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Interim report

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3 Background

Soils are the key foundation of land-based agricultural production but are often poorly understood and managed. World-wide soils knowledge is being lost, and the Pacific is no exception. In the Pacific much of the soil survey and research work was carried out prior to the 1990s. Post 2000 soil surveys are relatively rare, and many of the scientists and pedologists experienced in the Pacific are now retired. While much of the data remains intact and relevant, they are not easily accessible or understandable without expert interpretation and advice. The Pacific Soils Portal, an on-line soil information system, was the subject of a feasibility study funded by the French Government (Barringer, Gibb et al. 2006) to utilise existing soil data to improve management. Positive feedback was received during stakeholder engagement for that feasibility study, and the subsequent endorsement by key government officials from 19 Pacific island countries and territories (PICTS) through the Regional Conference of the Heads of Agriculture and Forestry Services (HOAFS) in both 2006 and again in 2008. The 2008 endorsement recommended that SPC/LRD collaborate with Manaaki Whenua Landcare Research (MWLR) to establish the portal as part of SPC/LRDs strategic plan. Unfortunately, the political situation in Fiji and the impact of the global financial crisis on funding intervened. The project stalled until the emergence of the Global Soil Partnership which led in October 2014 to the Pacific Soil Partnership and from meetings of that group to a new opportunity to develop a Pacific Soils Portal which culminated in this project.

The FAO Pacific Soil Partnership meeting held in Nadi (2015) reviewed the status and management of soils and the major required research areas in each member country (PSP 2016). The group identified how comprehensive nutrient budgeting and benchmarking soil biological function is essential for improving farm productivity and agricultural resilience on volcanic islands and coral atolls. At present, extension officers are unable to reliably ascertain which nutrients (or other factors such as pests, diseases, and other soil constraints) are limiting production let alone recommend optimal nutrient inputs. The lack of access to information on soil types and their distribution further limits the ability to extend the results from research studies or well-understood farming systems to other locations across the Pacific. The meeting concluded that to meet the immediate soil challenges in the PICTs three main activities must be undertaken:

1. Improving nutrient and water management in both high volcanic islands and low-lying atolls

2. Proceeding with the development of the Pacific Soils Portal originally proposed by the SPC and MWLR and incorporating recent developments in information and computing technology. The principle behind the portal is to make soils data more accessible to a full range of stakeholders and end-users. Accessibility both in terms of discoverability and accessibility, but also in terms of being more easily understood by stakeholders. The Pacific Soils Portal would also leverage work carried out by MWLR on its own Soils Portals (https://smap.landcareresearch.co.nz and https://soils.landcareresearch.co.nz).

3. Promoting innovation in capacity building and training with a particular focus on extension services for smallholder farmers.

The Pacific Regional Soil Partnership meeting (Nadi December 2015) and the Volcanic and Atoll Soil workshop (Nadi August 2016) identified that while there are many interacting barriers (Figure 1) the lack of soil knowledge contributes directly to inefficiencies and prevents effective management to improve yields and sustain the base in both the low and high input systems of the PICTs.

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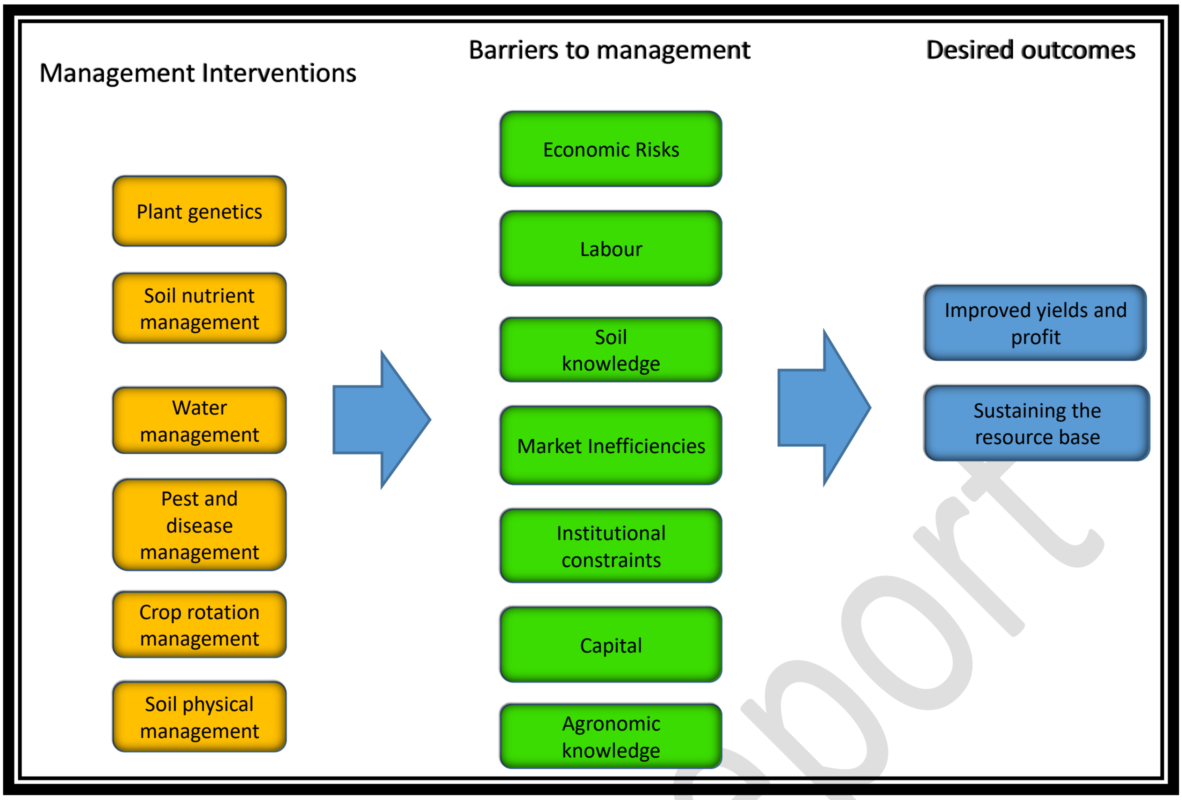

Figure 1. Current identified barriers to improving soil fertility management, yields and profit.

The idea of improving soil knowledge to provide a reliable foundation for sustainable intensification of agricultural systems forms the primary longer-term outcome of this current research project's pathway to impact (Figure 2). The pathway to impact enabled the setting of the 4 core research questions that the project investigated. These were:

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1. What are the barriers to adopting improved nutrient management systems?
2. What are the budgets for key nutrients and how can nutrient availability be managed in taro cropping systems to improve crop yield?
3. What soil sampling, testing and interpretation protocols should be used on different soil types across the Pacific?
4. What are the most effective methods for providing technical information to key stakeholders (e.g. farmers, family members, farm advisors, and input suppliers) by the soil portal so that management decisions are optimal?

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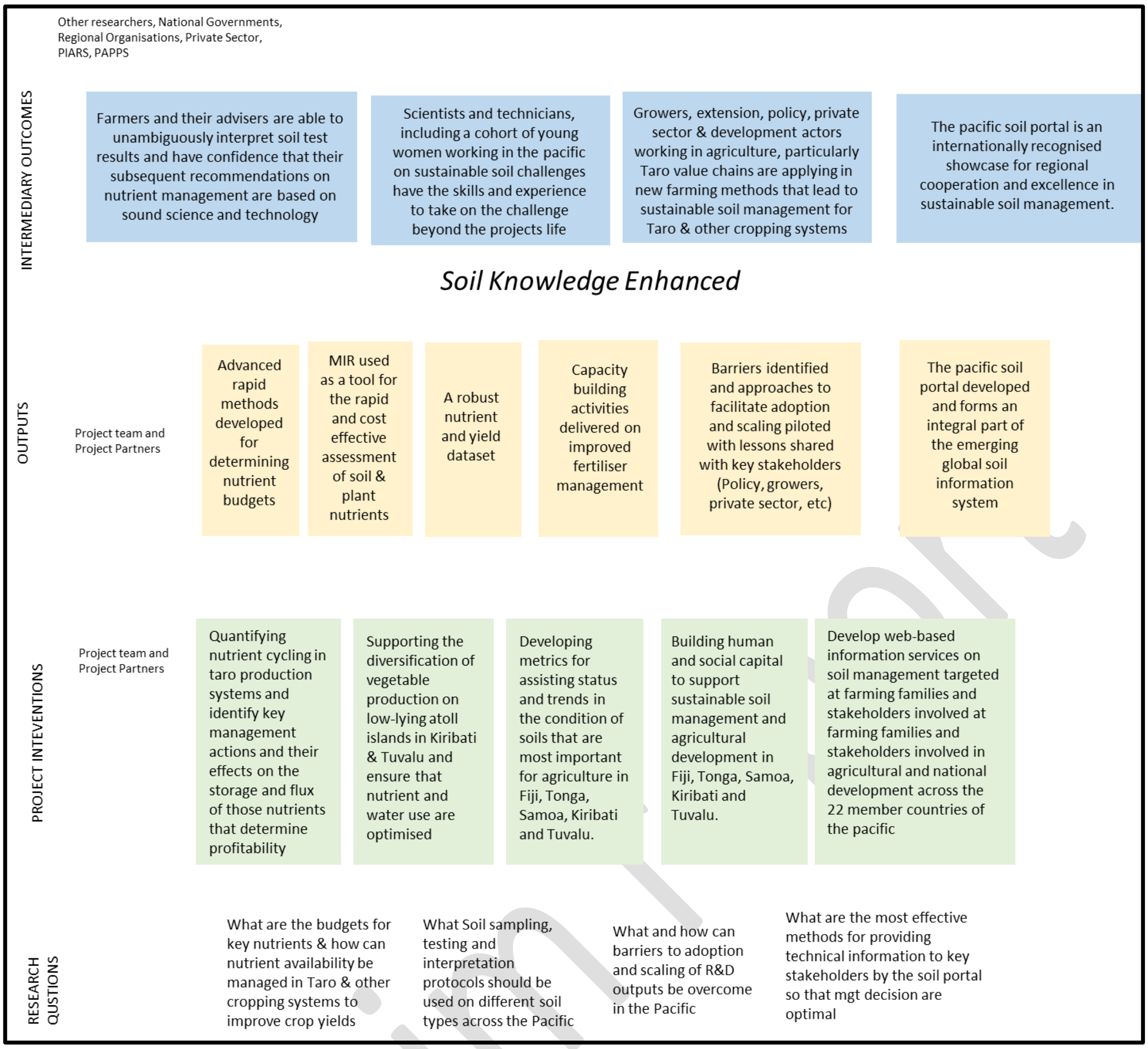

Figure 2. The project's pathway to impact research questions to intermediatory outcomes.

The longer-term outcome is to develop sustainable intensification of agricultural systems based on sound soil knowledge and farming system management (Figure 3).

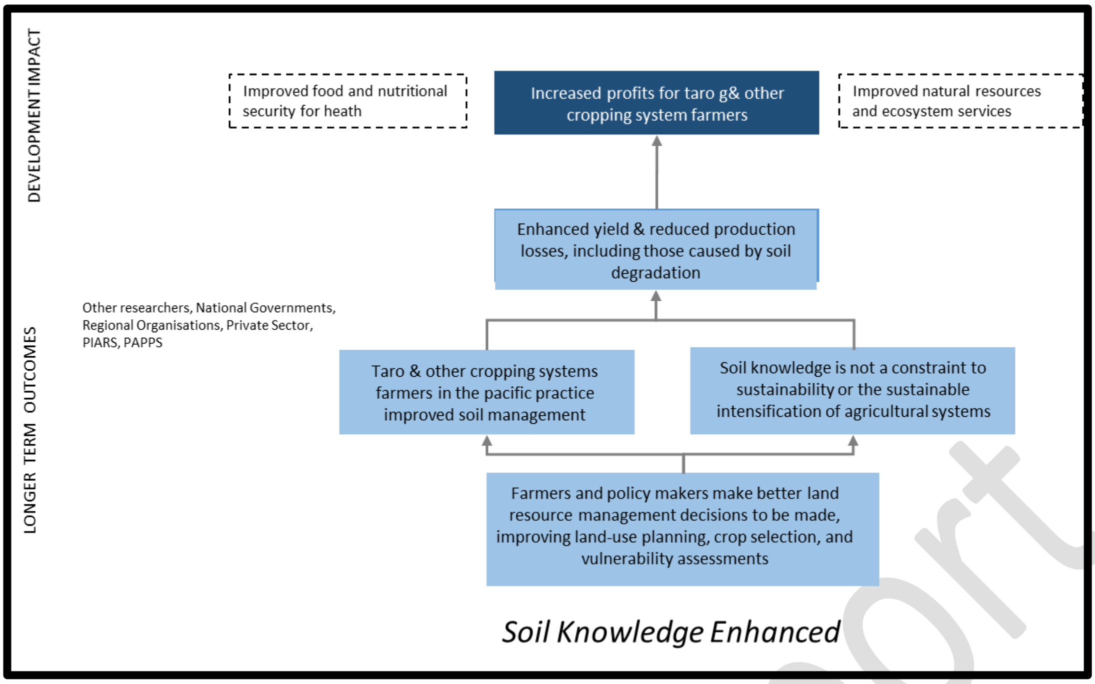

Figure 3. Pathway to impact-longer term outcomes to development impact.

During the project numerous obstacles have been encountered which have required project replanning. These included 3 category 5 cyclones, two disease outbreaks (COVID-19 in 2020 and Samoan Measles in 2019) and organisational issues. The biggest impact on the project has been the COVID-19 pandemic, which shut down international and domestic travel and logistics. It also meant that in-country project staff were mobilised for public health activities and associated tasks. In March-April 2020 the project team evaluated the original planned activities considering the COVID-19 restrictions and achieving the pathway to impact and as part of the monitoring and evaluation of the project the activities were modified to suit operation conditions. In-country managers independently reassessed and replanned project activities with the project team to meet the project pathway to impact. The project activities are documented in Section 6.

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4 Objectives

The aim of the project was to ensure that soil knowledge is enhanced and provides a reliable foundation for sustainable intensification of agricultural systems. The linkage between each research question and objective is presented in Table 1.

Table 1 Project research question and objectives.

Project Questions	Objectives	Title
What are the barriers to adopting improved nutrient management systems?	Identify past and *overcoming** current barriers.	Solutions
What are the budgets for key nutrients and how can nutrient availability be managed in production systems to improve crop yield?	Quantify nutrient cycling in island agricultural and production systems and undertake field trials to highlight the importance of budgeting for soil fertility management and increasing yield.	Nutrients
What soil sampling, testing and interpretation protocols should be used on different soil types across the Pacific?	Identify problems with current soil sampling, testing and interpretation protocols and develop soil-type specific protocols.	Testing
What are the most effective methods for providing technical information to key stakeholders by the soil portal so that management decisions are optimal?	Develop the Pacific Soil Portal to enable sustainable soil management in the farming systems of the region.	The Portal

*Objective 1 At the mid-term review as part of the monitoring and evaluation process the project team with ACIAR decided to shift focus from identifying barriers to adopting improved nutrient management systems to implementing an extension strategy that overcomes the barriers. This change was made to ensure greater project impact.

Objective 1 Solutions

The Solutions Objective explored barriers to the adoption of soil knowledge and piloted different solutions (i.e., traditional and non-traditional extension approaches) to enhance knowledge and uptake of soil technology and knowledge in the Pacific. The primary focus for this objective was Fiji and Tonga, the countries of the projects two main sites, with lessons and insights from these activities to be applied and adapted to other Pacific Island Countries and Territories.

Adoption and scaling of soil knowledge and technology in the Pacific has been an ongoing challenge for decades. The literature highlights a range of barriers from lack of knowledge, lack of access to knowledge, lack of market access, non-fit for purpose incentives and regulations, and lack of access to finance, to name a few.

This objective primarily focused on exploring barriers associated with knowledge, including sources of knowledge and the connections between sources. By using an agriculture knowledge and information systems lens the objective identified key actors in the soil knowledge and information system, how they work together or not and experimented with piloting fit for purpose solutions that leverage synergies and connections across the systems. It focused on identifying the different actors (e.g., farmers, agronomists, government, agribusiness, NGOs, etc), and piloting different approaches to be aimed at building capacity of individuals and connections across the system more

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broadly to enhance collective action for improved soil management policies and practices for sustainable soil at a farm, national and regional level.

Objective 2 Nutrients

The project's Nutrient Objective seeks to quantify nutrient cycling in island agricultural production systems and undertake field trials to highlight the importance of budgeting for soil fertility management. Through this objective country nutrient imbalances were determined and highlighted to government, growers and extension; and aimed to improve farm fertiliser management via measurement of nutrient flows and extension of findings. Development and verification of nutrient management practices was conducted through field testing of soil nutrients and plant yield. Introducing these practices was key for the wider adoption of improved nutrient practices across different agricultural industries on similar soil types.

Objective 3 Testing

Activity 3.1. Review current soil sampling, testing and interpretation protocols used in PICTs.

Effective nutrient management and soil monitoring and evaluation requires accurate measurement and interpretation. While this principle is easy to adopt, there are many challenges in developing practical systems of soil sampling, measurement and diagnosis, especially for complex smallholder systems such as those in the Pacific.

Sampling

In many nutrient studies, sampling is often confined to the upper 0-10 cm of the soil profile. However, the full root zone of the crop usually extends much deeper. The rooting depth for taro and some vegetable crops, e.g., is between 0-60 cm (HORT/2012/011), thus some of the large amount of nutrients exported below 10 cm. A key challenge for taro production is to define appropriate control volumes and sampling protocols to capture soil variability that enable calculation of robust nutrient budgets.

Measurement

Most testing procedures have been developed for permanent-charge soils, which dominate in temperate regions. Soils with variable charge are particularly common in Fiji, Samoa and Tonga. The use of permanent-charge methods on soils with variable charge will lead to inflated estimates of nutrient retention and supply. Concerns have been expressed that inappropriate methods are being used (Curtin, Naidu et al. 1991) leading to the risk of faulty recommendations on nutrient management.

In sharp contrast to the soils of the volcanic islands are those derived from calcareous parent materials (e.g., corals). These alkaline coarse textured soils are common on low-atolls (e.g., Tuvalu and Kiribati) and their fertility is controlled primarily by the composition and amount of organic matter. Multiple deficiencies of macronutrients (e.g., N, P, K, and S) and micronutrients (e.g., Fe, Cu, Mn, and Zn) are further exacerbated when these soils are used for agriculture. Interpreting soil test results is particularly difficult because methods have not been calibrated with crop growth and standard tests are not applicable because of the unusual physical and chemical properties of these soils (Deenik and Yost 2006).

