, roots and corm). Leaf and corm tissue will be tested for N, carbon, sodium, calcium and other micronutrients using mass spectrometry. Phenolics and calcium oxalates will be tested using high-performance liquid chromatography and cyanide content using the evolved cyanide method.

Height, leaf number and leaf length and width of the taro plants were tracked over the course of the experiment. Results thus far, suggest there is a significant relationship between plant height and salt treatment (df=4, f=80.56, p<0.001), whereby plant heights in 150 and 200mM NaCl treatments were significantly lower than in the control and 50mM treatments (Figure 62).

There was also a significant interaction between salt treatment and weeks in treatment (df=4, f=53.45, p<0.001), such that plant heights were seen to diverge in the second half of the treatment period (weeks 6-11).

Plants in 150 and 200mM NaCl treatments showed a significant decline in height compared to the control and 50mM treatments over weeks 6-11 (Figure 63). A significant relationship was also found between photosynthetic rate and plant treatment (*df*=4, *f*=5.347, *p*=0.007), whereby the photosynthetic rate of plants in the 200mM NaCl treatment was significantly lower compared to those in the control (Figure 64). Notably, despite significant differences in photosynthetic rate between treatments, there was no significant difference in light-adapted chlorophyll fluorescence between groups (*p*=0.1; Figure 65).

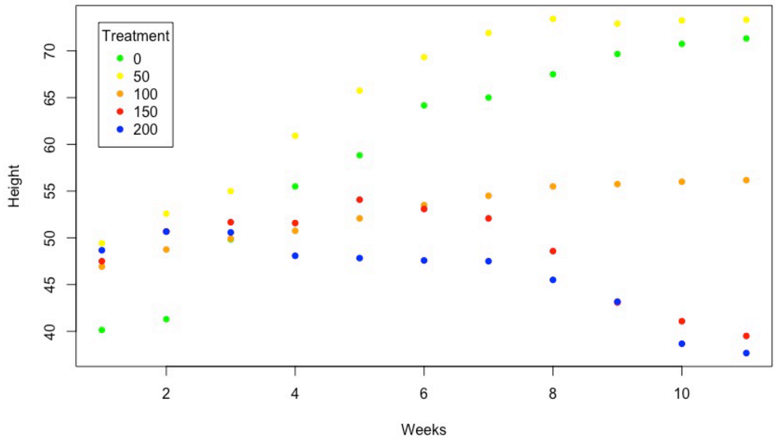


Figure 62. Height of taro plants watered with five different concentrations of NaCl (0-200mM) for 12 weeks.

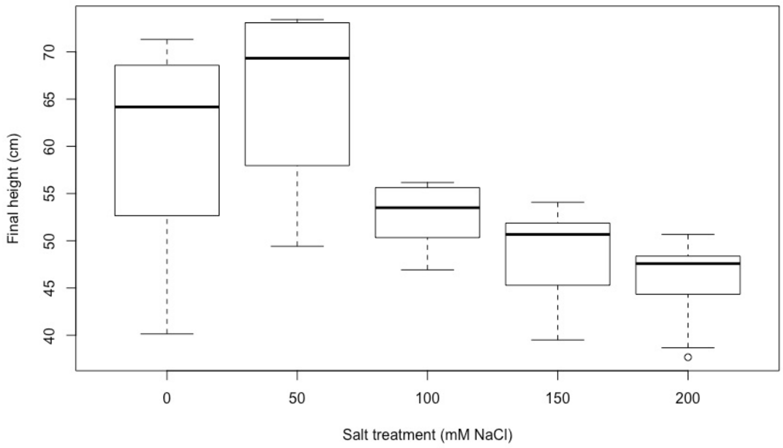


Figure 63. Height at the final harvest of taro plants, 12 weeks after being watered with different concentrations of sodium chloride. The boxplot shows the ranges, upper and lower quartiles and median for plant height (cm) across 5 salt treatments (0, 50, 100, 150 and 200 mM NaCl) after 11 weeks of treatment. Note the wide range of plants within each group. Plants were matched for height at the start of the experiment and this will be controlled for in the final statistical analysis.

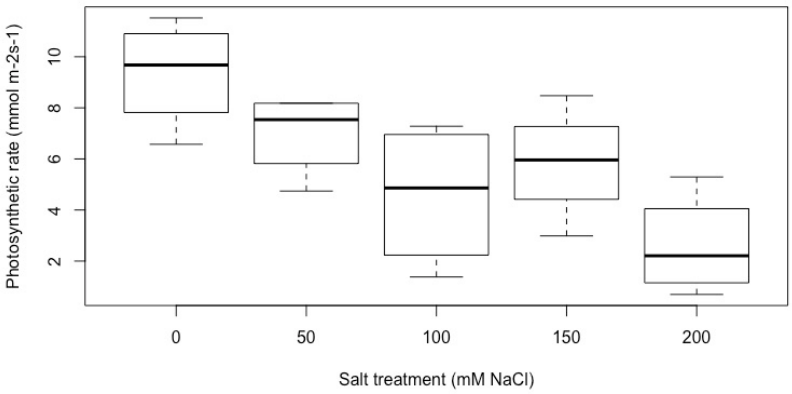


Figure 64. Photosynthetic rates of fully expanded leaves of taro plants grown at 5 concentrations of sodium chloride for 10 weeks. Measurements were made at 700 µmol quanta m^{-2} s^{-1} and 25 °C and approx. 50% humidity and 400 ppm CO_2.

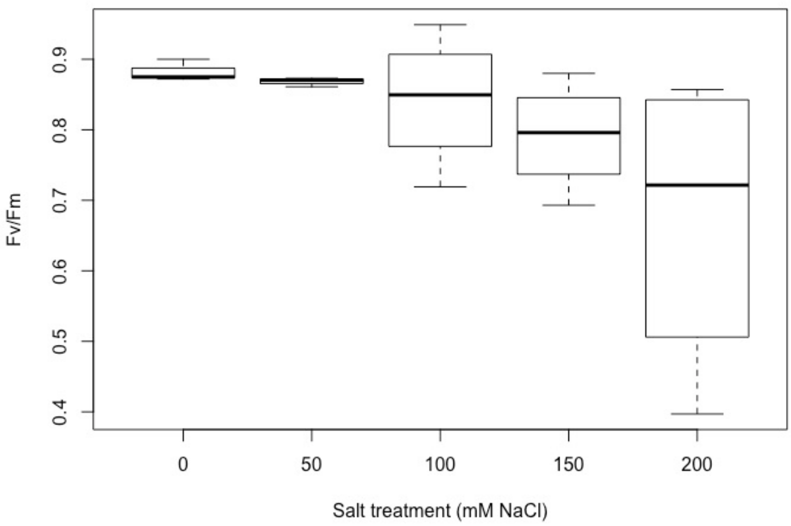


Figure 65. Boxplot showing the ranges, upper and lower quartiles and median for light-adapted chlorophyll fluorescence (Fv/Fm) across 5 salt treatments (0, 50, 100, 150 and 200 mM NaCl) after 11 weeks of treatment. Values below 7.5 indicate that the plant is stressed and that quantum efficiency is reduced.

7.8 Examining the value of SCFs using the APSIM Taro Module

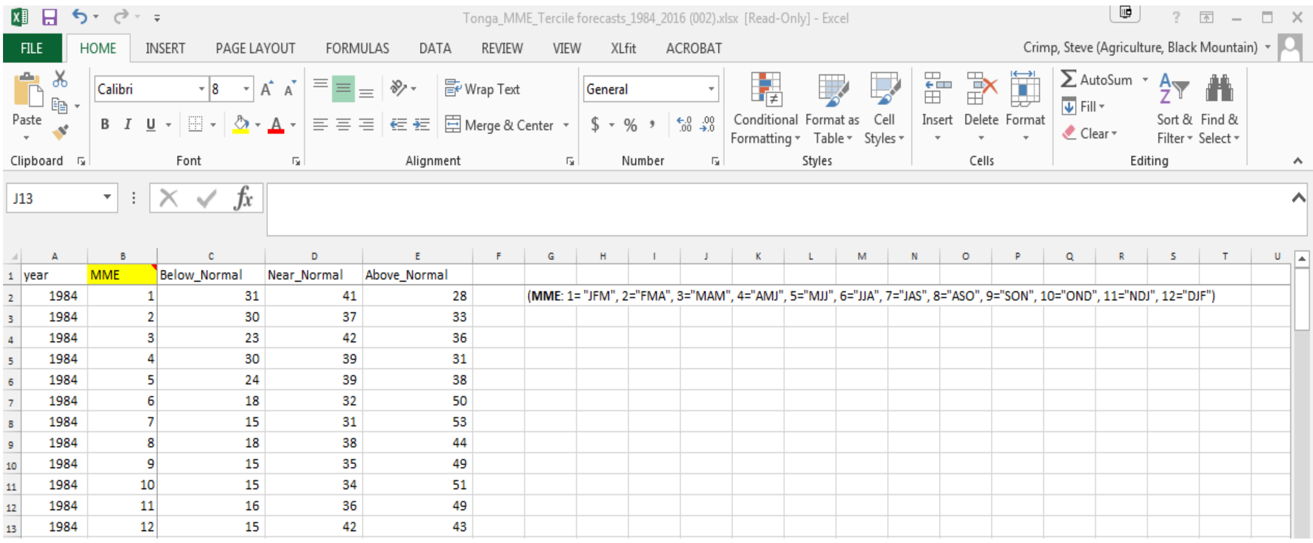
A multi-model ensemble (MME) rainfall hindcast produced by APCC was incorporated into the APSIM model for testing. User defined farm management decisions were coded into APSIM and these decisions were then varied in response to the MME hindcast data to determine if a production benefit was achieved. The APCC MME data used in this research activity represented three monthly tercile probabilities from a composite of ensemble forecasts from ten independent coupled ocean-atmosphere climate models.