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Activity 3.2. Utilise MIR to make rapid assessment of calcareous and volcanic soil fertility

The use of infra-red spectroscopy under laboratory conditions such as FT-IR (MIR, mid-infrared) spectroscopy to characterize soil properties of agronomic importance rapidly and cost-effectively is well-established. MIR has been demonstrated to be used for the simultaneous estimation of soil physical, chemical and biological properties including particle size – clay and sand content – soil mineralogy, soil organic carbon (SOC), total carbon (TC), total nitrogen (TN), soil pH, electrical conductivity (EC), cation exchange capacity (CEC), exchangeable cations such as Ca, Mg and K and available P (Stenberg, Viscarra Rossel et al. 2010, Soriano-Disla, Janik et al. 2014). MIR spectroscopy has also been used with success for determining soil chemical properties of Columbian and Hawaiian variable charge soils (McDowell, Bruland et al. 2012).

Recognising the potential of MIR spectroscopy and its impact on soil analysis operations, laboratory-based FT-IR (MIR) technology was introduced to ACIAR projects in the Philippines (SMCN/2009/031) and Myanmar (SMCN/2014/075) (Ringrose-Voase, Grealish et al. 2019). These projects demonstrated that adoption of MIR spectroscopy can be achieved through standard protocol development and training. Building on this work, the aim of SMCN/2016/111 was to introduce this new rapid soil measurement technique to the PICTs through building IR spectroscopic capacity at the Fiji Agricultural Chemistry Laboratory, Ministry of Agriculture (FACL MOA), based at Koronivia research station. More specifically, our objectives were to (1) introduce MIR soil sample preparations and measurement, as well as soil spectral inference and quality control analysis protocols at FACL MOA; to (2) test MIR spectroscopy for estimating soil properties of agronomic importance for calcareous and volcanic soils; and to (3) build pilot soil spectral reference libraries for the PICTs forming the basis for calibration model generation, ultimately enabling the rapid estimation of PICT soil fertility status and uptake of the technology as a valuable tool for rapid and cost-effective assessment of soil in the PICTs, complementary to traditional wet chemistry analysis.

Objective 4 The Portal

Soil surveys have been completed for most PICT countries in the 1960s, 1970s, 1980s and 1990s (Barringer, Gibb et al. 2006, Leslie 2010), intended to support better land-use planning and improve soil management. However, these 'legacy' soil surveys have been under-utilized. Thus, there was a significant opportunity to reanalyse much of these 'legacy data' and take advantage of some of the new technologies that have arisen from the digital information revolution. Much of the legacy soil information resided in government hard copy data, soil reports and scientific publications which were neither easy to obtain, nor easily interpreted by agricultural extension officers and farmers. Therefore reanalysis and repackaging of this PICT legacy soil information via a 'Pacific Soils Portal' has been discussed (Barringer, Gibb et al. 2006, SPC 2008b) and considered to be required (SPC 2008a). The incorporation of addition local soil data, where available was also discussed. Under this project the 'Pacific Soils Portal' was therefore developed, with the aim to become a key tool for PICT agricultural extension officers and farmers, facilitating:

- upscaling of research results,
- identification of strategic locations for future farming trials,
- incorporation of traditional knowledge into robust technical systems for describing and managing soils.

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5 Methodology

5.1 Objective 1 Solutions

Activity 1.1.

A rapid diagnosis of the Agricultural Knowledge and Information Systems in Fiji and Tonga was undertaken to reveal how soil knowledge and information is exchanged or communicated between people, networks, and institutions. The assessment was implemented in collaboration, using key informant interviews and small group discussion with 30+ farmers, government extension officers, the private sector, donor funded development programs, government research officers, farmer groups, government policy officers and NGOs. Key findings from the diagnosis highlighted the range of actors engaged in the soil knowledge and information system and case studies of effective extension and agricultural advisory approach (i.e., both traditional and non-traditional knowledge transfer approaches), the different sources of soil knowledge farmer draw upon and along with the degree of effectiveness of transfer and utilisation of the knowledge shared.

Activities 1.2 & 1.3.

Findings from the diagnostic assessments were used to identify opportunities to inform the design and implementation of different extension activities (pilot approaches) to identify context relevant approaches that could be used to share key results from Objectives 2, 3 and 4. The aim being to explore different approaches and processes that identify policy and practice priorities and co-created actionable activities that are contextually designed and owned by the stakeholders attending the meeting (e.g., farmers, private sector, extension officers and policy actors). These pilots were implemented in collaboration with contracted consultants in each PICT country, SPC, in-country partners and the leaders of Objectives 2, 3 & 4 to ensure the timings aligned with other activities where possible and the right stakeholders were invited to the meetings.

5.2 Objective 2 Nutrients

Activity 2.1. Calculate supra-national scale soil nutrient balances.

The method described in Stoovogel *et al*. (1993) was used to calculate supra-national scale soil nutrient balances. This method is based on determined country wide land/water classes (LWC) and land use systems (LUS) based on existing FAO data and soil mapping. The organic and inorganic fertiliser inputs for each LWC were determined from FAO records, country databases and existing knowledge. Wet and dry deposition are important in low input island systems and data is available for the Eastern Pacific. Outputs of nutrients were derived from harvested products in the FAO and country databases. For each LUS these figures are multiplied by nutrient contents in the harvested parts. Nutrient losses via leaching and nitrogen gas emissions were determined from the literature. Total elemental inputs from food imports were also determined.

The nutrient mass balance was calculated by:

Nutrient Mass Balance= Inputs -Outputs (Exported plant material)

N was assumed to have a 40% loss because it was surface applied.

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In Tonga the project team resampled locations from historic soil surveys (Gibbs 1976, Potter 1986, Cowie, Searle et al. 1991) through a collaboration with Monash University and the Crawford Fund. Shaun Krawitz, Monash Honour Student worked with MAFFF and CSIRO to undertake a research project. The findings can be found in Appendix 1.

Activity 2.2. Identify and set-up field sites.

Field sites were identified by project partners with the aim to enable the measurement and testing of nutrient flows within taro cropping systems. Participatory resource assessments regarding agricultural soil nutrient management challenges, barriers, impact pathways, and solutions were conducted.

Activity 2.3 & 2.4. Determining inputs and outputs at the plot level.

Prior to the taro growing season soil nutrient concentrations were determined. During the season inputs from organic and synthetic fertilisers were measured by field staff and/or the farmers. Nutrient output pathways were measured during the growing season and included any plant or residue that was removed from the site. Plant samples were collected and analysed for elemental content. Nutrient measurements and budgeting and soil fertility assessment by on-ground staff at farm measurement plots occurred in collaboration with the growers. These learning coalitions filled an important soil knowledge gap.

Activity 2.5. Soil water and nutrients

Chameleon soil water sensors and wetting front detectors are currently being used in LWR/2014/085 and LWR/2016/137 to improve water productivity in African farming systems. In this project, Chameleon field soil moisture and wetting front detectors were utilized to determine nutrient leaching (Fiji, Tonga) and improve irrigation scheduling (Kiribati and Tuvalu). Wetting front detectors were used to identity the depth of the rainfall and the irrigation wetting front and supplement the chameleon soil moisture sensors. At the Samoan sites, the soils were characterised for water retention and infiltration.

Activity 2.6-2.7. Extension activities

Soil nutrient budgeting and soil fertility information was disseminated to growers and extension officers to build the soil knowledge base.

5.3 Objective 3 Testing

Activity 3.1. Review current soil sampling, testing and interpretation protocols used in PICTs

SPC subcontracted Objective 3.1 activities which included reviewing soil sampling, testing and results interpretation to the University of the South Pacific's School of Agriculture, Geography, Environment and Ocean and Natural Sciences (USP SAGEONS), with Dr Md Abdul Kader as consultant in late October 2020. Two approaches were taken in conducting the review, those included a prepared survey questionnaire and consultations either face to face where possible or virtual (due to Covid travel restrictions). The questionnaire comprised of a total of 21 questions covering soil sampling and testing: i) selecting of areas to sample, ii) procedures to collect soil samples, iii) sampling equipment, iv) soil sample handling and information, and v) analysis methods for soil macro and micro-nutrients. For a wider participation, the questionnaire was sent to both the Soils Project's participating, and non-participating countries. However, the response was limited with only three regional laboratories which are operational in Fiji and Samoa participating.

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The laboratories, who participated, included the Fiji Agricultural Chemistry Laboratory, Ministry of Agriculture, the Scientific Research Organisation of Samoa (SROS) soil laboratory and the USP soil laboratory. Further discussions were then held with staff of these laboratories after the questionnaires were returned.

Activity 3.2. Utilise MIR to make rapid assessment of calcareous and volcanic soil fertility

Under Activity 3.2, the approach was taken to introduce laboratory-based MIR spectroscopic measurement capability at FACL MOA, Koronivia research station in Fiji and to assess its capability for making rapid assessment of calcareous and volcanic soil fertility.

A small (shoe box size) Bruker Alpha-II-FT-IR (MIR) instrument was purchased and installed at FACL MOA in May 2018. Following installation, a five-day hands-on "MIR spectroscopy" training course (5-11 May 2018) was held by Dr Anthony Ringrose-Voase, CSIRO, for eleven FACL MOA staff at Koronivia research station to introduce the main principles, protocols and step-by-step training materials regarding soil property estimation utilizing MIR (also see Figure 4 and Appendix 1) soil specimen preparation for MIR analysis,

1. operation of the MIR instrument through the Bruker Opus software including protocols for soil specimen scanning,
2. calibration model generation using a set of spectral data and associated analytical data using the Bruker Opus software, and
3. prediction of a range of soil properties using spectra and the calibration models established through the Bruker Opus software and a customized Excel Macro template.

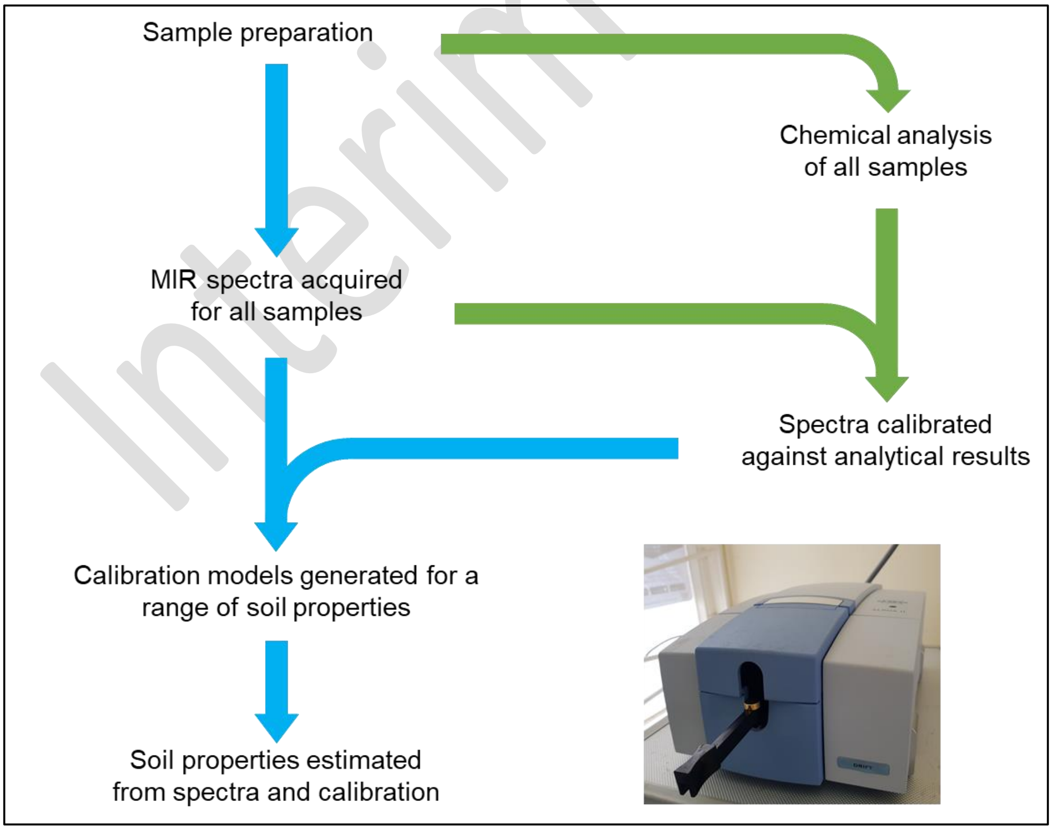

Figure 4 Workflow for soil property estimation utilizing MIR.

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For MIR analysis, the soil specimen was first air-dried and sieved to <2 mm, followed by oven drying at 40/60°C and fine grinding to a grain size of 0.5 mm by hand using an Agate mortar and pestle (Figure 5). All soil samples were analysed and loaded onto single sample plates in quadruplicates and from these diffuse reflectance MIR (DRIFT) spectra were obtained between 6,000 and 600 wave numbers (about 5 min per soil specimen scanned in quadruplicates). Wave numbers from 4,000 to 600 were then used for calibration model generation and soil property predictions. Soil samples used for the building of PICT spectral reference libraries were analysed for the soil chemical properties of interest using the soil analytical services laboratory at FACL, MOA. A sub-set of samples was also analysed at the Chemistry Centre, Department of Environment and Science, Queensland government, Australia, to compare the laboratory results between the laboratories.

The OPUS Quant 2 software module (Version 7.8, Bruker, Germany) was used to build Partial least squares regression (PLSR) models between MIR spectra and associated analytical soil chemistry data. Calibration models were constructed for each soil attribute individually, and the Quant 2 optimise facility was used to determine optimal spectral pre-processing prior to model building. The calibration models were then used to predict soil chemical properties from the spectra for each of the four replicates per soil specimen. Quant 2 reports the Mahalanobis distance (De Maesschalck, Jouan-Rimbaud et al. 2000) and F-statistics probability, which are used to test if spectra fall outside the spectral domain of the calibration set. The four replicate predictions were examined and any prediction results that were deemed outliers based on their Mahalanobis distance from the calibration set or did not fall within the range of the calibration, were excluded. The remaining replicate predictions were then averaged per soil specimen. In the instance of less than two acceptable predictions, no mean result was produced for that soil specimen and reported as “NA”. The latter quality control assessments of the predictions were implemented through a customized Excel Macro template for ease of use.

MIR was used to predict soil organic carbon content (%), pH in water, electrical conductivity (dS/m), total Nitrogen content (%), exchangeable cations of Ca, Mg, K, Na (me/100g), extractable Fe, Mn, Cu, Zn (mg/kg), and Olsen available P (mg/kg).

Figure 5 MIR soil specimen preparation in quadruplicates.

Following the “MIR spectroscopy” training course and in-country supervision through the CSIRO team, the team at FACL MOA led by Radheshni Singh started to get familiar with and independently set up MIR operations including spectral inference workflows using the OPUS software and quality control assessments using the customized Excel template. In the first instance, FACL MOA existing archival soil samples from across Taveuni, Fiji, were scanned with MIR with the aim to form the basis of building spectral reference libraries and calibration datasets to rapidly estimate soil chemical properties through MIR spectra for Taveuni. Subsequently, soil samples from ACIAR field trials in Taveuni, Fiji, and Tongatapu, Tonga, and from the new Soil Health Card program were processed using MIR and traditional soil laboratory analytical measurements to build regional and local MIR spectral reference libraries for the PICTs and to assess the predictive power of calibration models generated from these.

Due to the Covid-19 pandemic this activity was re-scoped and planned in-country refresher training and troubleshooting was conducted as best as possible through online platforms. This activity was also impacted by the damage of the Bruker MIR instrument in 2019 and subsequent repairs and testing in Australia, as well as FACL MOA wet chemistry laboratory renovations in 2020/2021. This meant that for the majority of 2019 and 2020, MIR analysis was paused at MOA FACL.

5.4 Objective 4 The Portal

Methodology (Activities 4.1-4.9) for developing a soils portal can be divided into four components

- User engagement and user needs
- Data discovery and harmonization
- Portal Design
- Governance

Component a. User Engagement and User Needs Assessment

Initially 12 personas were developed with three primary personas (agricultural extension officers in Fiji, Tonga and Samoa), and nine secondary personas (ranging from a Head of Extension, Research officer, Field Researcher, Policy Makers, Scientist, Fertiliser Salesperson, and a semi-Subsistence Farmer). Five additional personas were recorded during discussions at the project inception meeting, these included a larger commercial farmer and a Donor representative. These personas were developed by small groups of potential users with different backgrounds inventing a hypothetical user based on a known role (e.g., agricultural extension officer) and developing a user story about this person's job, what their information needs might be and then how these might be serviced.

These personas informed the high-level user requirements for the Pacific Soils Portal. All these requirements were summarised in a tabular format and were assessed against the available soil legacy data and prioritized to deliver against as many of the user needs within the limits imposed by available data and the resourcing for the project.

Component b. Data Discovery and Harmonization

Best available data

The objective of the soil portal is to make best available data easily accessible and available to users. These legacy data were not new and originated from multiple PICT countries, representing soils in difference of scales, and representing soil data from different time periods, and often were collected using different standards of classification or analysis depending on the practitioners involved.

Soil maps

For each PICT country, research soil survey history was identified, and the best available legacy soil maps acquired. Hard copy maps were scanned, and georeferenced map images digitized into GIS vector format, where possible the coordinate and projection information from the maps was used, and where insufficient projection or coordinate information was available, scanned images were georeferenced to the ESRI World Imagery data service.

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Any soil maps already in suitable digital form, along with digitized hard copy maps were re-projected to the standard projection of the World Geodetic System 1984 (WGS84), to prepare for the standards required for inclusion in the web map services of the portal.

References were recorded and where possible links to soil reports and maps made available in the Resources section for each PICT country's soil portal.

Collating soil profiles and analytical data

Similarly to soil maps, soil profile data were researched and collated from soil survey reports and other published legacy sources. Only profiles with a mapped or recorded location sufficiently accurate to be given a WGS84 latitude/longitude coordinate with an estimated accuracy of ±100m were included in the portal. Where possible profile locations were digitized from soil maps, or other small-scale maps in soil reports, and checked against any recorded location information.

Harmonizing soil profile data

In the context of the Pacific Soils Portal, data harmonization was followed to encompass the act of storing and managing data and associated metadata so that it conforms to international data standards and data sharing protocols.

Because some Tongan, Fijian and Samoan profile data were already held in the New Zealand National Soils Data Repository (NSDR), which already conforms to international standards and protocols, harmonization of data was achieved through entering the data from disparate sources into a consistent template and utilizing an existing database schema for laboratory methodology metadata to import the data into a database with the same schema as the NSDR.

Component c. Portal Design Principles

The Pacific Soils Portal follows simple design principles both in terms of technical approach and in terms of user interface. These include:

Standards-based: The portal was built around OGC software and standards to facilitate integration both within the portal components and between other systems that can more easily consume or interface with a portal that complies with internationally recognised standards.

Fast: The portal utilises Web Map Tile Service (WMTS) OGC standards to deliver pre-prepared image tiles of the soil map to the map user interface to give maximum draw performance combined with geographic coordinates captured by mouse click from the map interaction to initiate a point-in-polygon query to a separate PostGIS soils dataset to return query responses and soil fact sheet contents.