Hindcast outputs for the period 1985 to 2015 from the 10 seasonal prediction models were used. The selection of the models for this composite is based on availability of the longest and most continuous quality-controlled common hindcast datasets. The description of the models used is presented in Table 15. An equal weighting approach was used to determine the contribution of each ensemble member to the ensemble mean.

Table 15. A table containing a description of the individual models used in the MME.

Organisation	**Model Acronym**	**Model resolution**
Australian Bureau of Meteorology (BoM)	POAMA	T47 L17
Canadian Meteorological Service	MSC_GEM	2° X 2° L50
	MSC_GM2	T32 L10
	MSC_GM3	T63 L32
	MSC_SEF	T95 L27
Taiwan Central Weather Bureau	CWB	T42 L18
Seoul; National University	GCPS	T63 L21
Korea Meteorological Administration	GDAPS_F	T106 L21
National Institute for Meteorological Research	NIMR	5° X 4° L17
National Centers for Environmental Prediction	NCEP	T62 L64

The MME hindcast three monthly tercile probabilities were derived from a rolling three-month window and therefore included all calendar months i.e. JFM, FMA, MAM, AMJ, MJJ, JJA, JAS, ASO, SON, OND, NDJ, DJF (Figure 66).



year	MME	Below_Normal	Near_Normal	Above_Normal
1984	1	31	41	28
1984	2	30	37	33
1984	3	23	42	36
1984	4	30	39	31
1984	5	24	39	38
1984	6	18	32	50
1984	7	15	31	53
1984	8	18	38	44
1984	9	15	35	49
1984	10	15	34	51
1984	11	16	36	49
1984	12	15	42	43

Figure 66. A screen shot of the MME forecast information obtained from APCC.

As APSIM is a daily time-step model we were required to simplify the hindcast information received from APCC and apply the results to each day. To do this the mean probabilities from the MME hindcast data were modified in the following way:

- Step 1 - For each running three month period, the tercile with the highest probability of occurrence was assigned to that period e.g. if the tercile probabilities in MAM were 23% (tercile 1), 37% (tercile 2) and 40% (tercile 3), the period would be assigned a tercile 3 category. For three month periods where there was little difference in probability between two adjoining terciles e.g. tercile 1 and 2 or terciles 2 and 3, the period was allocated a tercile 2 category. This step provided a categorical estimation of each running three month period within the year.
- Step 2 – In order to present categorical information for each month of the year we took the values generated for each three month period and apportioned them to the first month. For example, if the categorical hindcast for AMJ was for a tercile 3 rainfall amount, the April month was assigned the tercile value of 3. For the MJJ period, if the tercile value was for tercile 2, this value was assigned to

the May month. This exercise was repeated until such time as each month was assigned a hindcast tercile category.

- Step 3 - The tercile category for each month was assigned to each day in the month in order to be consistent with the daily time-step computation undertaken by the ASPIM model.
- Step 4 - The daily tercile category information was included in the APSIM model meteorological file (Figure 67). Decision rules contingent on tercile rainfall information are developed in the manager folder of APSIM and these rules are enacted by reading the file containing the meteorological data. In Figure 67, the daily categorical tercile information is contained in the second last column.
- Step 5 - The observed tercile categories were determined from the monthly rainfall data for the period 1985 to 2015. The observed monthly values were apportioned to daily values based on the approach used for the hindcast data. The calculation of this set of values was to allow comparison between the hindcast and perfect knowledge of the weather conditions. In Figure 67, the daily categorical tercile based on observed data is contained in the last column.

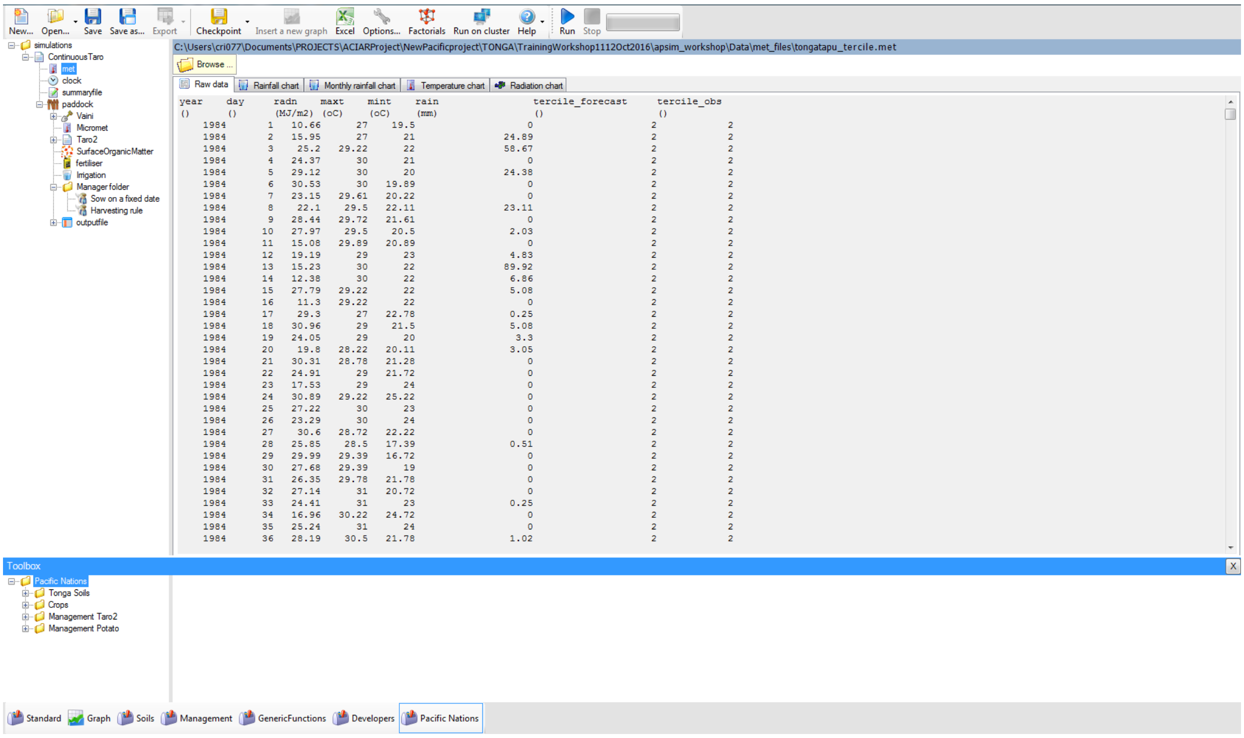


Figure 67. A screen shot of the APSIM climate file with both MME tercile values and observed tercile values.

7.8.1 Testing the value of the hindcast information

The aim of component of the project was to explore the potential taro yield benefit (or otherwise) of forecast-based management, and more broadly, to demonstrate the potential value of modelling approaches in identifying optimal management practices in Tonga.

A series of APSIM scenarios were configured to represent current ('baseline') taro management and possible management responses to three monthly (tercile) rainfall forecasts. Management details were sourced from key government and industry participants attending workshops held in Tonga in July 2015 as well as June and October 2016.

Irrigation of taro is rare to non-existent among the smallholder producers of Tonga but is increasingly being used in larger commercial operations to supplement natural rainfall during the hotter and drier periods of the year. Irrigation water is typically sourced from groundwater aquifers and delivered via surface dripper systems to individual plants.

Commercial farmers report substantial yield gains from the use of irrigation but acknowledge barriers to wider adoption including cost, access to irrigation quality water and competition for limited water resources across a range of users.

From a physiological/agronomic perspective, taro can be planted at any time of the year owing to the relatively consistent temperature profile and the good distribution of rainfall throughout the year.

However, there is uncertainty about the optimum planting date to maximise crop yield and the preferred planting windows are usually governed by market access and demand as well as other broader crop rotation considerations.

Three baseline management scenarios were configured in APSIM (Holzworth et al., 2014) to reflect ‘typical’ taro management in Tonga. These share the same planting density, sowing window and trigger (rainfall based), variety, starting soil water and mineral N concentrations (reset at the start of each year of the simulation).

They differ in the amount of applied basal N fertiliser (nil or 20kgN/ha) and irrigation (nil or 15mm/14 days).

The three baseline scenarios were run across four separate planting windows (Sep-Nov, Dec-Feb, Mar-May, June-Aug) to explore responses to sowing date/window. Each scenario was run over a 30 year period from 1985 to 2015 to capture seasonal climate variability effects. Full baseline scenario configuration details are shown in Table 16.

When asked to nominate potential management responses to a rainfall forecast for the next three months (immediately following the management decision in question), workshop attendees nominated variable irrigation, planting density, sowing time and fertiliser rates for consideration.

When presented with a tercile forecast of above average rainfall (i.e. tercile = 3) farmers will tend to plant earlier in the window, at a higher planting density, use less irrigation and higher rates of N fertiliser.

Conversely, when presented with a tercile forecast of below average rainfall (i.e. tercile = 1) farmers will tend to plant late in the window, at a low planting density, use more irrigation and lower rates of N fertiliser.

With a forecast of average rainfall (i.e. tercile = 2) farmers will revert to typical or current management practices. Each of these standalone management responses is considered in separate APSIM scenarios (see Table 17 columns 2 to 5) and then combined into one integrated scenario to also test if benefit is gained through variation of all the management decisions together (see Table 17 column 6).

As with the baseline scenarios, each tercile scenario is run across the four sowing windows described above.