Modular: The web site was developed independently from the web service and web map services which it consumes, so that each module can be updated, improved or added to without necessarily needing to make changes to any of the other modules.

Browser-based responsive web site design: A device independent web site was developed, which responds smoothly to the different size screens facilitating use of desktop, laptop, tablet and mobile devices using the same web site.

Map-based: The portal facilitates data discovery by location following the general user interface conventions of Google Earth and other web mapping standards to maximise ease of use.

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User-friendly: The portal was designed targeting non-technical users to minimize training requirements.

Metadata: These were developed to conform with Dublin Core and ISO 19115/19139 standards.

Component d. Governance

For the Pacific Soils Portal a governance structure was established that provides:

- Representation for participating countries in strategic decision-making while providing technical support through observers from MWLR, SPC, CSIRO and the GSP/PSP.
- A Data Sharing Agreement ratified by the Governance group to ensure that all parties are satisfied with the way in which data for their country are being shared. This includes support for internationally accepted compliance with privacy legislation.
- A Hosting strategy for the portal during and after the completion of the project.
- A funding strategy for the portal to provide support for the hosting agency, to manage support, technical updates/maintenance, and potential for the portal to expand to include additional country's soil data.

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6 Achievements against project activities and outputs/milestones

6.1 Achievements to date

Objective 1: Solutions

No.	Activity	Outputs/ milestones	Completion date	Comments
1.1	Identify barriers, incentives and opportunities within the agriculture innovation system that affect the diffusion and adoption of knowledge and technology in taro farming systems, including soils)	Key stakeholders engaged in the knowledge systems of the two main sites have been identified	1/10/19	A map of the actors in the Soil Knowledge& Information Systems in Fiji and Tonga was presented at the Mid-Term Review
1.2	Engage key stakeholders at the country level in a discussion about options / pilots for interventions to overcome barriers to adoption identified in the diagnostic study	A virtual training and extension plan has been developed	28/02/22	A virtual training and extension plan was developed as a response to COVID-19 – refer to Appendix 1. In addition to virtual trainings, contractors were engaged in countries where face to face workshops and training were possible. Approximately 775 people participated in face-to-face trainings and workshops. An addition 72 people participated in three (3) National Workshops to share lessons and raise awareness and knowledge about soil health and better soil management policies and practices, including fertiliser in Tonga. Two more national workshops are planned before the end of the project to share lessons and raise awareness and knowledge about soil health and better soil management policies and practices – one in Samoa and one in Fiji.

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1.3	Engage with key stakeholders at the regional level in a discussion about options / pilots for interventions to overcome barriers to adoption identified in the diagnostic study about the policy	A virtual training and extension plan has been developed	1/10/21	In addition to the above, online presentations to two virtual regional workshops were on: • Improved nutrient use and manure management towards sustainable and resilience; using soil test results to guide fertilizer use in Fiji, and Nutrient balance sheets in a Tongan cropping system to the FAO facilitated KJWA Pacific Chapter • the Importance of Soil Biodiversity for the Pacific Islands

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Objective 2: Nutrients

No.	Activity	Outputs/ milestones	Completion date	Comments
2.1	Calculate supra-national scale soil nutrient balances for Fiji, Tonga, Kiribati, Tuvalu, and Samoa.	Policy discussion paper under development. Paper submitted Pacific Science	1/10/21	Completed.
2.2-	In Fiji (volcanic) and Tonga (raised atoll with volcanic ash) (main sites) ~3 plots will be selected within 2 soils types and detailed nutrient budget undertaken (yrs1-4).	Teams have independently setup and managed field trials. Nutrient budgets have been calculated for individual crops, and modified	1/10/2021	COVID-19 has meant the local teams have had to setup and run the field trials independently. This seems to have worked.
2.3	In Samoa (volcanic) and Kiribati and Tuvalu (atolls) (satellite sites) 3 plots will be selected on 1 soil type (3 locations total) and a detailed nutrient budget undertaken (yrs1-4)	Teams have independently setup and managed field trials. Nutrient budgets have been calculated for individual crops, and modified	1/10/2021	Samoa and Kiribati successfully have setup new experimental plots. In Kiribati this has included micro-irrigation treatments. In Tuvalu we have had difficulty in establishing communications with the new project officer. In Samoa, the main experimental site at Nu'u has been established in 2020 out of the normal cropping window (dry season). The measles outbreak in the second half of 2019 interrupted all field activities at Nu'u and no crop was harvested in the 2019/2020 season. To compensate for this interruption, the site was re-established off-season, and intercropping taro/taro is planned for this year (for full details about the experiments in Samoa please refer to our Trip Report after our visit to Samoa in March 2020).
2.4	Calculate nutrient constraints for each soil type using data collected Activities 2.1-2.4. PC; Kiribati, Samoa and Tuvalu	Water fluxes and nutrient loss calculations	1/10/2021	Nutrient analysis has been undertaken for Samoa.
2.5	Measure biological function, water flux and nutrient losses	Water fluxes and nutrient loss calculations are being finalised for Samoa.	1/10/2021	In Kiribati on-site staff are making irrigation decisions and nutrient loss measurements independently.
2.6	Calculate nutrient constraints for each soil type using data collected Activities 2.1-2.4. PC; Fiji and Tonga;	Crops currently harvested but analysis not completed due to lab closure during the COVID-19 Pandemic	1/10/2021	COVID-19 Lab Closure. Samples will begin to get analysed shortly.

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2.7	Research extension to farmers, extension, and policy makers	Pacific Week of Agriculture.	1/10/2021	This planned activity has been refocused to be consolidated and coordinated with the planned extension and advisory activities under objective 3. A virtual training and extension plan has been developed.
2.8	Discontinued			
2.9	Discontinued			

Objective 3: Testing

No.	Activity	Outputs/ milestones	Completion date	Comments
3.1	Review current soil sampling, testing and interpretation protocols used in Pacific Islands.	SPC has subcontracted this task to Dr Kadar USP	1/12/2021	Completed
3.2	Utilise MIR to make rapid assessment of calcareous and volcanic soil fertility	Purchase of a Bruker Alpha-II-FT-IR (MIR) instrument and installation at FACL MOA. 1 x 5-Day "MIR spectroscopy" training course for 11 MOA staff at Koronivia Research Station FACL MOA (5-11 May 2018) plus soil survey and sampling methodology and meta-data collection introduction. FACL MOA team has independently set up and managed MIR operations. FACL MOA team has independently conducted MIR soil spectral inference using the BRUKER Opus software including quality control assessments. FACL MOA team has adopted MIR analysis in new National Soil Health Card program to build spectral libraries.	1/10/2021	Completed for volcanic soils. Assessments for calcareous soils impacted by Covid-19 pandemic.

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3.3	Measurement of gross soil biological function			Discontinued.
3.4	Research extension to farmers, extension, and policy makers.		1/10/2021	This planned activity has been refocused to be consolidated and coordinated with the planned extension and advisory activities

PC = partner country, A = Australia

Objective 4: Develop the Pacific Soil Portal to enable sustainable soil management in the farming systems of the region

No.	Activity	Outputs/ milestones	Completion date	Comments
4.1	Establish Portal Governance and Management	Initially representatives from all 5 countries met at Pacific Week of Agriculture in November 2019 and agreed to form a Pacific Soil Portal governance group. Subsequently MWLR prepared and circulated Terms of reference Data-sharing agreement A hosting options paper These were circulated for comment and then ratified by on-line vote	1/10/2021	With Covid travel restrictions the Governance group was forced to interact virtually. Terms of reference, a data sharing agreement and the hosting options paper were all agreed and ratified by the governance group via on-line voting. Subsequently several decisions relating to portal updates have been agreed via online voting as and when required.
4.2	Capture system requirements and capability of participating PICTs	Personna analysis of user types/use cases	1/6/2019	Completed with assistance from country partners.

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No.	Activity	Outputs/ milestones	Completion date	Comments
4.3	Develop the web-interface and supporting ICT infrastructure to deliver the agreed web-services via the Pacific Soil Portal	The web site and supporting ICT structure exist in two environments. A development and a testing instance on-premises, with a Stage and a Live version on Amazon Web Services (AWS). This is essential for seamless operation of the web site during maintenance and upgrades.	1/10/20	The portal was launched in AWS, administered by MWLR, with web map services also hosted by existing MWLR systems. Subsequently stand-alone GeoServer-based web map services were established to support the portal independent of MWLR's facilities.
4.4	Research extension to farmers, extension, and policy makers.			Impacted by Covid restrictions.
4.5	Data Capture and Harmonize existing soil and land resource information for the Pacific Soil Portal	Web map services prepared and "published" that reliably deliver the soil maps and profile data to the portal map interface.	1/10/2021	Data Capture is an on-going process, particularly in respect of soil profile data, but was completed sufficiently in terms of legacy soil maps and profile descriptions for portal launch in November 2019.
4.6	Soil Portal - Web Development	After a soft launch in October 2019, the PSP was formally launched in November 2020.	1/11/2020	The portal can be accessed at https://psp.landcareresearch.co.nz. This is a cloud-based implementation being served from Amazon, currently being managed by the developer, Manaaki Whenua Landcare Research (MWLR).
4.7	Host Setup	Currently being hosted by MWLR while transitional planning to a shared hosting and development plan can be finalised.	1/10/2021	This is a key ongoing issue to be resolved by the governance group. A plan to transition to SPC is under development.
4.8	Prepare a technical development plan that outlines future modules for the Pacific Soil Portal			Focus on hosting and support for existing portal implementation due to covid delays.
4.9	General communication and extension	Attended PWA in October 2019 – and with colleagues from Global Soil Partnership/Pacific Soil Partnership ran a live demonstration of the Samoa component of the PSP and carried out a user feedback workshop in Tonga.	1/10/2021	Limited by Covid restrictions and difficulty in mobilising country partners to assist remotely.

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7 Key results and discussion

7.1 Objective 1: Solutions

Overall, this objective has met its planned activities despite challenges and some delays due to COVID-19 and structural changes with SPC. In response to these challenges the planned activities were changed at the mid-term review. Some of the planned activities in Objective 3 were merged with the planned activities for Objective 1. The following results and discussion include both analysis of barriers completed prior to the COVID-19 outbreak and both pilots that combine both the planned engagement activities (Objective 1) and outreach and extension activities (Objective 3).

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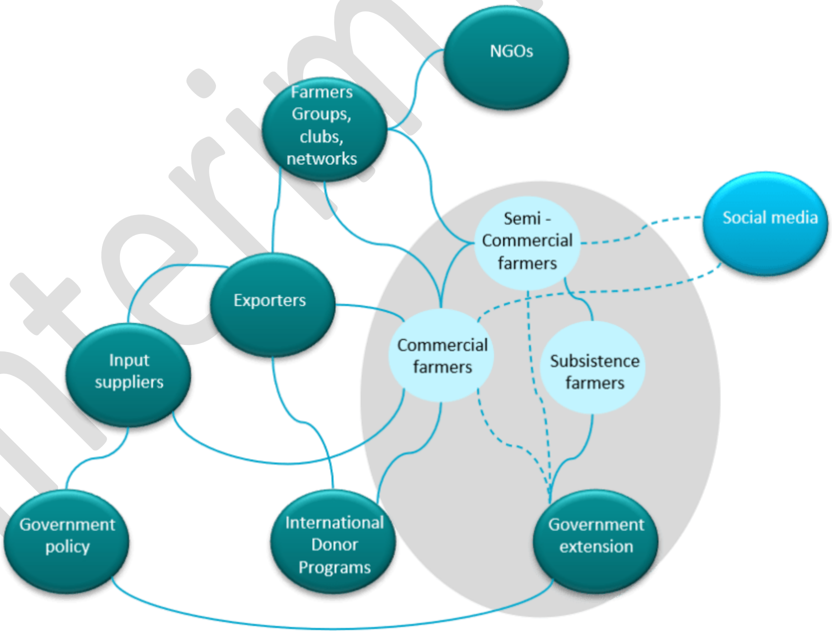
Identification of key barriers to adoption

A rapid assessment of the soil knowledge and information systems in Fiji and Tonga highlighted the following three key barriers to improving soil management:

1. Limited awareness across numerous system actors (e.g. farmers, extension, policy agribusiness, NGOs, etc) about the value of soil health for sustainable production,
2. Multiple sources of knowledge about soil health and sustainable soil management practices (both traditional and scientific),
3. A fragmented agricultural knowledge ecosystem with pockets of well-connected actors that facilitates knowledge transfer and adoption.



Generic map of the different sources of soil knowledge identified in the rapid assessment of the Soil Knowledge and Information Systems in Fiji and Tonga.

Pilots to overcome the barriers to adoption

Building on the findings from the rapid assessment of Fiji and Tonga's soil knowledge and information systems, the project team developed a series of experiments that piloted different approaches aimed at enhancing knowledge both on an individual and systems level. While the primary focused for this objective was Fiji and Tonga, the countries of the projects two main sites, with lessons and insights from these activities to be applied and adapted to other Pacific Island Countries and Territories.

These pilots included

1. **Traditional technical knowledge transfer via face-to-face trainings and workshops**

More than 775 farmers, extension officers, youth, researchers, agriculture students, religious groups, NGOs and agribusiness participated in face-to-face training activities delivered by the project in all 5 countries. Over 70% of these participants were farmers or youth. The subjects of the training included knowledge transfer on 1) soil health including testing and analysing soil nutrients, 2) sustainable fertiliser management, 3) pests and diseases 4) importance of soil management and crop health and potential production impacts, and 5) irrigation. Training reports from all countries included participants describing an increase in knowledge and skills in soil management.

These trainings and workshops targeted both government extension networks as well as emerging alternative soil knowledge transfer networks led by the private sector and NGOs. It was observed that the alternative knowledge transfer networks were often more cohesive and better connected to different sources of agronomic knowledge. For example, in Tonga the training targeted a commercial farmer group that is convened by an agribusiness. Reports from these trainings and workshops described more than an improved knowledge but also commitment to improved practice change. Following a soil health diagnosis training session, farmers described a commitment to changing their fertiliser practice to include single nutrient fertilisers. It is proposed that this group described a change beyond just awareness and knowledge, because of the strength of its connections between actors across the value chain (i.e. – including farmers, input suppliers, exporters, knowledge broker and researchers) and their ability to discuss what the practice change would mean and how it could happen.

2. **Leveraging online platforms to share key findings from the project**

The rapid assessment identified online knowledge sharing platforms as an emerging trend. This is no surprise, given the continual improvements in internet connectivity and access to mobile phones in all countries. In response to this trend the knowledge broker in Tonga brokered connections with three key stakeholders (an NGO, and Agribusiness and the Government) to include key project results and current soil health and management information on their platforms. These platforms are used by farmers, agricultural advisors, research scientists and others.

In response to the outbreak of COVID-19 the project also experimented with developing an online training program. As the pandemic evolved, this training program became a secondary priority, due to face-to-face training being possible in country. Going forward the materials developed can be shared with these platforms for broader distribution.

3. **Embedding into national programs and policies aimed at supporting improved agriculture policies and practices to share soil health and sustainable management**

The Fijian Government has created a soil health card. Our project partners in the Chemistry Lab in the Fijian Ministry of Agriculture (MoA) are playing a key role supporting this initiative with tailored soil sampling, analysis, and interpretation for individual farmers. As the initiative is rolled out across Fiji, a more comprehensive picture of the

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entire countries soil health is expected to emerge. This knowledge will then be used to provide local extension and agricultural advisory in different areas with context relevant soil management knowledge for transferring to farmers and other relevant actors.

4. **Leveraging existing regional platforms aimed at supporting improved agriculture policies and practices to share soil health and sustainable management knowledge**

The project invested in building relationships with other development and government led sustainable agriculture initiatives to help strengthen connections between key sources of knowledge for farmers and reduce the fragmentation issue identified in the rapid assessment. The result of these efforts included opportunities to increase awareness on the current soil health challenges in regions. Specifically, the team lead discussions on:

- National Nutrient Budgets and Soil Health, with policy makers at the regional heads of agriculture and forestry services pacific week of agriculture on
- Improved nutrient use and manure management towards sustainable and resilience; Using soil test results to guide fertiliser use, and Nutrient balance sheets in Tongan cropping systems with the Pacific Chapter of the KJWA initiative facilitated FAO, and
- Importance of Soil Biodiversity for the Pacific Islands with members of the FAO, SPC and SPREP.

The connections and relationships established and/or strengthen by project team members with these projects and policy platforms are expected to continue beyond the life of the project.

5. **Building cohesion by catalysing national workshops that include actors from across the value chain to discuss current and emerging soil health issues impacting agricultural production**

In Tonga, the project experimented with engaging a knowledge broker to build connections with key actors across the system including policy, extension, research, agribusiness, NGOs and farmers. The knowledge broker had both soil expertise and strong connections across the Tongan Agriculture sector. Their role was to engage with key stakeholders and catalyse discussions around challenges and opportunities for improving soil health and management practices. Namely this included facilitating 3 National workshops at Tonga Tapu, Haápai, and Éua to discuss the implications and potential response to declining soil fertility at both the farm and national level. Specifically, the discussions focused on declining soil carbon stocks and better nutrient management. The changing fertiliser practices was identified as a key priority at the end of the workshop. It was agreed that stakeholders from the workshop would work together to develop policy brief or voluntary guidelines around sustainable fertiliser to help address the declining soil fertility challenge facing Tonga's agriculture sector.

6. **Codifying good practice to support the creation of a community of local soil management experts in the region**

CSIRO, SPC and USP collaborated to create two manuals on soil sampling and soil analysis and interpretation. These manuals will support the creation of a network of local Soil Doctors in each country. The Soil Doctors will use the manuals to provide tailored advice to farmers that considers their unique soil conditions through sampling, analysis, and interpretation. This idea builds on the Plant Doctor program, which has had success in the Pacific. Discussions have commenced to connect the two agricultural advisory programs about combining to provide farmers with a more comprehensive diagnosis and assessment of issues affecting their farm. An example is pests and diseases that need soil management rather than pesticide management.

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Key insights and lessons learnt

Knowledge transfer and adoption in the Pacific has its own unique dynamics. These pilot experiments aimed to leverage and build synergies with the existing dynamics of the system to enhance soil knowledge and adoption of improved soil management practices and policies.

COVID-19 both created opportunities and challenges. While it created an opening to experiment with more alternative outreach and extension approaches which has led to some promising results it has also slowed the pace in which the activities could be implemented. Consequently, the results the pilots could only be described as indicative not conclusion. Despite this the following key insights and lessons learnt have been identified:

1. **There is no one approach to agricultural extension and advisory services in the pacific - Knowledge transfer approaches need to be context appropriate.**

The range of pilots experimented with highlight that there is no recipe that works in all contexts. While traditional government extension officer to farmer still works in some contexts it does not work in all. Farmers reported that Government extension is one of many knowledge sources for commercial and semi-commercial farmers. It was observed that a range of alternative agriculture advisory approaches to public extension have emerged in each country. These include online platforms, private sector-led advice (i.e. exporters) to farmers, farmer-led clubs and networks, agriculture schools, NGO-led advice, and donor development programs. Each approach has its strengths and weaknesses. The pilots aimed at better understanding if and how to leverage and build synergies with these different types of extension and how advisory services can enhance the understanding of what works in what context and to what end. Results so far suggest that it is important to recognise that different approaches have different reach and scale and taking a portfolio approach that connects with a range of different approaches rather than just relying on the traditional government extension can help enhance adoption of soil knowledge and ultimately improve the soil health of the Pacific Island Countries and Territories.

Food security can be directly linked to agriculture extension, and either it is commercial or subsistence systems. The extension administrators need to invest and revisit institutional policies to accommodate capacity building of extension personnel so that they can serve the farming community better to ensure food security. Currently, in the Pacific including Tonga, donors are increasingly using NGOs and minimizing investments in ministries of agriculture's extension services will improve extension delivery. In the 2020 vision of Pacific development, Commonwealth of Australian (2006) states that: agriculture extension services in the Pacific Islands are ineffective due to weak links and capabilities; it points out that in some countries there is little point to attempt to invest more in governmental extension services and promoted use of non-governmental organizations for agriculture extension purpose believing that this is a better option of solving the problems in extension delivery. This assessment advocates that shifting reliance from governmental to non–government without addressing individual and organizational capacity building needs of NGO's may not solve the issues of poor extension delivery. The ACIAR capacity building needs assessments and supported by this assessment identified that level of capacity building requirement is same for both NGO's and the government extension services.

2. **Look for opportunities to build on existing connections and relationships between the different actors in the knowledge system to improve adoption.**

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As suggested above there are numerous extension and advisory service approaches and models being implemented across the pacific and efforts should be made to connect with a range of different networks and approaches. For example, although farmer who attended the face-to-face training and workshop run by the project reported that they increase their knowledge, practice change was only reported by one commercial farmer group. The strength of the connections between actors along the value chain meant that they had the capacity to adopt and try new practices. This capacity was not demonstrated in other farmer groups who were less connected. Another example of this are the national workshops held in Tonga. These workshops built the participant's knowledge and helped catalyse a cohort of actors to move forward with an identified policy that can help enable practice change at a national scale. The actors all had an interest in soil health but were not necessarily working together on a common goal around it. The workshops helped to create this. The final example of this, is the Dr Soils initiative. This initiative not only builds on lessons and insights from an effective extension and advisory services project in the pacific, but discussions are also underway to collaborate to create a more comprehensive service for farmers and help avoid missed opportunities for enhancing the soil knowledge of farmers and influencing soil management practice change.

3. **Insights from pilot implementation can be used to inform implementation of the Pacific Islands Extension Strategy, which has underpinning principles of strengthening networks and partnerships.**

Strengthening connections and partnerships is an underpinning principle that guides the regional extension and policy. It recognises that public extension may be the traditional way to share knowledge with farmers, but due to a range of institutional challenges, funding, ongoing capability development, etc. other actors have stepped up to fill the extension and advisory service gap. Consequently, brokering formal and informal multi-stakeholder collaborations that include actors from across the value chain at a national and local level is important project design consideration. These collaborations help catalysing collective or joined up action needed to maintain a common pool of resources like soil at both farm, national and regional levels. Joining up the system is an important factor in achieving impact at scale, which can only be achieved through dedicated resources that should be built into future project designs.

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7.2 Objective 2 Nutrients

7.2.1 Island Nutrient Budgets

Pacific Island nutrient cycles have been increasingly modified since human settlement 2000 years ago. Agricultural intensification has resulted in further changes in the island nutrient flows. Country-scale agricultural land nutrient (nitrogen, phosphorus, and potassium) budgeting in Tonga, Fiji, Samoa, Kiribati, and Tuvalu were calculated from FAO country statistic data (1964-2018). Nutrient input data from birds, atmospheric dust and rainfall and human waste were calculated from literature values. Overall, there are nutrient imbalances in all countries and agricultural lands are exporting nitrogen, phosphorus, and potassium. The budgeting calculations did not consider nutrient losses via erosion, leaching and run-off or denitrification, and the net nutrient fluxes may well be greater than reported. The use of animal and human waste would help off-set this imbalance, but additional macro- and micro-nutrients would need to be added for balanced plant nutrition. While increasing fertiliser inputs will improve the nutrient balance and potential primary productivity, trade-offs such as nutrient losses will need to be considered. Improving nutrient budgets would need a farming systems approach, whereby the use of cover crops, crop rotations and legumes would augment the fertiliser applications. There were soil nutrient imbalances across all the island nations that were investigated (Table 2). Average potassium balance was negative for all the island nations and crop removal exceeded deposition and manure additions on the atolls and fertiliser additions on the volcanic and raised atolls (Table 2). There were no synthetic fertiliser additions in Kiribati and Tuvalu. Overall, there has been a long-term removal of soil nutrients, as evidenced in Kiribati, over the last 50 years across the studied island nations.

Table 2 Time weighted nutrient additions, removal, and mass balance (kg ha^{-1} yr^{-1}) for the agricultural areas of Kiribati, Tuvalu, Tonga, Fiji, and Samoa (1964-2017).

Country	Element	Output	Inputs			Mass Balance
		Crop Removal	Deposition	Fertiliser	Manure	
Kiribati	N	3.63	1.36	0	0.85	-1.43
	P	0.69	0.23	0	0.18	-0.29
	K	7.60	0.36	0	0.18	-7.06
Tuvalu	N	7.14	1.36	0	8.05	2.27
	P	0.36	0.23	0	1.68	1.55
	K	2.90	0.36	0	1.68	-0.86
Tonga	N	27.58	1.36	16.98	0.65	-20.86
	P	1.11	0.23	3.01	0.13	0.08
	K	14.11	0.36	22.25	0.13	-7.43
Fiji	N	10.17	1.36	4.56	3.31	-4.23
	P	1.31	0.23	0.73	0.69	-0.19
	K	12.41	0.36	1.21	0.69	-11.02
Samoa	N	26.83	1.36	0.38	2.76	-22.61
	P	1.47	0.23	0.16	0.57	-0.63
	K	16.91	0.36	0.25	0.57	-15.91

The nutrient balance calculation is based on FAO country statistical data, which is reliant on the submission of accurate data by each country. In some instances, the FAO will estimate data using appropriate methods when country data is missing. The data is only applicable for the agricultural production areas in general and the nutrient flux calculations are based on this area. This assumes a homogenesis nutrient management strategy for all the lands, whereas the strategy will be heterogenous. This means some areas will be over fertilised and some under fertilised.

This study is focused on the macronutrients (nitrogen, phosphorus, and potassium) and not the micronutrient and base cation imbalances. It is evident from many studies that micronutrient deficiencies (Halavatua, O'Sullivan et al. 1998) and base cation losses (Sharma 2018) are also prevalent across the Pacific Islands. Micronutrients are also being exported from agricultural lands and are a major production constraint and in some cases the primary cause of the yield gap. The imbalance in nitrogen, phosphorus, and potassium is only one aspect of plant nutrition and should be used to highlight the need to adequately understand the nutrient flows and management in agricultural systems. Furthermore, the importance of organic matter management should not be overlooked.

There has been significant carbon loss from Pacific Island farming systems; for example, studies in Fiji and Tonga indicate between 4-5% reduction in soil organic carbon (Halavatua, O'Sullivan et al. 1998, Sharma 2016a).

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The nutrient balance calculations did not include loss pathways other than nutrient export via the crop and ammonia volatilisation. There are potentially other significant nutrient loss pathways from agricultural lands. It is estimated that erosion rates of up to 50 Mg ha^{-1} yr^{-1} occur on volcanic islands and from storm damage on low lying atoll islands (ITPS 2015). There is also potential for deep leaching, run-off losses and gaseous losses. Currently there are no detailed studies on these nutrient losses. However, it does mean that nutrient balance calculations in this work will underestimate the mass balance deficit at the country scale. Finally, the approach used in this work does not consider the soil nitrogen, phosphorus, and potassium bank, but soil fertility is declining in Pacific Island cropping systems (Morrison and Gawander 2016).

Nutrient inputs from seabirds on PICTs play a key role in terrestrial food webs by transporting marine-based energy and nutrients to islands (Anderson and Polis 1999) and fertilising low input farming systems and terrestrial ecosystems. Sea-levels stabilised in the Pacific Ocean approximately 2500 years ago (Marshall and Jacobson 1985) and atoll and barrier reef vertical accretion also stabilised. Seabirds can potentially transfer significant amounts of nutrients from the ocean to land on an annual basis (Allaway and Ashford 1984) land surface and soils would have received nutrients via the deposition of seabird guano inputs and supported plant and ecosystem function. Christmas Island and Nauru represent extreme cases where the phosphate that built up over geological time was exploited for fertiliser. The input of nutrients via guano causes significantly increased primary productivity on islands (Polis, Anderson et al. 1997).

The settlement and agricultural development in the PICTs have resulted in a decrease in nutrient supply from nesting seabirds by extinction, due to habitat destruction and predation (Steadman 2006). This has reduced the ability of the landscape to support complex terrestrial systems and reduced primary productivity (Polis et al., 1997). Human settlement resulted in the disruption of the sea-to-land nutrient flows, decreasing nutrient availability and agricultural intensification depleted nutrients from the islands (Swift, Roberts et al. 2018). There is a suggestion that the change in terrestrial nutrient dynamics may also impact on the primary productivity of the fringing reef system (Morrison, Denton et al. 2013).

Land degradation has been evident to varying degrees ever since human settlement took place in the Pacific with the initial conversion of forested ecosystems to mixed agro-forestry systems (Kirch 1996). Recent evidence from Hawai'i indicates that these low-intensity farming systems resulted in soil nutrient removal through enhanced weathering, increased leaching, and crop removal. This may have caused slow yield declines over a period of about 500 years (Hartshorn, Chadwick et al. 2006). Overtime there has been a conversion of traditional agroforestry systems with typically long fallows, to systems with shortened fallows, and eventually to more intensive systems with exports and even shorter fallows. Typically, these steps have been made without adequate fertilisation and have resulted in the widespread falling of productivity. While there is some uncertainty about the effect that shortened fallows have on soil nutrient cycling in humid tropical shifting agriculture (Mertz 2002) there is ample evidence to show that nutrient inputs are required to maintain, and where possible, increase yields in agricultural farming systems (for example Angus and Peoples 2012). In all intensive-orientated farming systems, the endpoint of this continuum is continuous cultivation of the same piece of land, which leads to nutrient depletion (via crop harvest, erosion, and oxidation of organic matter), and therefore progressive yield decline. Soil fertility decline is a major production constraint and has been identified as a high research priority in taro agricultural systems (Guarino, Taylor et al. 2003).

The nutrients budget analysis (

) indicates that there is inadequate nitrogen, phosphorus, and potassium fertilisation in the agricultural production areas of Tuvalu, Tonga, Kiribati, Fiji, and Samoa. Other field-based studies have found that the depletion of soil nitrogen, phosphorus, and potassium levels have contributed to the yield decline of agricultural production, such as taro and sweet potato (Halavatua, O'Sullivan et al. 1998, Sharma 2016a), across many Pacific Island nations.

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Fijian taro farmers have identified that access to market, instability of market prices, transport, grower capability, production cost and agronomic supplies are production constraints which effect production profitability (Sharma, 2016). Plahe, Hawkes et al. (2013) have identified when institutional arrangements prevent access to market then agricultural development and access to capital is stifled. These underlying microeconomic issues appear to be preventing farmers from utilizing fertilisers and halting fertility decline. This requires investigation because the cause of these barriers may be complex and involve individual perceptions of risk, market inefficiencies, post-harvest losses, access to information and other institutional factors.

On atoll islands, such as Tuvalu and Kiribati, the soils are relatively infertile compared to the volcanic islands and have also lost soil nutrients due to tillage, deep drainage and crop export and reduction of nutrient inputs due to the decline in seabird population. While the potential for high-value crop exports from atolls is limited, production of fruit and vegetables for local urban markets is an important source of cash income for the underprivileged poor (White, Falkland et al. 2007). A further issue on these islands is the maintenance of ground water quality for domestic supply. It has been shown that agricultural production is a key source of N and faecal contamination of ground water lenses (van der Velde, Green et al. 2007, White and Falkland 2010). This has led to widespread restrictions on the use of synthetic fertilisers in many atoll nations and the subsequent development of organic agricultural production systems. Typically, organic nutrients are sourced from the household domestic kitchen wastes, but material is also collected from other locations such as forest and ground water reserves, harvested seaweed and driftwood and tide wrack. This harvesting of these source areas needs to be carefully managed so that nutrients are not mined, and systems are maintained. None-the-less the same issues still face organic growers in terms of nutrient management to maximise profitability and existing soil nutrient imbalances, poor soil health and the protection of ground water resources.

The under-fertilisation of agricultural lands of the Pacific Islands countries and territories is not unique and is an issue throughout the world (Silver, Perez et al. 2021). In the Pacific Islands the nutrient and protein content of traditional food crops, such as taro, have been shown to be correlated with the mineral content of the soil (Bradbury and Holloway 1988). Poor nutritional deficiency in food can originate in soil nutrient limitations and in the Pacific this is evident in several regions and reflected in human health (Bradbury and Holloway 1988, Lyons, Dean et al. 2020). Improved agricultural macro and micro-nutrient management is required not only to increase yield but nutritional food content. The measurement of nutrient flows through the Pacific Island food system is required to address human and livestock nutrition management

There is potential to improve the nutrient balance in agricultural soils using treated human and animal wastes in the studied countries. While technical and cultural aspects of wastes utilisation need to be solved, waste represents a potential source of agriculture fertiliser. However, there would still be a need to fortify the recycled waste with addition macro- and micro-nutrients for each soil and farming system to ensure a balance nutrient replenishment program. Additionally, the use of diverse cover crops, deep and shallow rooted, and legumes would improve soil health and soil carbon stocks. There is a need for Government and industry to develop programs that improve landowner knowledge of nutrient budgeting, the long-term implications of poor nutrient management on food and soil security, and options to improve soil and nutrient management. The measurement of nutrient flows through the Pacific Island food system is required to address human and livestock nutrition management

Country nutrient budgets reveal that on the islands of Kiribati, Tonga, Samoa, Fiji, and Tuvalu that agricultural lands are not adequately fertilised with nitrogen, phosphorus, and potassium. This constant nitrogen, phosphorus, and potassium export is contributing to yield decline, and soil and food system insecurity. The budgeting in this paper did not examine micronutrient and base cation export, but it could be expected that similar imbalances also occur and would be contributing to the measured yield gaps. The utilisation of human and animal waste would help to alleviate the nutrient imbalance, but additional macro- and micro-nutrient would need to be applied for balanced plant

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nutrition. The solution to improving soil and nutrient management will need to include crop rotations and residue management.

7.2.2 Soil organic carbon and nutrients

Soil organic carbon stocks have reduced in taro (Figure 6) and sugar cane cropping (30-40%; Morrison and Gawander 2016) areas in Fiji. The reduction in soil carbon stocks has been linked to declining soil fertility and production (Morrison and Gawander 2016, Sharma 2016b). The decline in soil organic matter is caused by intensification, inappropriate soil management and a failure to adequately fertilise the crop and the soil organic matter system (Hunt, Celestina et al. 2020, Giller, Hijbeek et al. 2021) and is not restricted to Pacific Island agriculture.

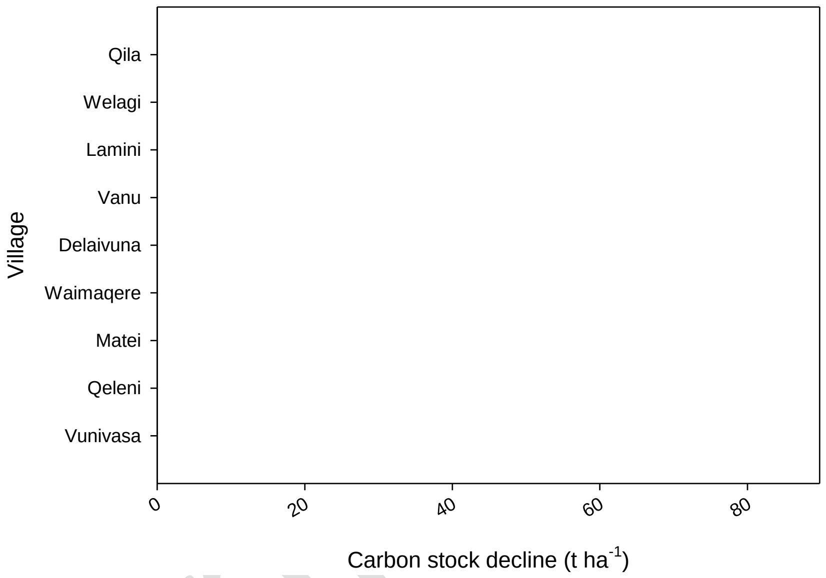

Figure 6. Organic carbon decline between 1990-2012 in Taveuni taro cropping areas, Fiji (Sharma 2016b).

In low input farming systems, the soil organic matter pool is critical to suppling macro nutrients, such as N, P and K, and micronutrients. The decline of the soil carbon represents a decline in the pool of organic matter pool of N, P, and S. It is possible to use organic matter stoichiometric ratio (C:N:P:S-10,000:833:200:143) to estimate the reduction of N:P:S (Kirkby, Richardson et al. 2013). In Taveuni the loss of the soil organic matter pool, as measured by the soil carbon reduction (Sharma 2018), has also significantly reduced the soil P, N and S pools (Figure 7). This means that the soil's functional ability to supply macro and micronutrient has also decreased and in low input farming systems this may be a key cause of the observed yield decline. The total soil nitrogen at some locations in Taveuni has declined, whereas the available soil phosphorus has not changed or decreased (Figure 7).