A further set of model runs replaces the forecast tercile with an observed tercile derived from the actual future rainfall (i.e. perfect knowledge). Full configuration details are shown in Table 17.

Table 16: Model configuration details for baseline scenarios.

Model Scenario	1. Baseline (Rainfed/Basal N)	2. Baseline (Rainfed/Top-dress N)	3, Baseline (Irrigated/Basal N)
Rainfall trigger (sow)	>15mm in 3 days	>15mm in 3 days	>15mm in 3 days
Sow window	Start Month 1 - End Month 3 Must sow end Month 3	Start Month 1 – End Month 3 Must sow end Month 3	Start Month 1 – End Month 3 Must sow end Month 3
N @ sowing	20kgN/ha	Nil	20kgN/ha
N top-dress dates (Days after Sowing _DAS)	N/A	60 & 90 DAS	N/A
Total N top-dress (kg N/ha)	Nil	40kgN/ha (split)	Nil
Irrigation cycle (days)	N/A	N/A	14 days
Rainfall trigger (irrigation)	N/A	N/A	<5mm in last 4 days
Irrigation amount (mm)	Nil	Nil	15mm
Reset N,Soil Water (H_2O), Organic Matter(OM)	Yes	Yes	Yes
Duration	1985-2015	1985-2015	1985-2015
Variety	Lauila	Lauila	Lauila
Density (plants/m2)	1	1	1
Soil water @ sowing (%)	100	100	100
NO_3-N @ sowing (kg N/ha)	42	42	42
NH_4-N @ sowing (kg N/ha)	12	12	12

Table 17. Model configuration details for tercile scenarios.

Model Scenario	4. Tercile based basal N	5. Tercile based density	6. Tercile based sowing	7. Tercile based irrigation	8. Tercile based management
Rainfall trigger (sow)	>15mm in 3 days	>15mm in 3 days	>15mm in 3 days	>15mm in 3 days	>15mm in 3 days
Sow window	Start Month 1 - End Month 3 Must sow end Month 3	Start Month 1 - End Month 3 Must sow end Month 3	Month 1: Tercile 3 Month 2: Tercile 2/3 Month 3: Tercile 1/2/3 Must sow end Month 3	Start Month 1 - End Month 3 Must sow end Month 3	Month 1: Tercile 3 Month 2: Tercile 2/3 Month 3: Tercile 1/2/3 Must sow end Month 3
N @ sowing	Tercile 1: 0kg N/ha Tercile 2: 20kg N/ha Tercile 3: 35kg N/ha	Tercile 1: 14kg N/ha Tercile 2: 20kg N/ha Tercile 3: 34kg N/ha	20kg N/ha	20kg N/ha	Tercile 1: 14kg N/ha Tercile 2: 20kg N/ha Tercile 3: 34kg N/ha
N top-dress dates	N/A	N/A	N/A	N/A	N/A
Total N top-dress (kg N/ha)	Nil	Nil	Nil	Nil	Nil
Irrigation cycle (days)	N/A	N/A	N/A	14 days	14 days
Rainfall trigger (irrigation)	N/A	N/A	N/A	<5mm in last 4 days	<5mm in last 4 days
Irrigation amount (mm)	Nil	Nil	Nil	Tercile 1: 20 mm Tercile 2: 15 mm Tercile 3: 10mm	Tercile 1: 20 mm Tercile 2: 15 mm Tercile 3: 10mm
Reset N, H_2O, OM	Yes	Yes	Yes	Yes	Yes
Duration	1985-2015	1985-2015	1985-2015	1985-2015	1985-2015
Variety	Lauila	Lauila	Lauila	Lauila	Lauila
Density (plants/m^2)	1	Tercile 1: 0.7 Tercile 2: 1 Tercile 3: 1.7	1	1	Tercile 1: 0.7 Tercile 2: 1 Tercile 3: 1.7
Soil water @ sowing (%)	100	100	100	100	100
NO_3-N @ sowing (kg N/ha)	42	42	42	42	42
NH_4-N @ sowing (kg N/ha)	12	12	12	12	12

Under baseline management conditions, average yield (1985-2015) across the four sowing windows was similar with just a 7% mean difference between the highest yield (December to February, 9.54t/ha) and the lowest yield (March to May, 8.8t/ha), thus affirming farmer uncertainty relating to optimum sowing time for taro (Table 18).

Basing sowing date selection on the rainfall forecast results in lower average yields, especially for the December to February sowing window where average yield drops by 17% relative to baseline management.

Table 18. Long-term (1985-2015) average corm yields (t/ha) for the sowing time scenarios. Minimum to maximum yield range shown in parentheses.

	Baseline	**Tercile based sowing**
Sow Window	(Rainfed/Basal N)	(forecast tercile)
March to May	8.88 (0.39-18.84)	8.43 (0.45-16.29)
June to August	9.18 (0.36-18.36)	9.06 (0.54-18.39)
September to November	8.91 (1.32-14.79)	8.55 (2.19-14.67)
December to February	9.54 (1.08-15.48)	7.89 (0.69-13.2)

Basing the at-sowing (i.e. basal) N fertiliser application rate on the rainfall forecast did not result in any substantial change in yield when compared with the baseline N management scenario (Table 19). There was a small simulated yield benefit across all planting windows (except December to February) for a top-dress application as opposed to a basal application of N fertiliser (Table 19).

Whilst there is no yield benefit from using the hindcast information to inform basal N amounts, there is a potential cost-saving benefit in years where using the forecast results in selection of a lower fertiliser rate compared to conventional practice (for the same yield).

Table 19. Long-term (1985-2015) average corm yields (t/ha) for the N fertiliser scenarios. Minimum to maximum yield range shown in parentheses.

	Baseline	**Baseline**	**Tercile based basal N**
Sow Window	(Rainfed/Basal N)	(Rainfed/Top-dress N)	(forecast tercile)
March to May	8.88 (0.39-18.84)	8.94 (0.39-19.11)	8.85 (0.39-18.99)
June to August	9.18 (0.36-18.36)	9.30 (0.36-18.48)	9.12 (0.36-18.45)
September to November	8.91 (1.32-14.79)	10.50 (1.32-14.79)	8.91 (1.32-14.79)
December to February	9.54 (1.08-15.48)	9.54 (1.08-15.48)	9.54 (1.08-15.42)

Basing plant density on the rainfall forecast resulted in small declines in average yield across all planting windows (Table 20).

This decline is attributable to the increased resource demand in years when crops are established at the higher density. In the absence of corresponding increases in resource supply (i.e. N, water), these more densely planted crops are exposed to stress conditions.

Table 20. Long-term (1985-2015) average corm yields (t/ha) for the planting density scenarios. Minimum to maximum yield range shown in parentheses.

	Baseline	**Tercile based density**
Sow Window	(Rainfed/Basal N)	(forecast tercile)
March to May	8.88 (0.39-18.84)	8.55 (0.39-17.52)
June to August	9.18 (0.36-18.36)	8.40 (0.63-16.86)
September to November	8.91 (1.32-14.79)	8.10 (1.02-14.46)
December to February	9.54 (1.08-15.48)	9.36 (0.69-16.47)

Shifting from rainfed to irrigated production (i.e. baseline scenarios) resulted in yield gains in almost all years of the simulation period (e.g. June to August sowing window, Table 18). The increase in average long-term yield ranged from 60% for the March to May sowing window to 43% for the December to February window (Table 21).

For farmers already using irrigation, the use of rainfall forecasts to select the irrigation rate did not substantially improve yield performance, although there are potential savings in water consumption in years when lower rates of irrigation are selected.

Whilst the use of the rainfall forecast does provide improved mean yields across all planting windows, these gains are quite modest (i.e. mean value of 2.1 t/ha). There were similar modest gains in production using the observed terciles over the rainfall forecast data. A more significant improvement is found in the lower yields i.e. 10th percentile to 25th percentile yields. At the 10th percentile level, comparisons of yields between baseline irrigation and forecast irrigation highlight a mean gain of 3.3 t/ha.

An additional gain from using the rainfall forecast is the potential savings in water consumption in years when lower rates of irrigation are selected compared against the fixed amount of water applied across all years as part of the baseline management.

Table 21. Long-term (1985-2015) average corm yields (t/ha) for the irrigation scenarios. Minimum to maximum yield range shown in parentheses.

	Baseline	**Baseline**	**Tercile based irrigation**
Sow Window	(Rainfed/Basal N)	(Irrigated/Basal N)	(forecast tercile)
March to May	8.88 (0.39-18.84)	14.19 (0.69-20.88)	14.70 (5.16-20.52)
June to August	9.18 (0.36-18.36)	13.95 (1.89-19.44)	14.10 (3.18-19.02)
September to November	8.91 (1.32-14.79)	13.56 (5.52-15.72)	13.68 (10.59-15.66)
December to February	9.54 (1.08-15.48)	13.62 (5.13-17.79)	13.71 (9.24-17.19)

When the aforementioned sowing date, N management, irrigation and density responses to the rainfall forecast are combined into the one scenario, the yield gap between the forecast and rainfed baseline yield ranged from 80% for the March to May window to 36% for the September to November window (Table 22).

The highest forecast-based average yield of 16.02 t/ha was achieved with the March to May sowing. In this scenario, the forecast yield exceeded the rainfed baseline yield in 28/30 years. This average yield was much higher than the equivalent forecast yields for each of the stand-alone management scenarios indicating synergistic benefits from combining the various management responses. For example, in years when a higher planting density was employed, the associated higher resource demand benefited from larger inputs of N and irrigation.

Consistent with the standalone management scenarios, there was negligible difference between yields for forecast and observed (i.e. perfect knowledge) tercile-based scenarios suggesting that any future improvement in forecast skill will not lead to substantial yield improvement.