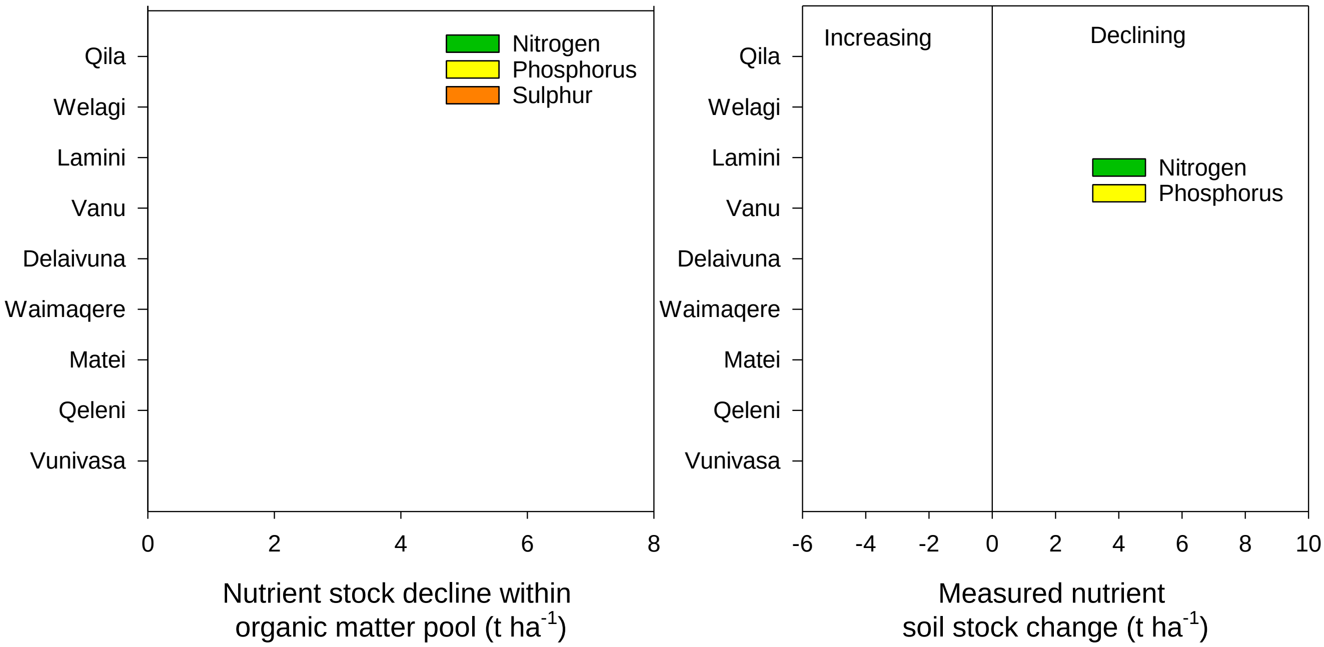

Figure 7. Nutrient stock decline within the soil organic matter pool calculated organic matter stoichiometric ratio. Measured soil nutrient stock change Taveuni, Fiji (Sharma 2016b).

During 2018 the Tongatapu soils were re-sampled at previously sampled historic locations (Gibbs 1976, Potter 1986, Cowie, Searle et al. 1991) by MAFFF and a Monash University student (Krawitz 2019). Figure 8 shows the sampling locations of these across Tongatapu (red and green dots). In Tonga a similar decline in soil carbon of between 30-50% has occurred in the Vaini, Lapaha, and Fahefa soil series. This would have also resulted in a decline in the available soil nitrogen, phosphorus, and sulphur pools.

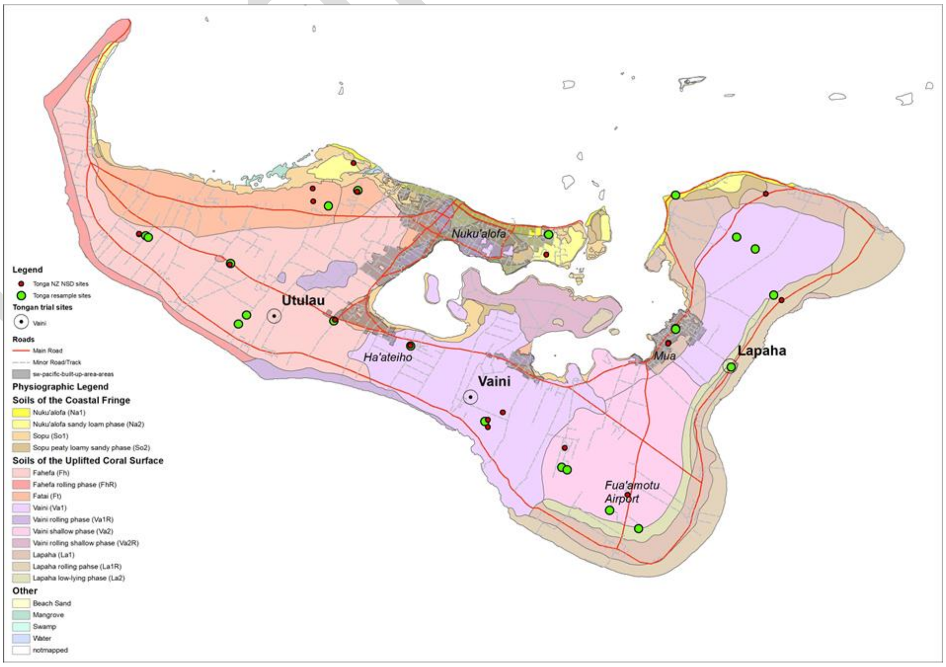

Figure 8 Tongatapu Soil map derived from the Pacific Soil Portal and the location of the historic and 2018 soil sampling locations. Locations of ACIAR field trials are also shown.

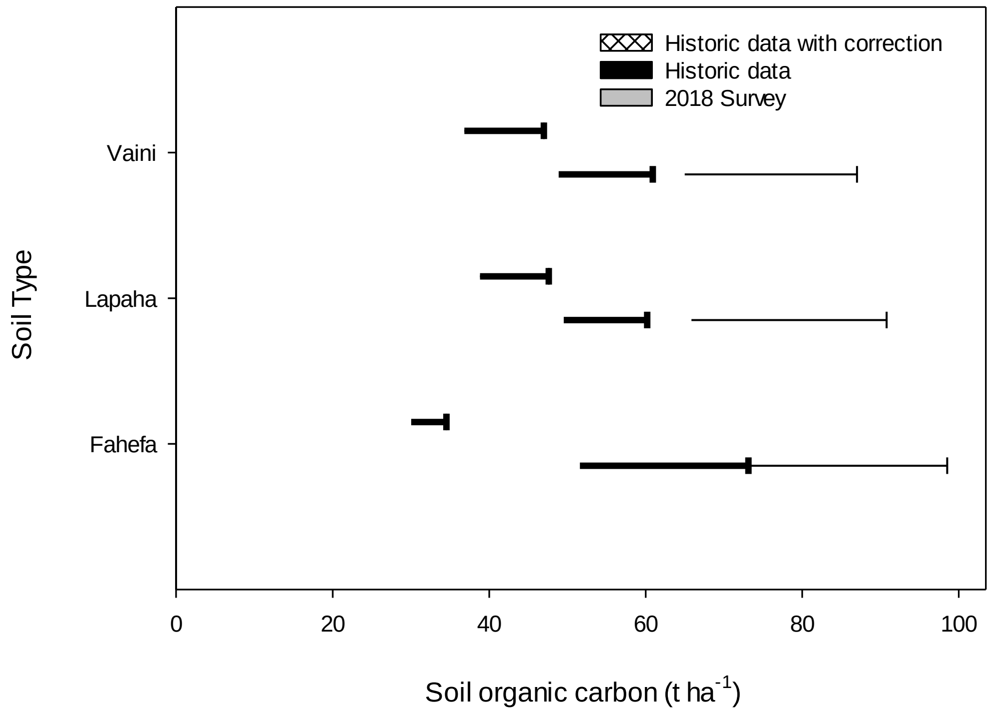

Figure 9. Preliminary analysis of organic carbon content in soils collected during historical sampling missions (Gibbs 1976, Potter 1986, Cowie, Searle et al. 1991) and 2018 soil survey Tongatapu. Historic data is the % carbon value as reported in the original report. Historic data with correction represents the same data but corrected to Dumas method C%.

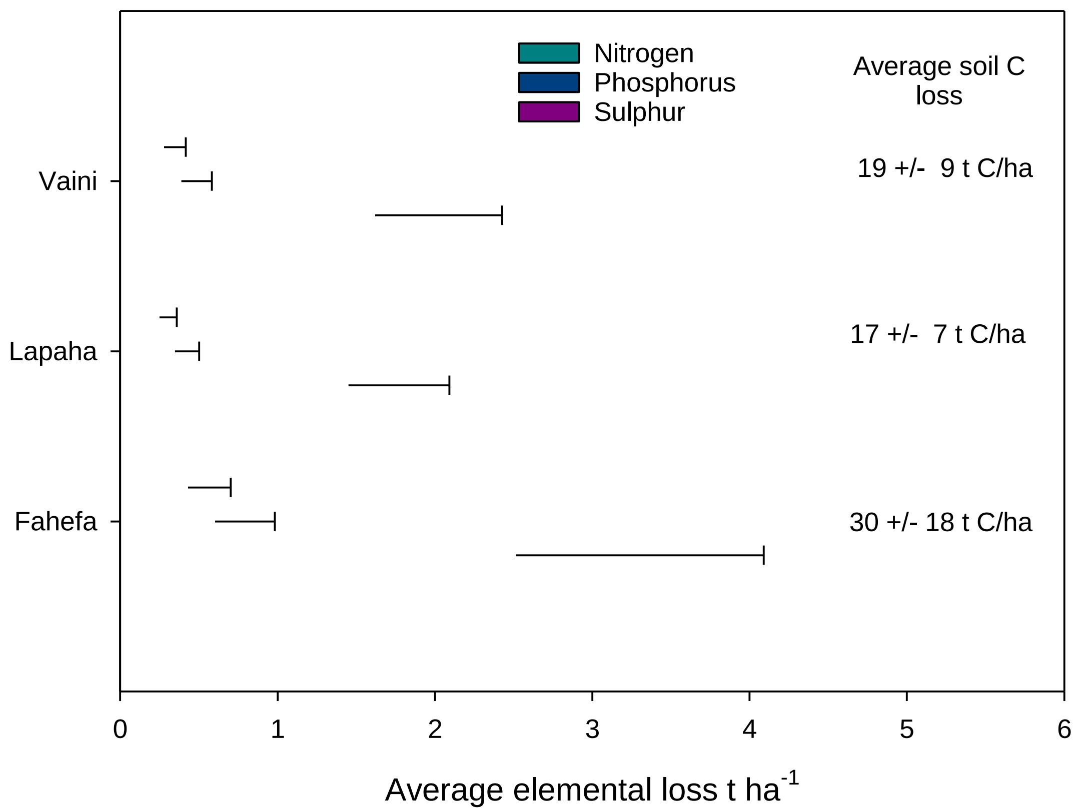

Figure 10. Preliminary analysis of nutrient stock decline (1990-2018) within the soil organic matter pool calculated from the organic matter stoichiometric ratio, Tongatapu, Tonga.

7.2.3 Tuvalu Nutrient Status Soil Survey

The project team replanned the activities for Tuvalu because COVID-19 prevented the on-ground training and establishment of field trial activities, the annual meeting, co-developed extension activities and face to face training. A nutrient soil survey program was developed by Selotia Tausi to cover the different communities in Tuvalu. Overall, 50 sites have been sampled (see detailed method appendix 1) and are currently being shipped to Australia for testing. Originally the samples were to go to Fiji, but the on-going COVID-19 outbreak shut the laboratory (2021). During the field sampling land holders were briefed on the importance of composting and soil nutrients. The soils will be used to develop a MIR and NIR calibration library for Pacific Island coral atoll soils.

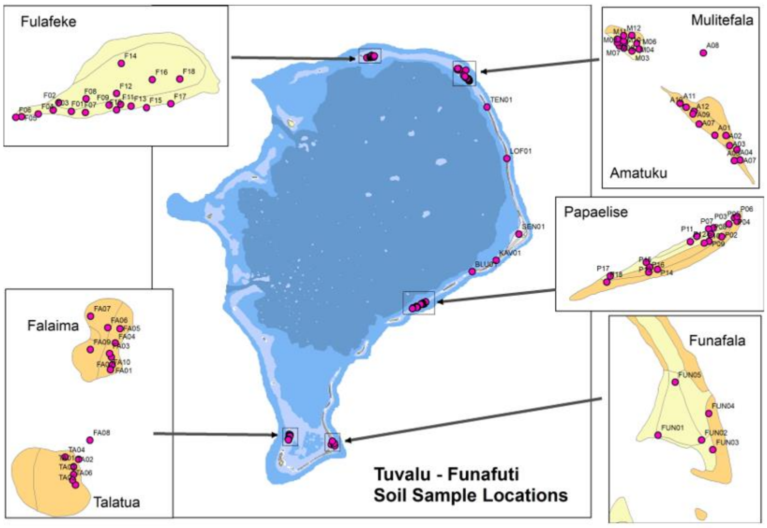

Figure 11. Field sampling locations in Tuvalu.

In conjunction with the soil nutrient status MELAD held a World Soils Day (4 December 2020) extension activity themed on "Keep soil alive, Protect soil biodiversity". A detailed report is in the supporting documents. The program included

- Soil and Health Overview (Overview on Tuvalu soil) by the Director of Agriculture, Mr. Uatea Vave
- Importance of Soil Health and its components, presented by Ms Selotia Tausi (ACIAR Project Coordinator)
- Soil Structure & Soil Texture leading by Mr. Sama Sapakuka (Principal Agroforestry Officer)
- Soil Biodiversity conducted by Ms Selotia Tausi includes the following topics.
    - What is Soil Biodiversity?
    - How soil biodiversity loss?
    - What we can do to prevent biodiversity loss?

After the formal meeting the group (25 people Figure 12) visited

1. Taiwan Technical Mission Garden (Fatoaga Fiafia), where the TTM leader Mr Roy Huan and his colleague invited the group in for a demonstration on how to make compost in their compost shed using heavy machines. They

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also distributed leaflets on compost preparation to the participants and they provide the participants some time for discussions (Figure 13).

2. The Agriculture Agroforestry Nursery where the agriculture staff conducted a demonstration on compost preparation and analysis the composts NPK content using a Palin in-field soil test (Figure 14).
3. The last event of the day was sightseeing to the Agroforestry sites and the Dumping sites to compare the sites and the types of soil.

The participants indicated that further on-farm soil testing was required and Selotia Tausi secured further Palin test kit samples to undertake field testing during the soil sampling program.

Figure 12. Audience at the Tuvalu World Soils Day event.

Figure 13. Field visit during the World Soils Day Event

Figure 14. In field soil testing using the Palin Test Kit, during the World Soils Day Field Event**.**

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7.2.4 Kiribati

An irrigation and compost field trial was conducted in Teriniban, North Tarawa, Kiribati and irrigation equipment was tested ALD Tanaea (Figure 15). The field trial in Teriniban was designed by ALD and conducted within on a local farm and consisted of above and below ground drip irrigation system and three different compost rate (0, 15, 30%) cabbage trial (Figure 16)Figure 16 Field trail design Teriniban, North Tarawa.. Fullstops were also installed (Figure 17) to guide irrigation scheduling and to periodically to measure nutrient fluxes.

Figure 15 Project field locations (red dots), Tarawa Kiribati.

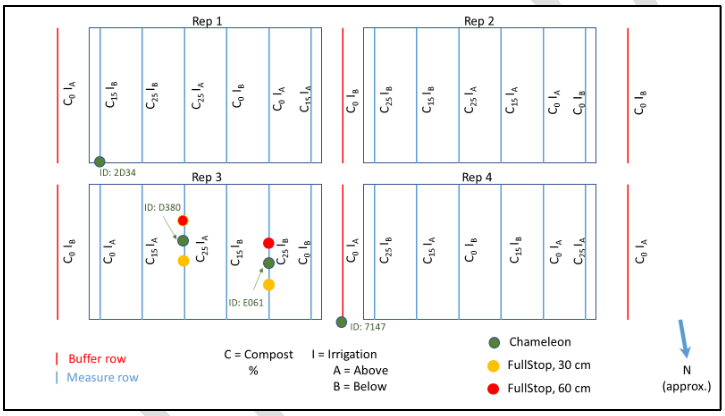

Figure 16 Field trail design Teriniban, North Tarawa.

Figure 17. ALD staff installing Fullstops at the field trial and checking the Fullstop Installation

The effect of the position of the irrigation line (above or below ground) had no effect on yield. However, the amount of compost added to the soil had a significant effect on cabbage yield (Figure 18). The compost is helping to correct the inherent nutrient deficiencies (Table 3). These results show that the application of 30% compost mix will improve yield and could be used to guide compost-soil mixes being developed for the food cubes. The field-stops were very usual to guide irrigation duration and the field trial staff terminated the irrigations based the “popping” of the indicator. There was no interaction between the irrigation method and compost amount.

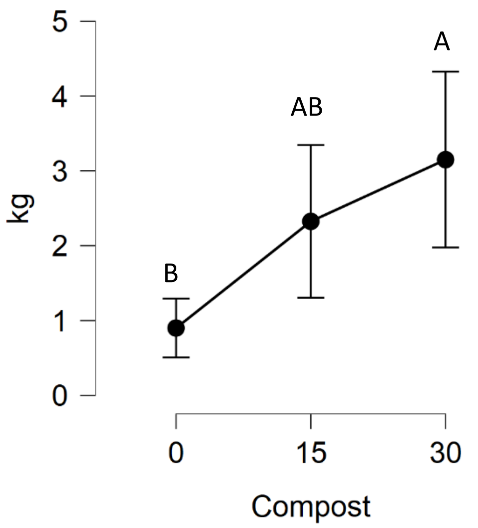

Figure 18 Influence compost (%) on cabbage yield. Compost and irrigation trial Kiribati. Significant difference at the p≤0.05.

Table 3. Soil test results for different trials at Tanaea, Kabuna, Tekaman and Beru

Sites	**pH Units**	**EC µSiemen**	**Nutrients (mg/l)**					
			N	P	K	Fe	Cu	Mn
Tanaea (tomato)	7.8	870	54	60	150	1.4	1.0	0.2
Tanaea (eggplant)	8.2	810	36	47	120			
Kabuna Trial	7.6	575	31.4	3	150	0.9	0.2	0.2
Kabuna (new)	7.8	425	38	24	75	1.0	2.0	0.2
Tekaman	7.9	676	54	40	55	0.2	1.0	0.2
St. Francis Beru	8.1	445	36	30	95	2.4	2.0	0.3

7.2.5 Samoa

Field trials

Field trials were setup at the Crop Development Station of the Samoan Ministry of Agriculture and Fisheries at Nu’u (13°49.829’S, 171°50.193’W, elevation: 71-m ASL) in August 2018 (henceforth Nu’u 1) and December 2020 (henceforth Nu’u 2), respectively. A remote site was also established at a commercial farm in southern Upolu (14°00.432’S, 171°39.492’W, elevation: 181-m ASL) in September 2018 (henceforth Faleãlili). Two additional field trials were setup, but they were subsequently discontinued; these included Nu’u 1 (established in February 2021 and discontinued in May 2021) and Tanumalala. The two locations are shown in Figure 19. The purpose of the 2021 Nu’u 1 site was to assess whether a first taro crop could be intercropped with a second taro crop planted about 2-4 months before harvesting. The rationale behind this approach was to explore opportunities to increase production within a narrower window (12-14 months instead of 16 months) while being able to maintain land capability. Tanumalala was a site established for demonstration purposes at a commercial farm located near the Crop Station at Nu’u. The experimental design at this site was like that of Nu’u 2, but with fewer treatments. Tanumalala was discontinued as

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it proved logistically difficult to monitor by SROS staff who preferred to use the already established site at Nu'u 2 for both research and demonstration purposes.

Figure 19 A map of Upolu showing the locations of the experimental sites established as part of this project in 2018 and 2020.