Table 22. Long-term (1985-2015) average corm yields (t/ha) for the combined management scenarios. Minimum to maximum yield range shown in parentheses.

	Baseline	**Baseline**	**Tercile based management**
Sow Window	(Rainfed/Basal N)	(Irrigated/Basal N)	(forecast tercile)
March to May	8.88 (0.39-18.84)	14.19 (1.02-20.88)	16.02 (11.19-20.76)
June to August	9.18 (0.36-18.36)	13.95 (1.89-19.44)	14.49 (9.42-19.11)
September to November	8.91 (1.32-14.79)	13.56 (5.52-15.72)	12.06 (6.75-16.02)
December to February	9.54 (1.08-15.48)	13.62 (5.13-17.79)	14.64 (7.5-19.08)

In order to explore the economic value of implementing the seasonal climate forecast we consulted with local experts in Tonga to provide estimates of operating costs and prices for taro. A number of assumptions are made in order to calculate these farm gate gross margins. These assumptions include:

- A taro fresh weight price of NZ$1.50/kg (local, internal market)
- Pre-sow tillage (3 events) at $200/ha
- Taro planting material 10c each.
- Herbicide costs of $75/ha
- Fertiliser costs of $4/kg N
- Costs of irrigation related labour: $75/event (assuming manual irrigation).
- Costs associated with planting labour assume a planting rate of 10 plants per minute at $5/hour
- Harvesting labour costs of $100/ha
- Transport costs of $750 per ha.

The results presented below represent the gross margins in New Zealand Dollars for taro grown in the March to May planting window. Based on the cost and price assumptions highlighted above, the implementation of irrigation could result in a mean farm gate GM of NZ$18,879 versus a GM of NZ$10,872 for the baseline case (Table 23). Using the seasonal forecast to guide decisions surrounding irrigation resulted in a mean GM of NZ$19,632.

As with the yield analysis above we also explored the GMs where all the management decisions we examined we informed by the seasonal climate forecast this resulted in a farm gate GM of NZ$21,244 suggesting an almost doubling of farm income (Table 23). These economic figures must be viewed with some caution as they have not been fully tested with a broader range of producers in Tonga, but do serve as a demonstration of the application of this new modelling capability.

One aspect that this economic analysis does highlight is that both the implementation of supplementary irrigation (informed by the SCF) and the use of the seasonal climate forecast to moderate all the farm management options serves to reduce the number of years of economic loss to zero. In both the baseline and the baseline plus irrigation case there were number of years were economic losses were incurred.

Table 23. Long-term (1985-2015) average farm gate gross margin ($NZ/ha) for baseline dryland, baseline irrigated and forecast tercile-based irrigation and combined management scenarios for the March to May sowing window. Minimum to maximum yield range shown in parentheses.

	Baseline	**Baseline**	**Tercile based irrigation**	**Tercile based management**
Sow Window	**(Rainfed/Basal N)**	**(Irrigated/Basal N)**	**(forecast tercile)**	**(forecast tercile)**
March to May	**10,872 (-1,847-25,837)**	**18,879 (-885-28,909)**	**19,632 (3,247-18,369)**	**21,244 (14,763-27,720)**

8 Impacts

8.1 Scientific impacts – now and in 5 years

The project has generated new knowledge within a number of scientific domains, with significant potential for impact on future research. Expanding the capability of APSIM to successfully simulate taro and cassava-based cropping systems will have a major impact on research aimed at improving the future productivity and sustainability of systems in which these crops are grown. This outcome is particularly important given that cassava constitutes the mainstay of staple production across much of the humid tropics and that taro currently plays this role in the Pacific (though even in this region, cassava is gaining ground as falling soil fertility and labour constraints provide increasing challenges for taro production).

Development and validation of the enhanced APSIM modelling capabilities as well as scenario testing across the two trial sites, has provided an opportunity to test modelled options in real-world situations, adapted to the context and experience of the farming community.

The project has resulted in a number of notable science impacts, these include:

- one PhD (nearing completion),
- one Masters (completed),
- seven honours projects (completed),
- one book chapter,
- six peer-reviewed papers,
- 24 seminars, conferences and public lectures and
- two papers currently under preparation (See full list in Appendix 1).

Members of the modelling team were also invited to join a global cassava model development initiative hosted by the CIAT and CCAFS initiative. This has led to sharing arrangements and attendance at two modelling workshops in Cali, Columbia in 2013 and 2014, and has facilitated the improvements in crop parameterisation in both DSSAT and APSIM platforms.

8.2 Capacity impacts – now and in 5 years

In terms of capacity impacts, this project has directly resulted in the enhanced capacity of the USP organic chemistry laboratory in Suva with the provision of equipment and training to allow rapid freeze drying of plant material. In addition drying equipment and training were also provided to Nishi Trading in order to allow the drying of plant material. In both instances this equipment and facilitated the undertaking of further experimental work with other agencies. Over time this will position USP and Nishi to undertake further agronomic research on local farming systems. This has already been seen in the case of Nishi, who now has a research project to examine the effectiveness of maize production in Tonga.

The support of nine students will have a long-term positive impact on ongoing cassava and taro research as well as the application of the work in the Pacific. Both the PhD and Masters students are engaged with agencies working in the Pacific. The knowledge they have gained will be applied to improve food security outcomes in the Pacific.

Two formal APSIM training workshops were undertaken in 2016 in Tonga; one held from the 7th to the 10th of June 2016 and the other held on the 11th and 12th of October 2016. The first training workshop trained 22 participants (comprised of both farmers, Government and Private extension staff as well as USP staff and students) and the second revisited training activities with 15 participants and helped to resolve simulation experiments they had developed as groups. One of the research applications was to examine the role of weed control for commercial taro production, with another related to maize and used to support the field trials already underway.

8.3 Community impacts – now and in 5 years

This project was not specifically designed to introduce new technologies or farming methods to farming communities but was to impart knowledge regarding the likely impacts of climate change on cassava and taro crop production in Fiji, Vanuatu and Tonga through the development and application of the APSIM Cassava and Taro modules. For this reason determination of community impacts is largely prospective.

8.3.1 Economic impacts

At a global scale cassava and taro represent staple crops of importance. In 2008, the FAO ranked cassava and taro as the third and fourteenth largest source of food carbohydrates in the tropics. Understanding the response of these important staples to future climate and other environmental conditions and applying this knowledge to enhance on-farm management will have important positive benefits for farm livelihoods. For farming households, improved cropping, water and nutrient management techniques will increase net household income through increased yields and/or a reduction in production costs.

Taro production in the South Pacific region averaged 360,000 tonnes per year for the nineteen years ending 2009, with PNG, Solomon Islands and Fiji the largest producers. The annual production of cassava was estimated to average 290,000 tonnes per year for the same period, with PNG, Tonga and Fiji the largest producers. While these crops are grown as a subsistence starchy staple by some households, these crops are also grown for sale thereby being a source of cash income. The 'roadside' price of taro is around Fj$1.50 kg. This is equivalent to A$833/tonne. The per kg value of cassava (roadside) is around Fj$1/kg which is equivalent to A$556/tonne. Hence, the imputed value of taro and cassava production in the South Pacific region is A$300 million per year for taro and A$161 million for cassava. (These figures are based on an exchange rate of Fj$1.8 for each A$1.00.)

While the full range of effects of climate change on the production levels of these crops are unknown, it is clear that climate variability and pest and disease pressures could have a significant impact on taro and cassava yield and quality. Even just a 10% climate change-induced reduction in total output (as seen in some instances from the modelling undertaken), is equivalent to A$30 million annual loss in the total value of taro and a A$16 million annual loss in the case of cassava. (Note that a 10% production loss due to extreme weather events and new pest and disease challenges is a subjective measure, but it is conservative when compared with losses of up to 80% due to historical climate extreme events.) Providing farmers with strategies to deal with climate change challenges is likely to reduce the size and impact of these losses. Again, assuming conservative outcomes (that is a 5% adoption rate and that only half of the climate change effects can be offset), the expected benefits of this research is A$0.6 million annually. Sensitivity analysis shows that even if only 25% of the climate change effects can be addressed the total annual benefit is still A$0.2 million annually or the entire ACIAR investment in this project recovered in three years.

Within the reported range of climate-related losses of between 10 and 70% of the total crop, a higher estimate of losses (e.g. 30%), seems plausible for exports (given that the export market demands large, blemish-free corms). On this basis, approximately US$12 million of export earnings could be lost each year. By developing more resilient cropping practices that reduced these losses (e.g. to only 10%) and with uptake again estimated at 15%, the total ACIAR investment in this project ($600,000) would be saved every year in the export sector alone.

8.3.2 Social impacts

Building the staple crop modelling framework has enabled the research team and local agricultural extension staff to work with local farming communities to explore options to improve and enhance current production. Enabling such interactions has the potential to have significant social and community impact. Without this added support, smallholder livelihood strategies will inevitably become even more constrained than at present, leading to both personal and communally-shared hardship and potential social dislocation as communities stagnate or lose further members to migration. Protecting against this source of adverse social impact is partially addressed by increasing productivity.

The modelling framework that has been developed in this project goes some way to allowing farming communities to examine more effective farm management options and hence positively impact on their food security and income generation potential. Further application with farming communities is essential to realising this outcome.

The modelling capacity for both taro and cassava will provide local extension agencies with additional tools to begin to examine more efficient, resilient and productive farming methods. This knowledge transfer using the developed models can be done in the absence of trials.

8.3.3 Environmental impacts

By developing a modelling framework that allows a range of management options to be explored this project has identified options that deliver both positive and negative environmental impacts. Better matching of cropping systems to current and near future climatic conditions may result in changes in water and nutrient use, possibly improving the environmental footprint of cropping system. However given the subsistence nature of these cropping systems (i.e. minimal inputs), these gains are likely to be very small. Intensification of crop production as a consequence of positive simulation information could potentially lead to soil fertility losses and erosion. However increased local yields may reduce other negative environmental impacts associated with food importation.

8.4 Communication and dissemination activities

The communication of outputs from this project have occurred at a number of levels. These include:

- Interaction (via workshops) with local extension staff and farmers, to discuss field demonstration trials and use the model in a participatory training mode (as above) as a tool to empower choice among a range of varieties and other management options;
- training opportunities with local extension staff in order to allow staff to apply the model in further extension strategies;
- presentations to local stakeholders and local policy makers, of experimental data and using the model in a more limited 'demonstration of scenarios' mode to advocate investment in specific extension strategies;
- presentations and information dissemination to national and regional agencies to raise awareness and promote use of the tool in guiding regional and national agriculture policies and strategies;
- presentations to donor organisations (similar approach - scientific evidence and scenario-based modelling) to advocate further investment in specific research areas or extension strategies; and participation in international conferences to increase scientific impacts among peer group of researchers and obtain feedback to the research effort.

Dissemination of scientific knowledge generated by the project has occurred through the production of scientific journal papers and through the support of a number of students. The translation of the Tongan material and incorporation of this material in farmer training programs run by Nishi Trading are likely to result in improved agronomic practises by local farmers working for Nishi.

9 Conclusions and recommendations

In the sections that follow we present the higher level conclusions of the research outputs and attempt to place these findings in the context of adaptation to climate variability and change.

9.1 Conclusions

The aim of this project has been to understand the impact of climate change on key Pacific production systems - specifically those based on the staple root crops, taro and cassava. To this end, the project has addressed four specific objectives:

- To understand the responses of cassava and taro crops to existing environmental drivers (climate, soil and nutrient interactions).
- To understand the responses of cassava and taro crops to enhanced CO_2 conditions.
- To develop the capacity to model crop and cropping system responses (within the APSIM framework).
- To identify promising strategies for farming systems adaptation.

Over the course of the project we have addressed each of the objectives above. This Final Report contains an overview of our achievements and the results of our field work, model development, model application, capacity building and experimental work.

The field trials were successfully established at the Korinivia Research Station, Suva, Fiji, the Vanuatu Agricultural Research and Training Centre, Luganville, Espirito Santo, Vanuatu and Nishi Trading, Nuku'alofa, Tonga. Each of these trials served to develop a data sets of crop physiological information in order to establish both a Cassava and Taro module in the APSIM framework.

The subsequent modules have been used to explore a number of strategies for farming systems adaptation to both climate variability and climate change. The resulting analyses highlights that despite significant annual rainfall, the use of supplementary watering (i.e. simple irrigation) proves to be an effective approach to manage both climate variability and change. The demonstrated, sustained improvement in production values, particularly for taro, across all three sites for the historical period 1980 to 2015 suggests that this adaptation would be an effective approach to improving agricultural production now, and also a promising option into the future. The modelling study also highlights that targeted chemical fertiliser use, combined with supplementary watering would also be an effective approach to raise current production levels for both cassava and taro.

The climate change analysis undertaken, as part of this project has gone some way to exploring the sensitivity of staple food production to climate change. The analysis showed that for Vanuatu and Fiji, yield is little affected by temperature increases up to 2°C but there is a noticeable decline of 10-12% at 3°C. In Tonga, average yield is lower than baseline for all temperature increase scenarios but lowest for the 3°C projection. The impact of future rainfall decline on both cassava and taro yields was typically small across all sites and can be attributed to the current high rainfall totals. The modest declines, simulated by a 15% reduction in annual rainfall could be successfully mitigated through supplementary watering.

The simulation studies also showed a modest positive yield response to increased atmospheric CO_2 concentrations. This reflects the typical 'CO_2 fertilisation' response of C3 crops such as taro. The experimental work undertaken provided much more extensive insights into the yield and quality implications of climate change on both cassava and taro, with difference identified for each of the staples. The experimental work showed that cassava had a slight positive above-ground response to higher concentrations (i.e. produced more leaves and stems), whereas taro showed slight declines in total leaf area. There is an increase in total biomass with increasing CO_2 concentration in both cassava and taro. In terms of total biomass accumulation, cassava demonstrated, an increase in biomass, largely associated with an increase in tuber number, with a plateauing of this response at 500ppm. For taro, there was a stepwise increase in total mass, corm number and corm mass with each increase in CO_2, with plateauing evident from the experimental results only at 900ppm.

Plants grown at higher CO_2 concentrations overall had higher rates of photosynthesis and lower transpiration rates. The results indicate that the most gains from CO_2 fertilisation will come in the next 30-50 years, after which the effects of rising CO_2 will be more modest. Transpiration rates show significant declines under higher CO_2 concentrations for cassava plants highlighting the use of less water to achieve the same amount of biomass (i.e. they are more water efficient). Taro did not show the same level of water use efficiency gain as cassava, thus, if water is limited, these data suggest that cassava is likely to perform better at high CO_2, but if there is ample water, then taro would be the better choice.

The experiments also served to highlight that the concentration of cyanide on a per mass basis does not change in cassava tubers, although the increase in tuber number per plant would highlight an increase in total cyanide due to a greater number of tubers.

We found a highly significant decrease in oxalic acid with increasing CO_2. This means that taro may become more palatable in future. This is the first time oxalic acid has been measured on taro growing in a controlled environment experiment.

In terms of the nutritional quality of these staples, the experiments showed that despite noticeable lower concentrations of N in taro corm tissue, the effect of eCO_2 treatments (400, 500, 700 and 900ppm) on the N concentration of storage organs in cassava and taro was not significant ($p=0.593$).

Zinc (Zn) and Iron (Fe), two of the most important in terms of human nutrition, were found to show minimal change in concentration in the leaves with increasing CO_2 although the decline in Zn in taro was much greater than for cassava.

With the possibility of sea level rise resulting in salt water intrusion of some low lying agricultural land this project also examined the sensitivity of cassava to changes in salinity. Cassava was shown to reduce its leaf area and increase the production of cyanide in response to greater salinity, thus making it less palatable

The project has resulted in a number of notable science and community impacts. Science outputs for the project include one PhD (nearing completion), one Masters (completed), seven honours projects, one book chapter, six peer-reviewed papers, 24 seminars, conferences and public lectures and two papers currently under preparation.

Members of the modelling team were also invited to join a global cassava model development initiative hosted by the CIAT and CCAFS initiative. This has led to sharing arrangements and attendance at two modelling workshops in Cali, Columbia in 2013 and 2014, and has facilitated the improvements in crop parameterisation in both DSSAT and APSIM platforms.

In terms of community impact, this project has directly resulted in the enhanced capacity of the USP organic chemistry laboratory in Suva with the provision of equipment and training to allow rapid freeze drying of plant material. In addition drying equipment and training were also provided to Nishi Trading in order to allow the drying of plant material. In both instances this equipment and facilitated the undertaking of further experimental work with other agencies.

9.2 Recommendations

This project has highlighted a number of promising options that could be pursued in order to maintain production of staples like cassava and taro under both climate variability and change. Over the course of the project the team has also identified a number of knowledge gaps that could begin to be addressed in further phases of activity. The recommendations are summarised below and include:

- The development of the both the Cassava and Taro modules have taken placed on a limited number of varieties as well as on a limited number of trails. To improve the current level of model validation the project team suggest that further trials be established to provide more extensive validation data.

- To enhance the number of varieties represented in the model it is recommended that more targeted trials be undertaken at both the Fiji and Tongan case study sites to include a range of other taro and cassava varieties. Including additional varieties, and varieties with different crop durations, within the two crop modules would assist in the identification of appropriate adaptation management for climate change.
- The project team have also identified the need to consider building a modelling capacity for other staples like sweetpotato, to allow to examination of inter-cropping and rotational options across Pacific sites.
- The legacy of the project would be enhanced by the submission of the Taro and Cassava prototype models into the released version of APSIM. It is recommended that the Cassava prototype is further developed, by including more of the effects of enhanced CO_2 concentrations on plant growth (other than radiation and transpiration efficiency changes), nutrient changes and cyanide and oxalate production in the modules, building on relationships established during related project work (Section 7.4)
- The merit of adaptation options has been evaluated in terms of increases in yield only, which were modest for some adaptation options. It is recommended that adaptation options also be evaluated in terms of the profitability of the options before release as recommendations for adoption.
- The current level of community engagement has been limited for this project due to the experimental nature of the activities undertaken. With the development of the crop modules much more scope now exists to engage with communities to examine adaptation and management options.

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10.2 List of publications produced by project

Bredeson JV, Lyons JB, Prochnik SE, Wu GA, Ha CM, Edsinger E, Grimwood J, Schmutz J, Rabbi IY, Egesi C, **Nauluvula** P, **LeBot** V, Ndunguru J, Mkamilo G, Bart RS, Setter TL, **Gleadow** RM, Kulakow P, Ferguson ME, Rounsley S, Rokhsar, DS. (2016), Sequencing wild and cultivated cassava and related species reveals extensive interspecific hybridization and genetic diversity *Nature Biotechechnology* 34, 562–570.

Brown, A, Cavagnaro TR, **Gleadow** RM, Miller RE (2016), Interactions between temperature and drought stress on yield and nutritional quality of cassava (*Manihot esculenta* Cranz.). *Global Change Biology* 22, 3461–3473.

Cvitanovic, C., **Crimp**, **S.**, Fleming, A., Bell, J., Howden, M., Hobday, A. J., Taylor, M., Cunningham, R. (2016), 'Linking adaptation science to action to build food secure Pacific Island communities' (2016) 11 Climate Risk Management 53-62.