The climate for Upolu is tropical, hot, humid, and rainy throughout the year, with relative maximum rainfall occurring from December to March and minimum from June to September. The mean annual rainfall is 2800 mm. Rainfall occurs in the form of downpours or thunderstorms, which are often intense but usually short-lived; except in the period from December to March, when rainfall duration increases. Temperatures vary little throughout the year, and they are slightly warmer between December and April compared to the period between May and November. On average, the thermal amplitude between day and night is about 10°C, with night temperatures typically above 20°C. Mean relative humidity is approximately 80%. Historic rainfall and temperature records for Upolu are shown in

Table 4

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Table 4. Long-term monthly rainfall, number of rainy days per month, and mean minimum (T_{Min}) and mean maximum (T_{Max}) temperature records for Upolu (Samoa).

Month	Rainfall (mm)	Rainy days	T_{Min} (°C)	T_{Max} (°C)
January	450	19	24	30
February	380	18	24	30
March	350	17	24	30
April	250	15	24	30
May	160	13	24	30
June	120	11	24	29
July	80	8	23	29
August	80	9	23	29
September	130	12	23	29
October	170	14	24	30
November	260	16	24	30
December	370	17	24	30
Year	2800	169	23.7	29.7

The trials at Nu'u 1 and Faleãlili were laid-out in a completely randomised block (n = 4) design and were established to compare the agronomic performance of taro (Colocasia esculenta L., Schott) with and without (control) legume (*Mucuna pruriens* L., DC and *Erythrina subumbrans* Hassk., Merr.) intercropping (Figure 20). The taro variety used at all sites was Samoa II, which is resistant to taro leaf blight (*Phytophthora colocasiae* Racib.) (Brooks, 2005). The trial sites had 12 plots (dimensions: 7-m long by 6-m wide) and there was a 0.5-m buffer between-plots. Within each plot, there were 42 taro plants, which were established using a 1×1-m planting system (Boampong et al., 2020). At Nu'u 1, taro was planted in late August 2018 and harvested on 12th March 2019. At Faleãlili, taro was planted in late September 2018 and harvested on 7th May 2019. Both legumes were established simultaneously with the taro crops to test their ability to supply nitrogen to the crop and consequently reduce the reliance on applied nitrogen (e.g., synthetic fertiliser, organic amendment). The legume plants were trimmed as needed to ensure they did not grow outside the designated experimental plot area. Any overgrown part of the legume plants that extended outside the plots were cut away and mulched down on the same plot to ensure no additional nutrients were removed from the plot.

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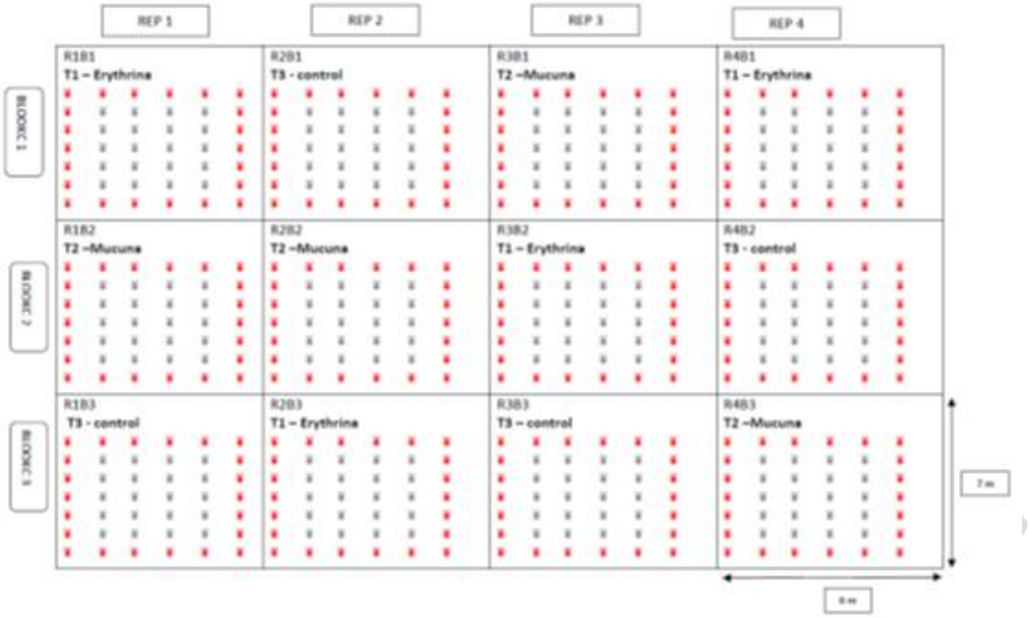

Figure 20 . A diagram showing the lay-out of the experiments at Nu'u 1 and Faleãlili during the 2018-2019 crop season (not-to-scale). Treatment 1 (T1): taro intercropped with *Erythrina subumbrans*, Treatment 2 (T2): taro intercropped with *Mucuna pruriens*, and Treatment 3 (T3): control (no legume). Each '¥' denotes a taro plant; red symbol denotes crop rows used as buffer between-plots. Plots dimensions were 6-m × 7-m, and the planting arrangement was 1-m × 1-m.

At Nu'u 2, the trial was also laid-out in a completely randomised block design (n = 3) to compare the agronomic performance of taro with and without addition of soil amendments; namely: NPK+S fertiliser (12:8:15+3, commercially known as Blaukorn Classic®) and composted poultry manure (>¾ by weight was poultry manure with the balance made up of malt waste from breweries, desiccated coconuts, and coral chips) (Figure 21). These fertiliser materials are commonly used in situations where taro crops are supplied with external nutrients. A split-plot design was used to compare taro yield and nutrient use efficiency as affected by amendment type and placement (surface application *vs*. incorporated). For the surface application treatment, the amendment was spread around and in proximity of the taro plant. For the incorporation treatment, the amendment was placed beneath the taro plant in the hole dug by the field operator at planting (at approximately 100-150 mm below the soil surface). A thin layer of soil was added on top of the amendment to avoid direct contact between this and the taro plant. Both amendments were applied at planting at a standard rate of 50 g product (fresh weight basis) per plant, which equated to the 'half-hand full' rate used by local farmers. Therefore, the application rate used at Nu'u 2 represented the standard local practice, and the planting system was the same as Nu'u 1 and Faleãlili.

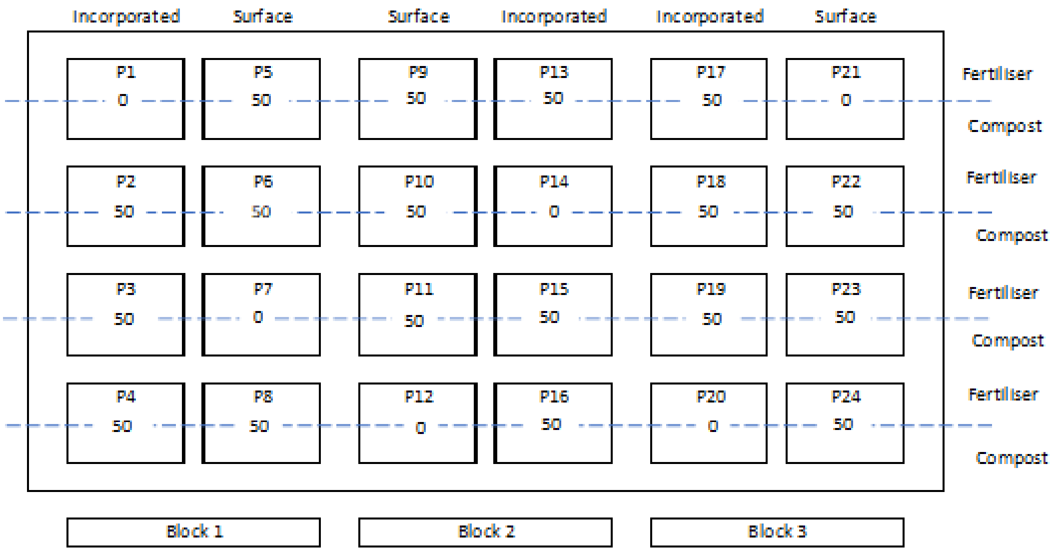

Figure 21 A diagram showing the lay-out of the experiment at Nu'u 2 during the 2020-2021 crop season. 'Surface': surface application of fertiliser or compost, 'Incorporated': fertiliser or compost incorporated beneath the taro plant at planting. The numbers '0' and '50' denote the amendment application rate expressed as grams of product (fresh basis) per plant, and where zero-amendment is the control. P1-P24 denote plot number. The planting system was identical to that reported in Figure 20.

Soil measurements and analyses

Soil analyses were conducted at SROS (Scientific Research Organization of Samoa at Apia) prior to the experiments using the methods adopted by SPACNET (The South Pacific Agricultural Chemistry Laboratory Network), which are quoted in **Table 5**. At Nu'u 1, soil chemical analyses were repeated on samples taken immediately after harvest (March 2019), and analyses conducted at SROS. Sub-samples from Nu'u 1 and additional samples collected from Faleãlili immediately before harvest were packed and sent for chemical analyses to the CSIRO Laboratories at the Waite Campus in South Australia. These samples had to be quarantined and irradiated upon arrival to Australia and so analytical results could have been affected because of the gamma radiation treatment (Horowitz and Hulin, 1971). Despite this, it was possible to conduct basic measurements of soil physical and hydraulic properties not affected by gamma radiation treatment.

At all sites, the soils are classified as well-drained (Soil Survey Division Staff, 1993). Before the experiments were established, both the Nu'u and Faleãlili sites had been used for taro production. Soil bulk density (ρ_b) was determined as per Blake and Hartge (1986) by taking 40-cm^3 cores. The soil in the cores was then weighted, placed in an oven at 105°C for 72 hours, and re-weighted for determination of dry weight and gravimetric soil water content. Unconfined, saturated infiltration rates were measured in the field with the double-ring infiltrometer method (Parr and Bertrand 1960). Infiltration rates were obtained by differentiating Kostiakov's function (Equation 1) with respect to time to describe the relationship between the rate of infiltration and time (Equation 2).

$$F_t = a \times t^n \qquad (1)$$

$$I_t = a \times n \times t^{n-1} \qquad (2)$$

where F_t is cumulative infiltration (mm) at time t (h), and a and n are constants, and I_t is instantaneous infiltration rate (mm h^{-1}).

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Table 5 Baseline characterisation of soils at the experimental sites. Nomenclature: ρ_b, (dry) soil bulk density; EC, electrical conductivity of soil; SOC, soil organic carbon; N, nitrogen; P, phosphorus; K, potassium. Depth range: 0-150 mm. For particle size analysis, the soil was sieved, and measurements conducted on the <2 mm fraction.

Determination	Unit	Nu'u 1	Nu'u 2	Faleãlili	Analytical method
Sand (>20 µm)	% (w/w)	27.6	25.2	25.3	
Silt (2-20 µm)	% (w/w)	42.3	43.4	52.0	Bouyoucos (1962)
Clay (<2 µm)	% (w/w)	30.1	31.4	22.7	
Textural class	-	Clay loam	Clay loam	Silt loam	Australian Soil Texture Triangle
ρ_b	g cm^{-3}	0.886	-	0.916	Blake and Hartge (1986)
Cumulative infiltration	mm	$F_t = 363.3t^{0.68}$	-	-	Parr and Bertrand (1960)
Infiltration rate	mm	$I_R = 204.28t^{-0.35}$	-	-	Parr and Bertrand (1960)
Soil $pH_{1:5}$ (soil/water)	-	5.62 ± 0.56	6.60	4.50	Rayment and Lyons (2011)
$EC_{1:5}$ of soil (soil/water)	µS cm^{-1}	2.92 ± 0.60	-	-	Rayment and Lyons (2011)
SOC	% (w/w)	3.30 ± 1.16	12.65	3.50	Walkley and Black (1934)
Total N	% (w/w)	0.66 ± 0.21	1.12	0.25	Bremner (1960)
Soil extractable P	mg kg^{-1}	2.69 ± 4.74	28.7	14.6	Olsen et al. (1954)
Soil exchangeable K	cmol kg^{-1}	0.46 ± 0.07	0.77	0.45	MAFF (1986, Method No.: 63)

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Soil water retention curves for Nu'u 1 and Faleãlili were determined at the Soil Physics Laboratory at CSIRO at Black Mountain (Canberra, Australia). The relationship between matric potential and water content was determined on soil cores (dimensions: 50 mm in diameter, 50 mm long). The cores were manually taken for the middle point of the following depth intervals: 0-150, 150-300, and 300-600 mm, respectively. Soil water contents were determined at 0.1, 10, 30, 50, 100, 340, and 600 cm tensions using ceramic suction plates, and subsequently at 15 bar using a pressure plate apparatus, as described by McIntyre (1974). The laboratory determination of drained upper limit and crop lower limit was subsequently approximated by soil water contents measured at potentials of 100 cm (DUL_{100}) and 15 bar (LL_{15}), respectively (Cresswell, 2002). When equilibration was reached, defined as a change in soil mass <0.05 g over a 24-hour period, the soil cores were removed from the plates, weighed, and returned to the plates where the process was repeated for successive water potentials. After the 15-bar measurement was completed, the cores were placed in an oven at 105°C for 72 hours to determine the gravimetric water content at each incremental tension. The gravimetric water content was then expressed volumetrically by multiplying it by the soil bulk density. Dynamic changes in volume because of changes in water content were negligible and so the volume of soil used for density calculations equated the volume of the cylinder. The van Genuchten (1980) functions were fitted to measured data to describe the relationship between soil water content (expressed volumetrically) and water potential (Equations 3-5). The van Genuchten model parameter α and exponent η were estimated based on the approach described by Ngo-Cong et al. (2021*a*-*b*).

$$S_e = [1/1+(\alpha h)^n]^m \quad (3)$$

where

$$m = 1 - (1/n) \quad (4)$$

and

$$S_e = (\theta - \theta_r) / (\theta_S - \theta_r) \quad (5a)$$

$$\theta = \theta_r + (\theta_S - \theta_r) \times S_e \quad (5b)$$

where S_e is effective saturation, h is the pressure head (cm), θ is the soil water content, θ_S and θ_r are the saturated and residual water contents (all in $cm^3\ cm^{-3}$), respectively, and α (cm^{-1}) and η (dimensionless) are fitting parameters that describe the shape of the water retention function.

Crop measurements and analyses

Taro yield was determined by removing and weighting the eight central plants from each plot. The corms were then separated from the rest of the plant and weighted, and yield expressed as kg dry matter (DM) per ha (the average DM content of the taro corms was 35.67 ± 4.509%, w/w). Corm and total plant biomass were used to determine harvest Index expressed as percentage (Antille and Moody, 2021). For Nu'u 1 and Faleãlili, corm dimensions (circumference and length) were also measured (Appendix 2). Nutrient off-take was estimated using elemental (N, P, K, Ca, and Mg) concentrations in corm available in the literature for average crop yields in Samoa (e.g., Fa'amatuainu and Amosa, 2016; Anand and Flores-Guinto, 2017). In this study, only the corms were removed from the field at harvest, with the rest of the plant biomass being returned to the soil. Therefore, nutrient off-take equates to the corm biomass (DM basis) multiplied by the assumed elemental concentration and is expressed as kg (element) per ha. The field-scale nutrient balance was estimated from the difference between nutrient inputs (e.g., applied nutrients in amendments such as compost and fertiliser, and via nitrogen fixation in legume-intercropped taro) and nutrient outputs (off-take in corm). Nutrient inputs for controls were assumed to be zero and so the nutrient balance was always negative (net off-take). For legume-intercropped taro, it was considered that in the year of establishment the legume plants would contribute about 50 kg N ha^{-1} per year. Reported N supply rates from intercropped legumes in taro crops range between 40 and 180 kg N ha^{-1} per year (e.g., Houngnandan et al., 2000; Hauser and Nolte, 2001; Anand, 2018). The rationale for choosing a N supply rate within the lower range of reported values corresponded with the stage of development of legumes at the sites, and the fact that only about ⅓ to ½ of the area between-taro rows were covered by legumes (as determined by visual assessment at harvest). Differences in yield between amendment-treated or legume-intercropped taro and controls, relative to nutrient supplied as amendment or via N fixation, were used to denote the agronomic efficiency (AE), as shown in Equation (6) (after Antille and Moody, 2021):

$$AE = (Y_{F\neq 0} - Y_{F=0}) / \text{Rate} \quad (6)$$

where AE is agronomic efficiency (kg kg^{-1}), $Y_{F\neq 0}$ and $Y_{F=0}$ are DM yields of amended-treated taro and control, and rate is the amount of given nutrient supplied as amendment, respectively (all in kg ha^{-1}).

Results and Discussion

Soil measurements and analyses

Results from soil analyses conducted after harvest at Nu'u 1 and Faleãlili are reported in Appendix 1. Overall, there were no statistical differences before vs. after harvest or between control and treatments (legumes) in any of the soil parameters analysed. For some parameters (e.g., soil extractable P), the analyses conducted at the Waite Laboratories yielded relatively higher values than those reported by SROS, which was explained by the effect of gamma radiation on the soil samples (Horowitz and Hulin, 1971).

Figure 22 show the soil water retention characteristics for Nu'u 1 and Faleãlili in which the volumetric water content measured at tensions of 100 cm of H_2O and 15300 cm H_2O (15 bar) are the laboratory determinations of drained

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upper limit (DUL_{100}) and crop lower limit (LL_{15}), respectively. Measured datapoints at tensions between saturation and 15 bar are reported in Table 6 (Appendix 3).