Gleadow RM and Møller BL. (2014), Cyanogenic glucosides- synthesis, physiology and plasticity. *Annual Review of Plant Biology* (Gleadow-invited review) 65: 155-85.

Gleadow RM, Pegg A, Blomstedt CK (2016), Resilience of cassava (*Manihot esculenta* Crantz) to salinity: implications for food security in low lying regions. *Journal of Experimental Botany* 67: 5403-5413.

Taylor M, **Crimp S**, Dawson B, McGregor A, Cvitanovic C, Lough J, Thomson L, Howden M (2016), Adapting Pacific agriculture and forestry to climate change: management measures and investments. Chapter 10. pp. 483-518. In: Taylor M, McGregor A, Dawson B (Eds) Vulnerability of Pacific Island Agriculture and Forestry to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia.

11 Appendixes

Appendix 1: Science outputs

The project has resulted in a number of notable science and community impacts. Science outputs for the project include one PhD (nearing completion), one Masters (completed), seven honours projects, one book chapter, six peer-reviewed papers, 24 seminars, conferences and public lectures and two papers currently under preparation. These are as follows:

PhD Thesis

Mr Poasa Nauluvula (2018), "Understanding the sensitivity of cassava to rapid global climate change". University of the South Pacific.

Masters Thesis

Mr Pakoa Leo (2015), Growth and Developmental Responses of Taro, (*Colocasia esculenta* (L.) Schott) to Three Nitrogen Fertilizer Levels; Developing key insights for the purpose of Simulating management impacts using a biophysical crop model, University of the South Pacific, Samoa

Honours theses

Georgia Lloyd (2017), Effects of salinity on the growth and nutrition of taro (*Colocasia esculenta* (L.) Schott). Monash University, Melbourne.

Laura Steel (2015/2016), The effects of nitrogen concentration on morphology and biomass partitioning in taro (*Colocasia esculenta* (L.) Schott). Monash University, Melbourne.

Amelia Pegg (2014), The effects of salinity on the growth and toxicity of cassava (*Manihot esculenta* Crantz). Monash University, Melbourne.

Nikolai Macnee (2012), Responses of cassava and taro to elevated carbon dioxide. Monash University, Melbourne.

Alicia Brown (2011), The interaction of temperature and drought on cyanogenesis in cassava (*Manihot esculenta* Crantz) [experimental work supported by AusAID]. Monash University, Melbourne.

Melissa Bain (2010), The molecular and environmental regulation of cyanogenesis in cassava (*Manihot esculenta*). [experimental work supported by AusAID]. Monash University, Melbourne.

Rebecca Vandegeer (2010), The effect of drought on the growth and nutritional quality of cassava (*Manihot esculenta* Crantz). [experimental work supported by AusAID]. Monash University, Melbourne.

List of Publications arising from this project

1) Bredeson JV, Lyons JB, Prochnik SE, Wu GA, Ha CM, Edsinger E, Grimwood J, Schmutz J, Rabbi IY, Egesi C, **Nauluvula** P, **LeBot** V, Ndunguru J, Mkamilo G, Bart RS, Setter TL, **Gleadow** RM, Kulakow P, Ferguson ME, Rounsley S, Rokhsar, DS. (2016), Sequencing wild and cultivated cassava and related species reveals extensive interspecific hybridization and genetic diversity *Nature Biotechechnology* 34, 562–570.
2) **Gleadow** RM, Pegg A, Blomstedt CK (2016), Resilience of cassava (*Manihot esculenta* Crantz) to salinity: implications for food security in low lying regions. *Journal of Experimental Botany* 67: 5403-5413.

3) C. Cvitanovic, S. **Crimp**, A. Fleming, J. Bell, M. Howden, A. J. Hobday, M. Taylor & R. Cunningham (2016), 'Linking adaptation science to action to build food secure Pacific Island communities' (2016) 11 Climate Risk Management 53-62.
4) Taylor M, **Crimp** S, Dawson B, McGregor A, Cvitanovic C, Lough J, Thomson L, Howden M (2016), Adapting Pacific agriculture and forestry to climate change: management measures and investments. Chapter 10. pp. 483-518. In: Taylor M, McGregor A, Dawson B (Eds) Vulnerability of Pacific Island Agriculture and Forestry to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia.
5) Brown, A, Cavagnaro TR, **Gleadow** RM, Miller RE (2016), Interactions between temperature and drought stress on yield and nutritional quality of cassava (*Manihot esculenta* Cranz.). *Global Change Biology* 22, 3461–3473.
6) **Gleadow** RM and Møller BL. (2014), Cyanogenic glucosides- synthesis, physiology and plasticity. *Annual Review of Plant Biology* (Gleadow-invited review) 65: 155-85.

Seminars, Conference Presentations and Public lectures

1) Is there a trade-off between crop yield and nutritional value of food? University of the Third Age (U3A) Chadstone, Vic. 6 June 2017, 90 minutes.
2) Predicting the growth, resource partitioning and nutritional value of tuberous crops in response to environmental challenges. Gordon Research Conference 'CO_2 Assimilation in Plants from Genome to Biome', Lucca, Italy. 1 May 2017.
3) Impact of rising carbon dioxide on food security. University of Newcastle, NSW, 9 June 2017.
4) Impact of rising carbon dioxide on food security: the good, the bad and the surprising. ACIAR John Dillon Fellows seminar and panel discussion (3 hours), St Kilda, Vic. 16 Feb 2017.
5) Plants that kill: How climate change is changing our food. STEM Talks presentation, Faculty of Science, Monash, styled on TED talk, National Science Week, 16th August 2016.
6) Effect of salinity on defence metabolism in cassava, Climate change symposium, ComBio2016, Brisbane, October 2016.
7) Elevated CO_2 drought & nutrient supply affect growth, resource partitioning and nutritional quality of cassava and taro. Society of Experimental Biology annual meeting, Brighton, UK, July 7 2016,
8) Plant-growth defence trade-offs: implications for food security in a warming world. Department of Genetics, UC Berkeley, USA, Dec 16 2015.
9) Impact of rising carbon dioxide on food security: the good, the bad and the surprising. The University of the Third Age (U3A) Chadstone, Vic. 10 November 2015,
10) Plant defence-growth trade offs in a high CO_2 world: implications for food security, Plant Plasticity Centre, University of Copenhagen, 2 Sept. 2014
11) Elevated CO_2, drought & nutrient supply affect growth & nutritional quality of cassava & taro, International Horticultural Congress, Brisbane, 22 Aug 2014,
12) Pacific food security in a changing world. 29th International Horticulture Conference, Brisbane August 2014.
13) Plant defence-growth trade-offs in a high CO_2 world: implications for food security, Global Ecology, Carnegie Institute, Stanford University, California, USA, 17 July 2014.
14) Elevated CO_2, drought and nutrient supply affect growth and nutritional quality of cassava and taro. International Horticultural Congress, Gleadow, MacNee, Webber, Cavagnaro, Miller, Crimp. 18-22 August 2014, Brisbane.

15) Responses of cyanogenic tropical crops to climate change. ComBio2013, Perth, October 2013.
16) Responses of tropical root crops to climate change - implications for Pacific food security. American Geophysical Union Fall meeting. San Francisco. Gleadow, Macnee, Lisson, Hargreaves, Webber , Nauluvula, Crimp. December 2013 (poster).
17) Changes in defence chemistry of plants grown at elevated CO_2 may reduce their nutritional value. International Chemical Ecology Conference, Melbourne, Australia, August 2013.
18) Food security and sustainability Workshop on Sustainability in Education, Monash Sustainability Centre, 1 March, 2013. (15 minute talk, 60 minute panel).
19) Changes in defence chemistry of plants grown at elevated CO_2 may reduce their nutritional value. International Chemical Ecology Conference, Melbourne, Australia, August 2013.
20) Plant responses to global change: consequences for food security Olinda Probus Club, Vic. 24 March 14 2012, 50 minutes.
21) Understanding the sensitivity of a Pacific staple crop (Cassava) to elevated CO_2 and rapid climate change Report for the Secretariat of the Pacific Community (SPC). June 2012.
22) Understanding the implications of climate change for Pacific staple food production - a Cassava case study. 10th International Conference on Southern Hemisphere Meteorology and Oceanography, April 2012.
23) Implications of climate change for Pacific staple food production - a Cassava case study. Increasing Agricultural Commodity Trade (IACT) Programme, March 2012.

Appendix 2 Literature review - taro

Literature Review by Laura Steel for her honours project.

Introduction

Edible aroids are consumed by 200 million people in tropical regions around the world (Plucknett, 1976; Wang, 1983; Chandra, 1984). One of these, taro (*Colocasia esculenta* (L.) Schott) is an important food staple for the inhabitants of a large number of tropical and sub-tropical regions, namely in Southeast Asia and the Pacific. It is believed that Taro originated in North Eastern India and Asia (Kuruvilla and Singh, 1981; Hanson and Imamuddin, 1983; Ivancic, 1992). Today, it is cultivated in over 65 countries worldwide (USDA, 2001), with two gene pools for cultivated taro, one in Asia and the other in the Pacific (Lebot & Aradhya, 1991; Noyer et al., 2003; Kreike et al., 2004). Taro is one of the top five food crops for most Pacific Island countries, and for many consumers it is the first or second most important staple on a daily basis (McGregor et al., 2011).

The plant's storage organ, a corm, grows below ground and is rich in carbohydrates, but relatively low in micronutrients compared with other staples, such as coconuts and plantains. Taro plants also contain anti-nutritional compounds such as calcium oxalates and cyanogenic glucosides that function as chemical defences against herbivores. This review examines the role of taro in maintaining food security in the Pacific Islands, as well as some of the threats posed by climate change.