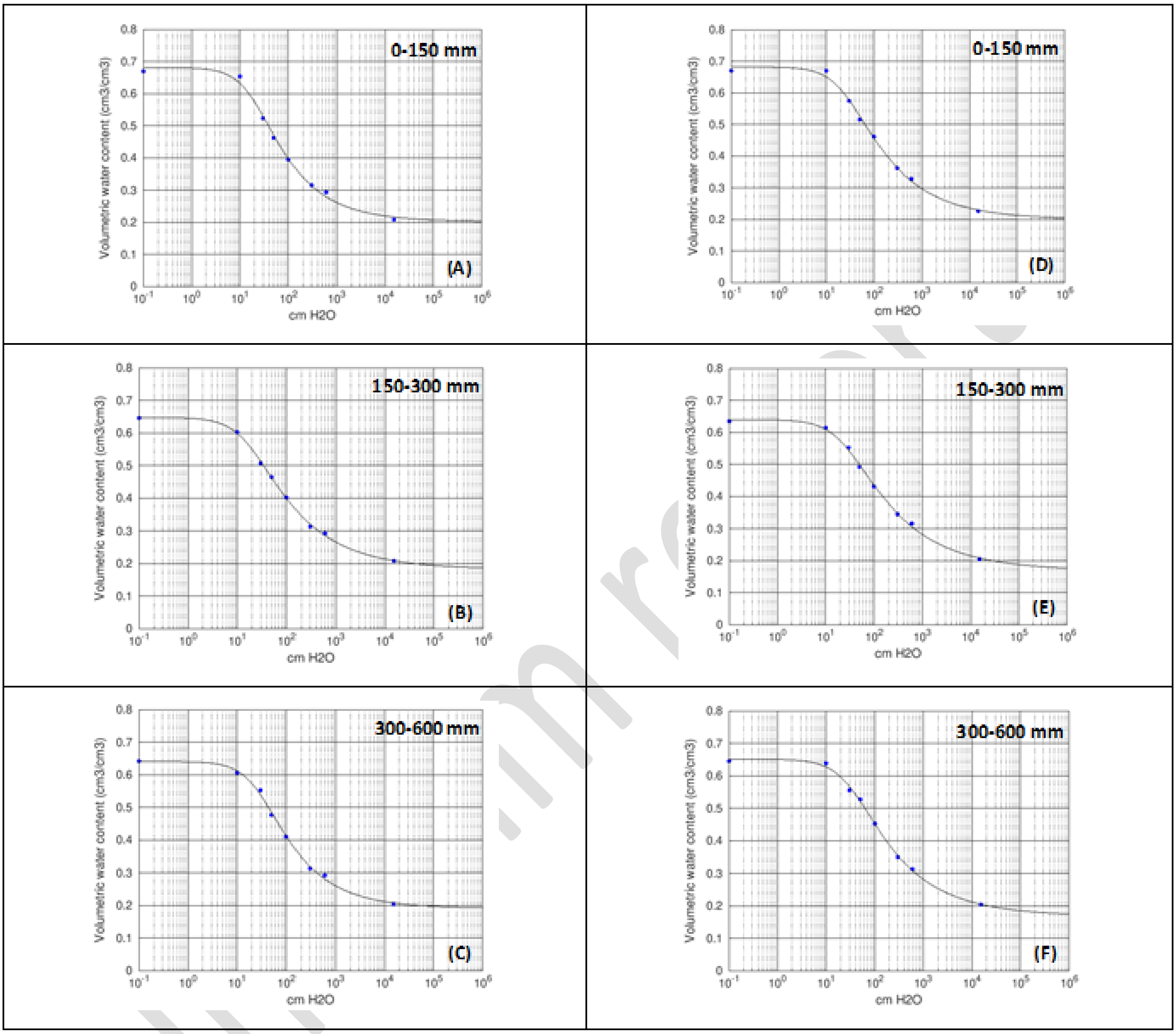

Figure 22 Soil water retention characteristics of the Nu'u 1 (A-C) and Faleãlili (D-F) sites for three different depth intervals. Blue dots show measured data points and black solid lines denotes the fitted van Genuchten (1980) model. Soil bulk density and the van Genuchten model parameters are shown in Table 3.

Table 6. van Genuchten (1980) model parameters used for representing the relationship between the soil water content (expressed volumetrically) and water potential of the Nu'u 1 and Faleālili sites (Figures 4A-F). Where: ρ_b is (dry) soil bulk density, ϑ_S and ϑ_r are saturation and residual soil water contents, α and η are fitting parameters of the VG model (Equations 3-5), R^2 is the coefficient of determination, and DUL_{100}, LL_{15} and PAWC are laboratory measurements of drained upper limit, crop lower limit and plant available water capacity, respectively.

Site	Depth	ρ_b	ϑ_S	ϑ_r	α	η	R^2	DUL_{100}	LL_{15}	PAWC
-	(mm)	(g cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})	-	-	-	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})
Nu'u 1	0-150	0.876	0.6812	0.2027	0.0522	1.5289	0.9949	0.3945	0.2081	0.1865
	150-300	0.885	0.6476	0.1827	0.0574	1.4235	0.9991	0.4019	0.2079	0.1940
	300-600	0.897	0.6405	0.1913	0.0359	1.5212	0.9973	0.4100	0.2052	0.2048
Faleālili	0-150	0.874	0.6824	0.2006	0.0389	1.4374	0.9957	0.4613	0.2269	0.2344
	150-300	0.916	0.6397	0.1696	0.0391	1.3899	0.9982	0.4304	0.2054	0.2250
	300-600	0.958	0.6513	0.1693	0.0313	1.4207	0.9978	0.4528	0.2043	0.2485

Crop measurements and analyses: Determining inputs and outputs at the plot level

Corm yields obtained at Nu'u 1 and Faleālili are shown in Figures 5A and 5B, respectively. At the Nu'u 1 site, overall statistical differences between control and legume-intercropped taro were not significant, and there were no differences between the *Erythrina* and *Mucuna* treatments (P-values >0.05). Average corm yield measured at Nu'u 1 (2730 kg DM ha^{-1}) was 1370 kg DM ha^{-1} lower than the national average (≈4100 kg DM ha^{-1}) recorded over the five-year period prior to these experiments (Alexandra et al., 2020). The attainable corm yield in Samoa has been estimated at 6150 kg DM ha^{-1} (FAO, https://www.fao.org/3/ad513e/ad513e0c.htm#bm12.1). For rainfed cropping systems, the attainable yield is defined as that achieved through skilful use of the best available technology, and it may be regarded as an approximation of the water-limited yield (Hall et al., 2013; Sadras et al., 2015). From these results, and based on previously published data, it can be inferred that the yield gap between actual, field-measured, and attainable yields was approximately 3400 kg DM ha^{-1}. Corm yields obtained at the Faleālili site were only significant between *Erythrina* and control (P<0.05); however, these differences were small. Differences between the two legume treatments, and between *Mucuna* and control were not significant (P>0.05). As discussed for Nu'u 1, the estimated yield gap between the average legume-intercropped taro (3340 kg DM ha^{-1}) and the national average was about 750 kg DM ha^{-1} and about 2800 kg DM ha^{-1} compared with the attainable yield.

Interim report

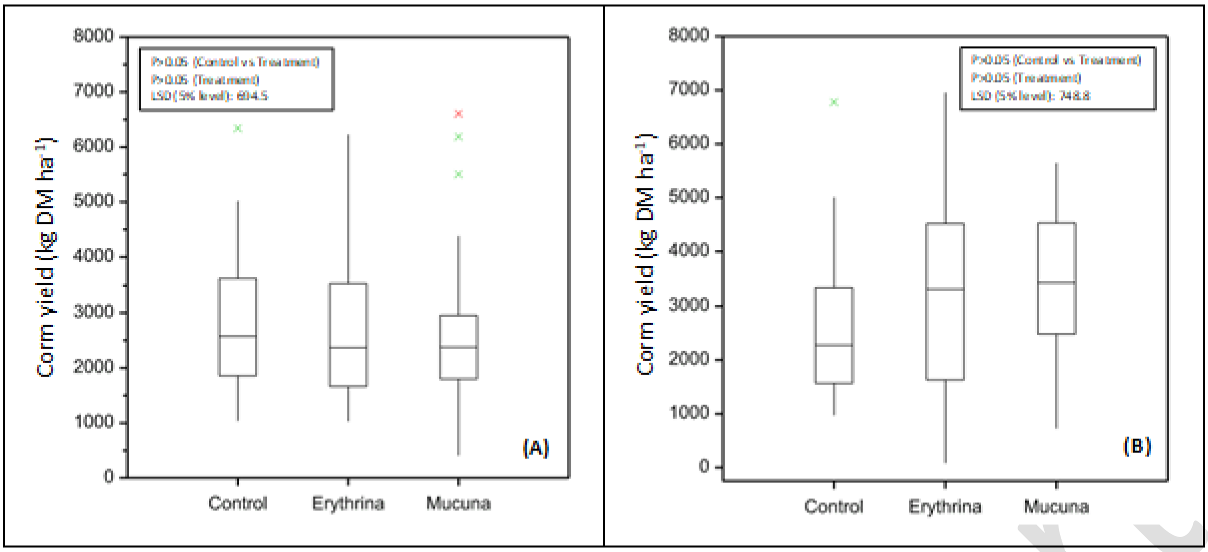

Figure 23 . Corm yields recorded at Nu'u 1 (A) and Faleãlili (B) in 2018-2019 and expressed in kg dry matter (DM) per ha. The box spans the interquartile range of the values in the variate (Q_3-Q_1) with the middle line indicating the median (Q_2). Whiskers extend to the most extreme data values within the inner 'fences', which are at a distance of 1.5 times the interquartile range beyond the quartiles (or the maximum value if that is smaller). Individual outliers are identified with a green cross and 'far' outliers (beyond the outer 'fences') are at a distance of 3 times the interquartile range beyond the quartiles.

Results suggested that the efficacy of legume intercropping as a strategy to increase the productivity of taro is limited. Therefore, the use of legumes may be discouraged in lower fertility soils such as the Nu'u 1 site, which exhibited rather low soil extractable P levels (Table 2). When attempting to intercrop legumes with taro, the following management aspects should be considered:

1. Intercropping will likely increase the risk of water deficits occurring, particularly if the crop cycle extends into the 'dry' season due to the selected planting date.
2. Legumes will likely reduce the availability of soil P to the taro crop in soils that are under-supplied with P (e.g., Olsen's P below 20 mg kg^{-1}), as legumes are known to take-up substantial amounts of P (Mengel et al., 2001). Similar effects may be encountered with other nutrients (e.g., K, Ca, Mg) if their levels in soil are below critical levels for growing taro.
3. Low soil P supply will reduce N uptake by the taro crop because of the significant N × P effect on N uptake (Fageria, 2001; Fageria et al., 2017) (regardless of N being available to the taro crop as a result of N fixation by the legume) (Baligar et al., 2001).
4. Soil application of P, whether as fertiliser or organic amendment, should account for P uptake by the legume (which may lead to temporary immobilisation of P in legume biomass) when this is intercropped with taro. The same applies to other key nutrients (e.g., K, Ca, Mg) used by legumes in fairly large quantities.
5. Fertilisation strategies need to be targeted to meet the nutrient requirements of both legume and taro crops so that N fixation (and N supply to the growing taro) is not compromised and uptake of other nutrients is not limited by soil/fertiliser availability. However, this will require careful optimisation of the system to ensure increased water use by legumes (due to the likely increased biomass in response to applied fertiliser) does not limit water (and therefore nutrient) uptake by the growing taro (co-limitation) (Aulakh and Malhi, 2005; Sadras, 2005).

There were no statistical differences in harvest Index between control and treatments or between-treatments, which was observed at both sites (P-values >0.05). Averaged across treatments, harvest Indexes were 0.531 at Nu'u 1 and 0.587 kg kg^{-1} at Faleãlili (Figure 24).

Interim report

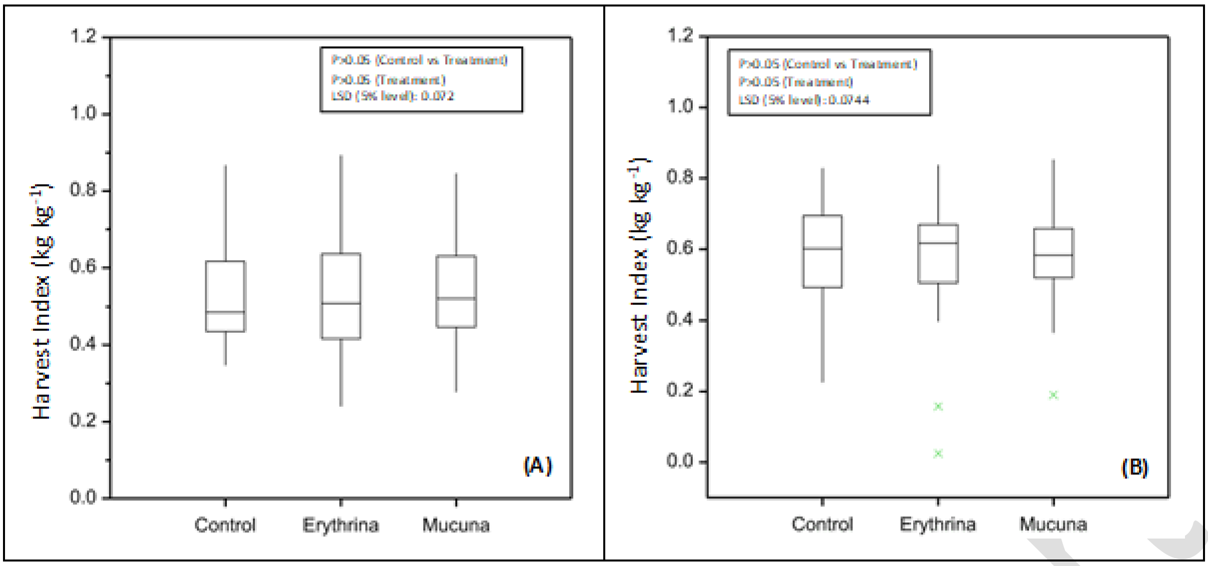

Figure 24. Harvest Indexes recorded at Nu'u 1 (A) and Faleãlili (B) in 2018-2019. Data shown in boxplots are as described in the caption of Figure 23.

Corm yields obtained at Nu'u 2 in 2020-2021 are shown in Figure 25. Overall, there were significant differences in corm yields between control and treatments ($P<0.05$), but amendment type (fertiliser *vs*. compost) or placement (surface-applied *vs*. incorporated) effects were not significant (P-values >0.05). On average, yields obtained in amendment-treated crop were about 950 kg DM ha^{-1} lower than the national average and about 40%-50% lower than the attainable yield for Samoa. Results obtained at Nu'u 2 suggested that the overall agronomic performance of amendment-treated crops was more constrained by management factors other than plant nutrition. Technical officers responsible for the field experiments were unable to visit the site while in lockdown and were also affected by their re-location from MAF to SROS. This meant that the experiments were unattended for extended periods and that routine crop protection practices (especially weed control) could not be appropriately performed, which therefore had adverse effects on yield and nutrient recovery (as discussed later). Yields at Nu'u 2 were within the range of yields recorded at Nu'u 1, which had been appropriately managed in terms of weed control but had had no nutrients applied (except for N derived from legumes). The challenges faced by technical officers and field personnel during the 2020-2021 season were mostly outside their control. However, this served to increase their awareness of the need to maintain 'good' crop husbandry if high-performing crops were to be produced. There appeared to be scope to increase actual, field-measured yields by about 3000 kg DM ha^{-1} and the national average yield by about 2000 kg DM ha^{-1} if best management practices for nutrients and crop protection were to be implemented.

Interim report

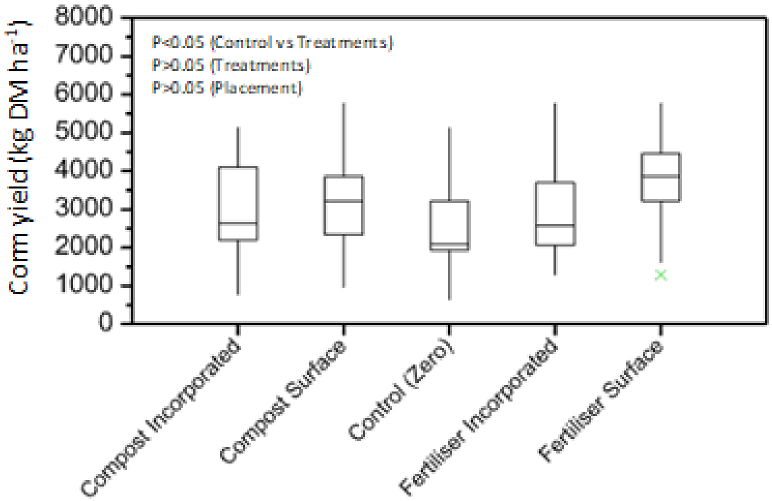

Figure 25. Corm yields recorded at Nu'u 2 in 2020-2021 and expressed in kg dry matter (DM) per ha. Data shown in boxplots are as described in the caption of Figure 5.

Harvest Indexes recorded at Nu'u 2 are shown in Figure 8. Mean values (from 0.578 to 0.606 kg kg^{-1}) were within the range reported for the other two sites (Figure 24). Differences between control and treatments, and between-treatments (amendment type and placement) were not significant (P-values >0.05). Agronomic efficiency calculations for this site were: 11.3 kg DM kg^{-1} N, 38.9 kg DM kg^{-1} P, 10.9 kg DM kg^{-1} K for fertiliser-treated crop, and 12.3 kg DM kg^{-1} N, 62.2 kg DM kg^{-1} P, and 20.4 kg DM kg^{-1} K for compost-treated crop, respectively.

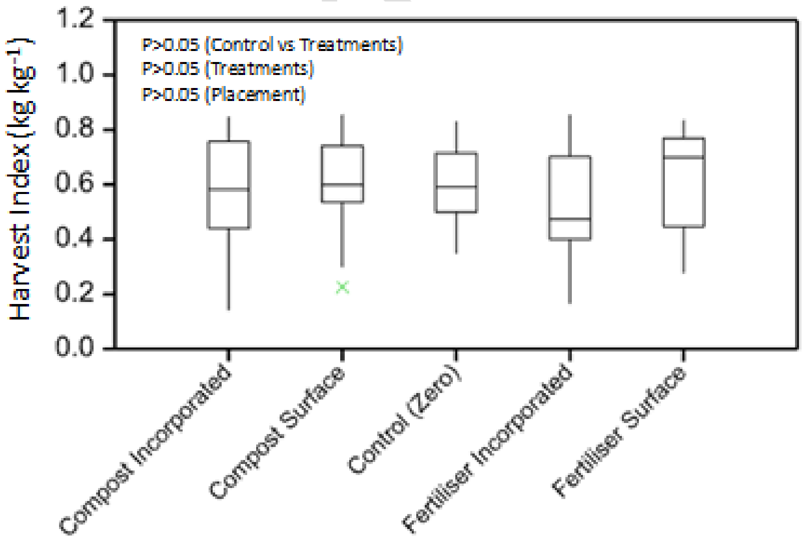

Figure 26 Harvest Indexes recorded at Nu'u 2 in 2020-2021. Data shown in boxplots are as described in the caption of Figure 5.

Table 7. Elemental composition of taro corms used to estimate nutrient off-take at harvest. Values compiled and averaged from multiple sources (e.g., Fa'amatuainu and Amosa, 2016; Anand and Flores-Guinto, 2017). SD is standard deviation. The mean taro corm DM was 35.67 ± 4.509% (w/w).shows the elemental nutrient composition used to derive nutrient off-take, which was subsequently used with DM yield data to provide field-scale nutrient balance estimates.

Table 7. Elemental composition of taro corms used to estimate nutrient off-take at harvest. Values compiled and averaged from multiple sources (e.g., Fa'amatuainu and Amosa, 2016; Anand and Flores-Guinto, 2017). SD is standard deviation. The mean taro corm DM was 35.67 ± 4.509% (w/w).