There are many challenges facing the production of taro as an export commodity and dietary staple. To guarantee the root crops continued success cultivators will require better knowledge and information concerning appropriate levels of fertiliser for optimal growth and development in a changing climate.

In 1978, taro was classified by The National Academy of Sciences as a neglected food crop with promising economic potential, however, there has been very little change in its status since then (Goenaga, 1995). This review is the first literature review on the biology of taro, the purpose is, therefore, to compile information of the physiology of Taro (*Colocasia esculenta* (L.) Schott), and the predicted responses to climate change. First, the importance of root crops in achieving and maintaining food security is discussed. Second, the growth and development of taro and its responses to environmental variables such as temperature and N availability are described. Finally, I outline an experimental design for research to address significant gaps in existing knowledge.

Food security and climate change

Climate change has the potential to cause drastic changes to agroecosystems in the Pacific, with some island countries already experiencing crop failures (World Bank, 2011). This has demonstrated the need to adapt in order to mitigate the effects of climate change in this region. Communities that rely on agriculture for their livelihoods are particularly at risk, as crop failure and loss of livestock would threaten their means of subsistence. For some Pacific Island countries, over 75% of the poor rely directly or indirectly on livelihoods linked to agriculture (FAO, 2011). The production of staple crops is critical the preservation of food security.

Producing substantial amounts of food for an increasing population is arguably the greatest challenge facing the world today (FAO, 2011). Over the past twenty years, food production (total/capita) has declined by 5-37% across the Pacific (WRI, 2011). This recent decline in agricultural production can be connected to changes in population growth and climate, such as more infrequent and unpredictable rainfall. Delayed rains during the harvest period can cause food shortages and subsequent spikes in the prices of staple foods, posing a significant threat to security (FAO, 2008).

Taro provides instrumental food security, both in the domestic market and in export earnings (Revill et al., 2005). It is considered a staple food crop in parts of Africa, Asia and the Pacific Islands (Agueguia et al., 1992). Taro is a significant commodity, supplying Pacific Island countries with 10,000-12,000 tonnes of export annually (valued at USD 6 million), 95% of which is from Fiji (McGregor et al., 2011). This can be attributed to the crop versatility and expanding uses, such as, the development of taro animal feed and the potential of taro alcohol as a fuel for remote islands (Griffin 1982).

Taro also has socio-economic importance which stems from its association with royalty, feasting, and traditional gift giving (Deo et al., 2009). This cultural identification has prompted an increase in the export market for Pacific Islanders living in Australia, New Zealand and western North America (Onwueme, 1999).

Morphology: *Colocasia esculenta*

Taro (*Colocasia esculenta* (L.) Schott) is a member of the Araceace family (aroids, or aroid lilies), which consists of about 110 genera with over 2500 species (Lebot, 2009). *Colocasia* belongs to the subfamily Aroideae, the main characteristics of which are; unisexual flowers, usually clustered, and rather simple spathes, leaf-like bracts that enclose the flower clusters (Lebot, 2009). Taro is an herbaceous, perennial root crop, 0.5-1.5m tall with leaves growing from the apical bud at the top of the corm and roots growing from the lower portion.

The central corm, a rounded underground storage organ, lies just below the soil surface with the root system residing primarily in the top one metre of soil. The corm serves as a storage area for nutrients and is similar to those found in cassava (*Manihot esculenta*), carrot (*Daucus carota*) and sweet potato (*Ipomoea batatas*) (Deo et al., 2009). Taro does not have a traditional stem but rather a series of long petioles, branching upwards and outwards from the base of the plant (Figure 11.2.1: Lebot, 2009). The length of the petioles can vary with genotype, from less than 30cm to more than 1.5m and the size of the leaves is influenced strongly by environment (Lebot, 2009). New petioles growing from the base of an established plant that emerge from the soil as seemingly separate individuals are called ‘suckers’. Genotypes with a large number of suckers are often not agriculturally desirable as they generally have a lower yield (Lebot, 2009).

Figure 11.2.1: Sketch of *Colocasia esculenta* (L.) Schott (taro) morphology depicting root system, petioles, and leaves (Lebot, 2009).

Taxonomically, there are eight varieties of taro, two of which are commonly cultivated (O'Sullivan et al., 1996). *Colocasia esculenta* (L.) Schott var. esculenta, sometimes referred to as the 'dasheen type', is characterised by a large tubular central corm with only a few side tubers or 'cormels' (Figure 11.2.2A; Deo et al., 2009). The cormels are often absent in dasheen taro plants, with the mother corm serving as the main storage organ (IPGRI, 1999). The second variation is *Colocasia esculenta* (L.) Schott var. *antiquorum* which has a small globular central corm with numerous comparatively large cormels arising from the corm (Figure 11.2.2B; Deo et al., 2009). This is known as the 'eddoe' type and these plants may have 5-20 cormels as big as the mother corm (Purseglove, 1972; Lebot and Aradhya, 1991; IPGRI, 1999). The Asia Pacific region is dominated by the dasheen type while *C. esculenta* var. *antiquorum* is preferred in areas where taro in grown for its leaves (O'Sullivan et al., 1996). The eddoe type is often considered genetically less improved and lower yielding than the dasheen type (Lebot, 2009).

Figure 11.2.2: (A) *C. esculenta* var. *esculenta* (dasheen) and (B) *C. esculenta* var. *antiquorum* (eddoe) (Deo et al., 2009).

Composition: Nutritional value and chemical defence

The taro corm is predominantly starch, making it low in fat (0.47%) and protein (6.43%) but rich in carbohydrates (85.65%), as well as being easy to digest (Oke, 1990; Adane et al. 2013). It contains some essential amino acids, but is lower in isoleucine, tryptophan and methionine (Onwueme, 1978). The corm size and shape are often dependent upon the types of plating material used as well as ecological factors, in particular soil composition (Lebot, 2009). The corm consists of a skin, cortex and core. The skin is fibrous with scales and can be smooth. The cortex lies between the skin and root initials and consists mainly of parenchymatic tissues (Lebot, 2009). The core contains similar tissues but may also include fibres. The taro leaves have a higher protein content and are an excellent source of carotene, potassium, calcium, phosphorous, iron, riboflavin, thiamine, niacin, vitamin A, vitamin C, vitamin B-complex and dietary fibre (Onwueme, 1978; Lambert, 1982; Hanson and Imamuddin, 1983; Bradbury and Holloway, 1988; Lee, 1999, Opara, 2001).

Taro possesses chemical defences, the side effects of which can be harmful if ingested by humans. Calcium oxalates (CaC2O4) are a characteristic defence of the aroids. They exist as raphides, needle-like crystals, in both monohydrate and dihydrate forms, which can be identified by their shape (Bradbury and Nixon, 1998). According to Holloway et al. (1989), the oxalate content for taro grown in Fiji ranges from 278 to 574 mg/100 fresh weight (mean 426 mg/100 g fresh weight). They are potentially dangerous to humans if taro is ingest raw. Common side effects include; swelling of the lips, mouth and throat, and choking, while more severe reactions result in breathing difficulties, liver or kidney damage, and even death (Bradbury and Nixon, 1998). Calcium oxalates can be removed through prolonged cooking or boiling (Moy et al*.,* 1979).

Cyanogenic glucosides are a class of plant allelochemicals present in the Araceae family (Siegler, 1981; Van Wyk, 1989). Taro plants synthesis cyanogenic glucosides (Triglochinin) as a natural defence against herbivory, releasing toxic hydrogen cyanide gas when the plant tissue is damaged. In cultivated taro, these concentrations are very low (Bradbury , Egan & Matthews 1995), thus do not pose a threat to human health. According to a study carried out by Bradbury, Egan and Matthews, wild varieties of *Colocasia esculenta* (Papua New Guinea) contain much larger amounts of cyanide then cultivated varieties, some of which show a complete absence of cyanide (1995). The study also found that there is a much more cyanide (7-30 times) located in the leaves as opposed to the stem. The same relative composition can be seen in cassava (Cooke and de la Cruz, 1982), where the cyanogenic glucosides are made in the leaves before being redistributed to the tubers (Makame et al., 1987). The higher concentration of cyanogenic glucosides in the leaves when compared to the stem is thought to be consistent with the idea that the leaves are more exposed and therefore more likely to be subjected to predation (Bradbury et al., 1995). The absence of cyanogenic glucosides in certain varieties indicates that the allelochemical defence is not universal in taro, however, there is a lack of knowledge and research on the ideal environmental conditions and nutrient levels for successfully encouraging corm growth and development or discouraging the production of chemical defences.

Growth: responses to temperature and resource availability

It is believed that Taro was introduced to the Pacific by Austronesian sailors, settling the islands of Melanesia and later Fiji (Horrocks and Nunn, 2006). Taro was most likely already cultivated by the indigenous people in New Guinea which allowed cultivars to be distributed into the Pacific Islands by the Austronesians (Yen, 1982, 1991). Today, taro is grown in many countries across Asia, Africa, and in some parts of America (Table 11.2.1; Lebot, 2009). Production is particularly high throughout Nigeria, however, Egypt has by far the highest average yield (Table 11.2.1; Lebot, 2009).

Table 11.2.1: Major aroid producing countries in 2006. Source: www.fao.org (2007) (Lebot, 2009).

Region	Country	Production (thousand t)	Area (thousand ha)	Average yield (t/ha)
Africa	Nigeria	5473	712	7.7
	Ghana	1660	260	6.4
	Cameroon	1200	220	5.5
	Ivory Coast	360	260	1.4
	Madagascar	200	30	6.7
	Rwanda	125.4	25.3	5
	Central African Rep.	100	37	2.7
	Egypt	100	3.4	29.4
	Congo	66	16	4.1
	Burundi	62	15	4.1
	Gabon	59	9.5	6.2
	Chad	38	12.5	3
	Guinea	30.5	4.9	6.2
	Sao Tomé and Principe	28	3.1	9
	Liberia	25.5	3	8.5
America	Dominica	11.2	1.2	9.7
	Trinidad and Tobago	4.9	0.5	10.2
	USA	1.8	0.2	12
Asia	China	1540	87.5	17.6
	Japan	184.6	15	12.3
	Philippines	111.9	18.2	6.2
	Thailand	78.4	7	11.2
	Solomon Islands	40	2	20
	Fiji Islands	38	3.2	11.9

Taro has a similar growth cycle to other aroids, which consists of six major growth phases; root formation, shoot development, increase in corn size, rapid dry matter accumulation in the aerial parts, predominant corm and cormel growth to maturity stage and, corm and cormel dormancy (Figure 11.2.3; Lebot, 2009). Shortly after a sucker is planted it begins to rapidly produce new roots (2-6 days after planting). During this phase, the plant relies on water and nutrient reserves. This initial phase can last 1-3 weeks, generally until the plant has established a functional root system. From weeks 3-10, new leaves are produced that allow the young plant to develop a functional canopy of 4-5 well-developed leaves. During weeks 10-20 the plant produces a shallow but extensive root system, radiating from 1-2m. The plant will also produce new leaves to replace any senescing ones. Dasheen-type plants tend to produce 5 or 6 leaves per main stem (Lebot, 2009). Between weeks 20-30, the plant grows to its greatest height and dry matter accumulates in the petioles which stiffen. From week 25 on, plant height declines while the main corm grows up until maturity (30-40 weeks, depending on plant genotype). After week 40, taro plants become dormant for 1-2 months until the climate is suitable for growth. Corm quality will deteriorate when the plant uses its own reserves in order to initiate new growth. In order to maintain corm quality, it is necessary to replant cultivars annually (Lebot, 2009).

Paradales (1985) found that total, corm, and vegetative dry matter differed significantly between most stages of crop growth, regardless of variety. When the dry matter accumulation in leaves and petioles started to decline up to 3 months after planting, there was a rapid increase in corm growth that followed a generally curvilinear pattern of accumulation (Paradales, 1985). Being able to predict biomass production is vital to scheduled harvesting (Shih and Snyder, 1984; Mohankumar and Sadanandan, 1990; Goenaga, 1995; Chan, 1996).

Figure 11.2.3: Growth Cycle of Taro (Lebot, 2009).

Taro requires a moist environment in order to achieve optimal corm production (Ezumah and Pluckett, 1973). As such, the main factor limiting crop yield in taro is water availability (Lebot, 2009). An even distribution of approximately 2,500mm annual rainfall is required for satisfactory growth and yield (Kay, 1973). Leaf area is often used as a measure of plant growth and development as it is relevant to transpiration and photosynthesis, making it an important determinant for dry matter accumulation and yield in taro (Satou et al., 1978, 1988; Jacobs and Chand, 1992; Chan et al., 1995, 1998). A deficit in soil moisture during the early growth and development of taro plants results in a distinct reduction in leaf area, the number of leaves, plant height, and corm yield (Paradales, 1979). Taro is sensitive to irrigation, preferring intensive cultivation (36t/ha in 8-10 months) compared to 20 t/ha in 12 months for the traditional Cuban taro cropping system (Rodriguez-Manzano et al., 2004).

The temperature range for maximum photosynthesis in taro is 25-35°C, with an optimum of 30°C (Lebot, 2009). Lower temperatures increase the number of days it takes plants to reach maturity and the lower the temperature, the smaller the corm yield (Prasad and Singh, 1991). Whether or not plants are shaded has a significant effect on corm yield and dry matter (%), as well as shoot and sucker weight, total plant dry weight, and the number of suckers (Table 11.2.2; Rogers and Iosefa, 1993).

Table 11.2.2: Effects of shade on taro (Rogers and Isefa, 1993).

	Fresh corm Yield kg/ha	Dry corm Yield kg/ha	Corm Dry matter %	Shoot Dry weight kg/ha	Sucker Dry weight kg/ha	Total plant Dry weight kg/ha	Suckers No.
Shade	5182	1614	31.0	404	1619	3637	93
No shade	4977	1424	28.5	271	987	2862	69

Nitrogen plays an important role in the growth and development of taro plants, however, high N uptake can result in copious leaf area development which can cause partial shading, and ultimately, reduced corn growth rates (Lebot, 2009). Upland rainfed taro, usually exhibit greater dry mass allocation in the corms under optimum N supply while in lowland irrigated taro, the corm dry mass is relatively low and stable across different N systems (Manrique, 1994). Nitrogen deficient plants usually experience stunted growth, with smaller, paler leaves. Current fertiliser rates are based on the crop's nutrient removal with wide variation in corm nutrient concentration (Blamey, 1996).

It is widely accepted that higher temperatures and elevated concentrations of atmospheric CO2 increase crop productivity in temperate regions. The impacts climate change will have on tropical crops and regions with already high temperatures are unknown. The nutritional content and quality of a crop is as important as the crop yield when considering future food security. It has been suggested that increasing atmospheric CO2 concentrations in staple foods such as cassava can reduced the plant protein content while also increasing the concentration of plant toxins (Gleadow et al*.,* 2009a). There is still much research to be done in this area and a great need to expand upon our understanding of the relationships between the yield and nutrition of food crops, particularly in relation to factors such as temperature and N availability.

Further study

The global yield of food crops has risen over the last twenty years (Fischer et al., 2014), largely owing to improvements in agricultural understanding and developments in the application of N-based fertilisers. However, there are some major food crops, such as taro, that have been neglected and remain under researched. This can be attributed to a lower profile and subsequent lack of funding. In 2009, Deo et al*.* stated that 'any research benefiting (taro) production would be worthwhile and beneficial to the entire Pacific region'. Similarly, a study of the Pacific Island taro market completed McGregor et al*.* in 2011 found that 'increased taro exports would result in significant benefits for large numbers of low-income rural people'.

A large portion of crop research is supported by International Agricultural Research Centres (IARCs). Despite the significant role played by taro in maintaining Pacific Island food security, there has been little to no IARC research conducted on *Colocasia esculenta* (L.) Schott. In order to discern the best methods for continued success in cultivating taro in the Pacific. I propose the development of a model for growth and resource allocation in taro. This model will assist in predicting how the species will respond to rising temperatures and inform cultivators on appropriate N supplementation for ideal corm development. Improving our understanding of taro growth patterns is the first step to constructing a theory for appropriate N application in a warmer climate.

Conclusion

The importance of taro in Pacific Island countries and its role in maintaining food security demonstrates the need to develop a model for agricultural management strategies in response to climate change. Given that there is little to no existing data on the growth of taro under elevated temperatures and different levels of N fertiliser the primary research aim for the proposed project will be to discern how *Colocasia esculenta* (L.) Schott responds to warmer environments with relatively higher or lower levels of N. The primary objective is to collect sufficient data to build a model suitable for predicting ideal N levels for growth and nutritional content in taro under warmer conditions. The secondary objective is to examine the conditions under which resources are allocated to chemical defences, such as calcium oxalates and cyanogenic glucosides, and to what extent.

Project description

This project forms a part of a study by the Plant Ecophysiology Group in conjunction with CSIRO, ACIAR and Fijian partners to understand the impact of climate change on taro (*Colocasia esculenta* (L.) Schott). The lack of existing data makes it difficult to develop a model for its growth and physiology in different environments. I will be growing taro at different levels of N fertiliser under controlled conditions in order to monitor plant growth, phenology, photosynthetic rates and biomass. These measurements will then be integrated with any existing data sets. This data will ultimately be used to develop an APSIM model to simulate biophysical processes in agricultural systems, in relation to the economic and ecological outcomes of management practices in the face of climate risk. Chemical analysis may also be used to determine the levels of nutritional and anti-nutritional compounds such as total N, protein, calcium oxalate and cyanogenic glucosides.

The study will involve 110 *Colocasia esculenta* (L.) Schott plants grown under a natural photoperiod in a greenhouse at 25-28°C in 5 nutrient treatment groups – 2.5, 5, 10, 15, and 20 mM N. Each plant will be watered by a sprinkler for 1 minute each day, in addition to receiving 1L of water containing the corresponding N solution twice a week. Measurements will be taken on a weekly basis, including; plant height, number of suckers, number of leaves and degree of senescence, length and width of healthy leafs, and lengths of petioles. Harvests will be done at 3 and 8 months and the biomass of roots and shoots will be calculated based on dry weight. Photosynthetic rates will be measured using the Li-Cor 6400 and further chemical analysis to test for cyanogenic glucosides and calcium oxalates may be carried out.

Nitrogen is an essential to plant growth and development. This project aims to discover how variation in N availability, in conjunction with increased temperatures, affects the physiology and resource allocation of *Colocasia esculenta* (L.) Schott. The general hypothesis is that plant growth will be greater in the presence of higher N levels. However, there may be a reduction in corm size where the plant experiences an abundance of N as well as when experiencing an N deficit. It is expected that low N availability will not facilitate large amounts of corm development. On the other hand, given that the corm is a storage organ, the consistent availability of adequate N may result in reduced pressure for the plants to devote resources to storage. In these instances, it is expected that higher resource allocation, and subsequently greater biomass, would be apparent in other areas, such as leaves, roots, and defence systems.

Photo: Kava ceremony to celebrate the successful completion of the first harvest.