Element	Unit	Mean concentration ± SD
Nitrogen, N	%, w/w (dry basis)	0.76 ± 0.142
Phosphorus, P	%, w/w (dry basis)	0.24 ± 0.012
Potassium, K	%, w/w (dry basis)	1.45 ± 0.289
Calcium, Ca	%, w/w (dry basis)	0.10 ± 0.025
Magnesium, Mg	%, w/w (dry basis)	0.15 ± 0.021

Figure 27 and Figure 28 show nutrient off-take as estimated for the three experimental sites based on the taro corm yields reported in Figures 5 and 7, and the average elemental composition of taro corms presented in Table 4. Given that treatment differences in yield encountered at Nu'u 1 and Faleãlili were not significant (except for the small yield difference between control and *Erythrina* at the Faleãlili site), nutrient off-take data were consolidated into single figures per site. For Nu'u 2, nutrient off-take data are presented by amendment type as other treatment effects (amendment placement) on yield were not significant (Figure 7).

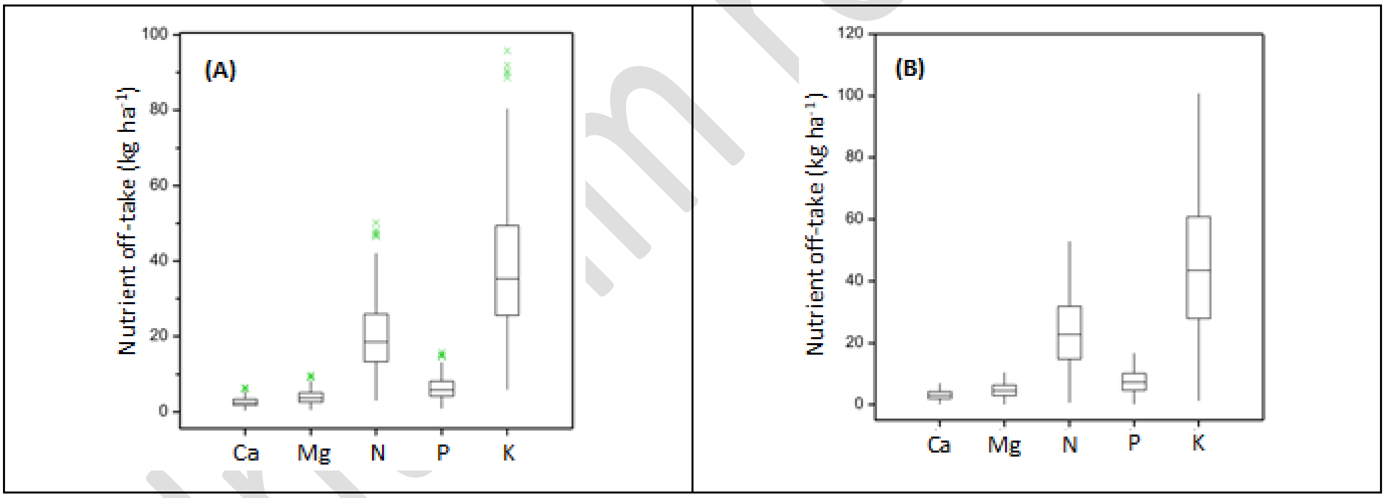

Figure 27. Estimated nutrient off-take in taro corms at Nu'u 1 (A) and Faleãlili (B) in 2018-2019. Data shown in boxplots are as described in the caption of Figure 5.

Interim report

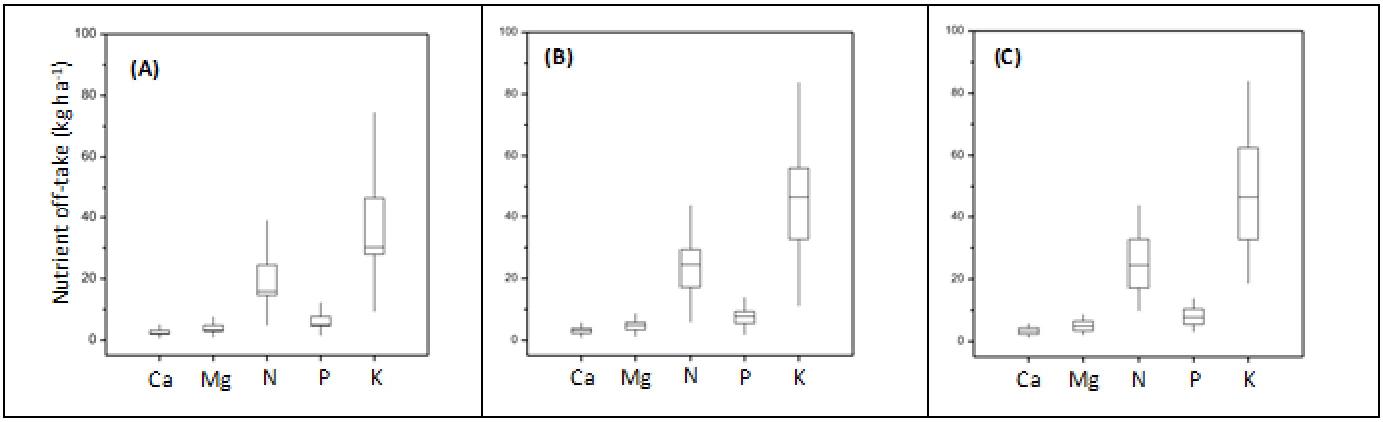

Figure 28 Estimated nutrient off-take in taro corms at Nu'u 2 in 2020-2021; (A): Control (zero-amendment), (B): Compost and (C) NPK+S fertiliser applied at 50 g (product) per plant. Data shown in boxplots are as described in the caption of Figure 5.

The information presented in Figure 27 and Figure 28 was subsequently used to provide field-scale nutrient balance estimates for five major elements. Based on the assumptions made in the analyses, these estimates showed negative balances across all five nutrients when legumes were intercropped with taro, including for N. The apparent N, P, and K surplus estimated at Nu'u 2 for fertiliser- and compost-treated taro crops did not correspond with the yields recorded at this site. This suggested that corm yields were more constrained by factors other than nutritional (importantly weed control) and that any apparent nutrient surplus was due to poor use efficiency of applied nutrients as compost or fertiliser. Average nutrient off-take ratios were, approximately, 6:2:11:1:1 (N:P:K:Ca:Mg), which may be used as guidance for fertilising taro crops if the strategy was to work on a nutrient replacement basis.

Interim report

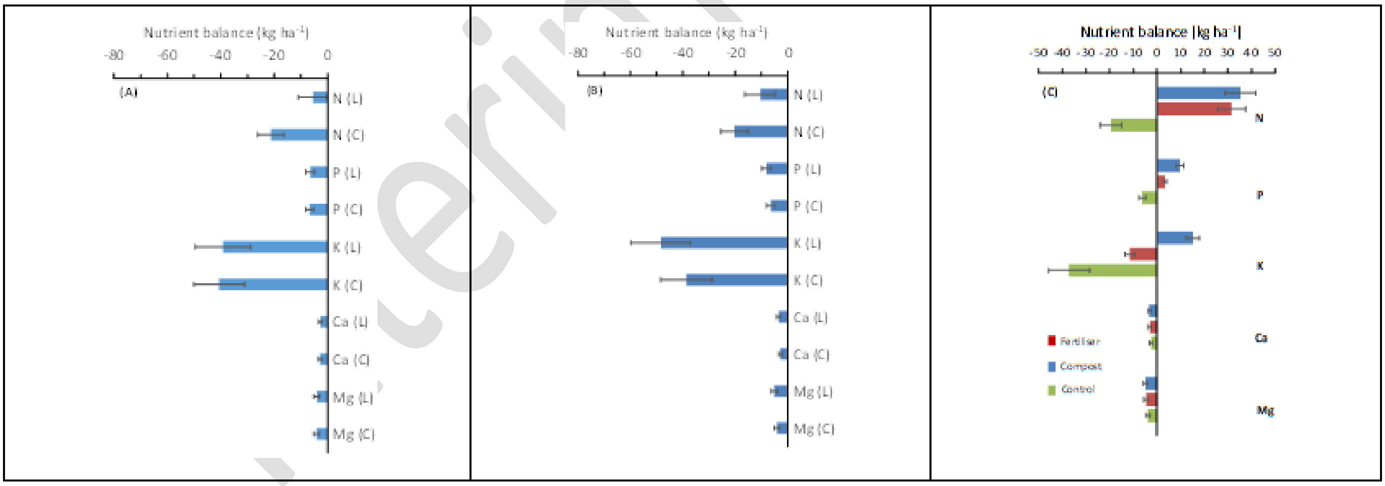

Figure 29 . Estimated field-scale (macro) nutrient balance at three experimental sites as affected by nutrient management practice. From left to right, (A): Nu'u 1 (2018-2019), (B): Faleãlili (2018-2019), and (C): Nu'u 2 (2020-2021). In Figures (A) and (B), the letters (L) and (C) following the nutrient symbol denote 'legume' intercropping and 'control', respectively. In Figure (C), 'fertiliser' is NPK+S (12:8:15+3, commercially known as Blaukorn Classic®) and 'compost' is composted poultry manure (>¾ by weight).

Towards improved nutrient recommendations for taro

Application of nitrogen to a crop should be based on the yield-to-nitrogen response relationship (Figure 30), from which the most economic rate of nitrogen can be derived (James and Godwin, 2003; Antille and Moody, 2021). Since the response to applied nitrogen is site (soil-related effects) and year (climate-related effects) specific, a family of response curves constructed over multiple years at a given location can provide the required confidence to make fertiliser-N decisions at such location (Welsh et al., 2021). The optimum economic rate can be then adjusted using the yield-to-nitrogen response relationship developed with historical data and the price ratio (that is the unit price of N relative to the unit price of the crop; Kachanoski, 2009). This approach forms the basis for making nitrogen recommendations. Further work needs to be undertaken to establish yield-to-nitrogen response relationships at key locations in Samoa and be able to provide nitrogen management advice to local farmers. The experimental station of MAF at Nu'u together with the Samoa Farmers Association (https://pacificfarmers.com/), and the technical assistance of SROS may offer opportunities for such work to be conducted.

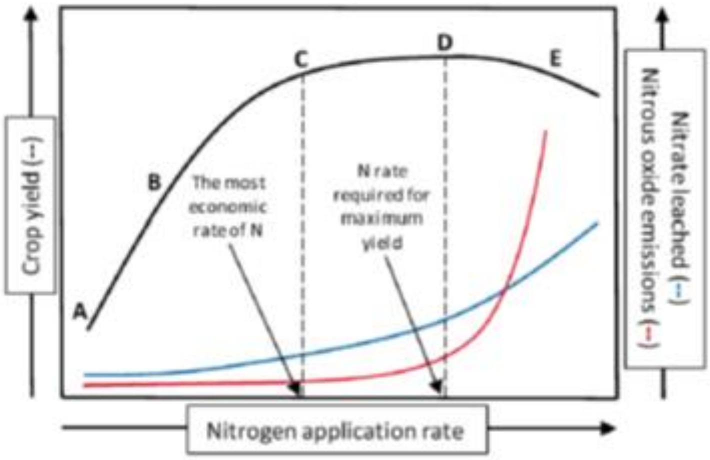

Figure 30. Conceptual diagram showing a typical yield-to-nitrogen (N) response relationship (black curve), and the increased risk of N lost through leaching (blue curve) and nitrous oxide emissions (red curve) when a critical level of N applied as fertilizer is exceeded (after DEFRA, 2010; Antille and Moody, 2021). Note the non-linear response of soil N_2O to increased N fertiliser rate (Scheer et al., 2016). Letters show: (A) crop yield as a function of soil N supply, (B) at low N application rates, there is a significant and profitable yield response to increasing rates of N, (C) the most economic rate of N (MERN) denotes the point at which the cost of any additional N is greater than the value of the extra crop yield produced, and where MERN ≤ N_{MAX}. This N application rate will return the maximum profit from the fertilizer applied. At N rates up to, and including, the most economic (optimum) N rate, there is a roughly constant amount of residual soil N that may be lost by leaching or denitrification, (D) N application rate (N_{MAX}) required for maximum yield (Y_{MAX}), which is not justified due to loss of economic return from N applied as fertilizer (except when MERN = N_{MAX}), and (E) yield or crop quality penalties may occur and thus marginal returns on fertiliser inputs are increasingly negative. At this point, there is also an increased risk of environmental losses of N (Delin et al., 2015; Scheer et al., 2016) due to proportionally larger surplus of applied N.

It is also suggested that application of phosphorus, potassium, and possibly calcium and magnesium, be based on a replacement strategy. Soil nutrient Indexes applicable to Samoan soils need to be developed and critical (or target) Indexes below/above which agronomic and/or profitable responses are/not likely to be encountered. Soils in which a given nutrient Index is above the target Index, application of that nutrient may be omitted as there would be no agronomic or economic incentive to do that so. Specifically for phosphorus, its application to high P Index soils needs to be avoided as this may increase the risk of environmental losses (from soil to water) through processes such as erosion and runoff (e.g., Tunney et al., 1997; Sharpley et al., 2001). By contrast, soils in which the nutrient Index is below the target Index, application of that nutrient cannot be avoided if yield and economic return from applied nutrients are to be optimised. For these low Index soils, there should be a long-term policy of building-up deficient nutrients allowing for progressive correction of the Index towards target levels. Soils in which nutrient levels are at the target Index, the objective would be to maintain it and apply nutrients on a replacement basis. Application of a given nutrient to soils that are at the target Index may be omitted in some years when, for example, the price ratio is too narrow (nutrient price too high or crop price too low, or both). Soil testing for determining P, K, Ca, and Mg Indexes may be conducted at regular time intervals (e.g., 3-4 years), with an annual fertilisation plan that takes account of the rotation developed afterwards. For N, soil testing may be omitted as obtaining reliable analytical results while being able to accurately quantify soil N supply rates under the local Samoan conditions could prove difficult. Noting also that the conditions in which soil samples are preserved while in transit from the field to the laboratory, and the storage time and conditions before they are analysed, significantly influence available N fractions (Bailey et al., 2022). Therefore, derivation of the optimum N application rate (MERN) from the yield-to-nitrogen response (Figure 30) is a more reliable approach to formulating N recommendations and it will also help reduce the cost of soil analyses.

A conceptual framework that may be used to support the development of nutrient recommendations for taro production systems is presented in Figure 31. The proposed framework highlights the focus (productivity, profitability, environmental) of nutrient management strategies (build-up, maintain, omit) based upon the primary factors that determine the recommendation for specific nutrients (response, replacement). The approach establishes a criterion for determining the 'right rate' and emphasises that all 4R (Right source, Right rate, Right time, Right place) Nutrient Stewardship Principles (Roberts, 2007) must be always observed.

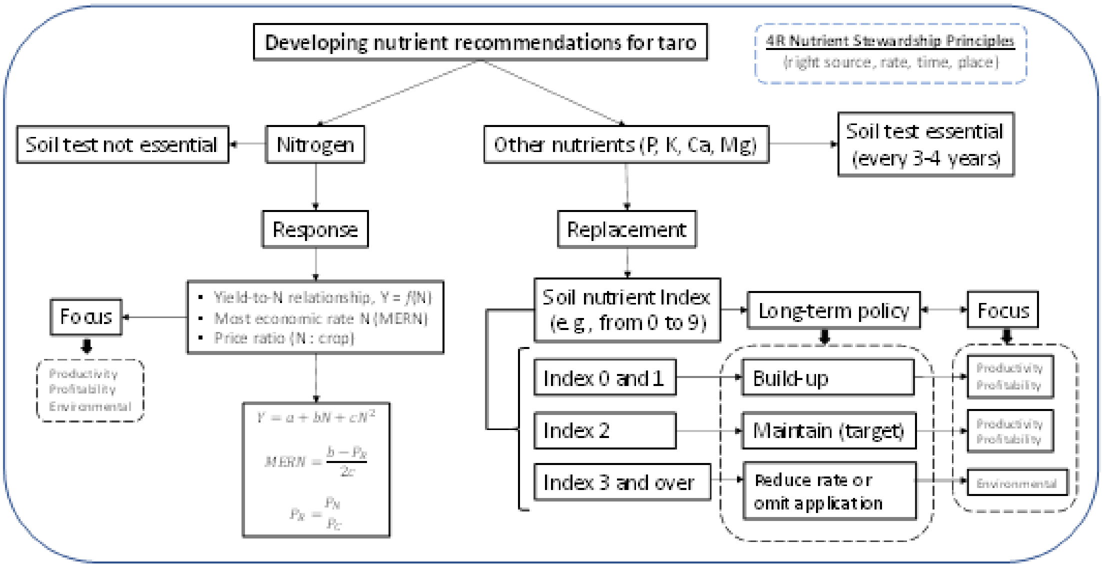

Figure 31. Conceptual framework to support the development of nutrient recommendations for taro production systems. The yield-to-nitrogen response assumes a quadratic-plateau relationship (Abraham and Rao, 1966) where: *Y* is yield, N is nitrogen application rate, and *a*, *b* and *c* are regression coefficients; MERN is the most economic rate of nitrogen (defined in Figure 12) and can be derived directly from the response curve; and P_R, P_N and P_C are price ratio, price of nitrogen and price of crop, respectively. The numerical scale used to define soil nutrient Index (from 0 to 9) is given as example and it may be modified to suit specific requirements. The 4R Nutrient Stewardship Principles (Roberts, 2007) must be always observed.

Table 5 shows how the soil nutrient Index concept (Figure 13) may be translated into fertiliser recommendations. For this, phosphorus is used as example, and it is assumed that the target corm yield is equivalent to the attainable yield (Y_a = 6150 kg DM ha^{-1}). A similar procedure may be then applied to the case of K, Ca, and Mg. However, it should be noted that the information presented in Table 5 requires validation and therefore may not be used to formulate fertiliser recommendations at this stage. This information is presented for the sake of providing a worked example.

Further work needs to be conducted to validate these concepts. In Table 8 if soil P Index is 3, the recommended rate may be omitted (or reduced) if for example the price ratio is narrow, or soil extractable P levels are above the middle point of the Olsen's range (>35 mg kg^{-1}).

Table 8. Formulating a fertiliser recommendation based on the soil nutrient Index concept presented in Figure 13. Phosphorus is used as example and it is assumed that the target corm yield is equivalent to the attainable yield (Y_a = 6150 kg DM ha^{-1}). Soil Olsen's P ranges and soil P Indexes adapted from DEFRA (2010).

Soil Olsen's P	**Soil P Index**	**Strategy**	**Recommended rate**	
(mg kg^{-1})	-	-	(kg P ha^{-1})	(kg P_2O_5 ha^{-1})
0-9	0	Build-up	28	65
10-15.	1	Build-up	22	50
16-25	2	Maintain	15	35
26-45	3	Reduce/Omit	9	20
46-70	4	Omit	0	0
71-100	5	Omit	0	0

Experimental work in Samoa was conducted to investigate field-scale nutrient cycling in rainfed taro production systems and demonstrate the importance of nutrient budgeting for soil fertility management. This work suffered from disruptions caused first by the measles outbreak in September 2019 (which extended until February 2020) and subsequently by COVID-19 in March 2020 (which also prevented CSIRO officers from travelling to the country). Further disruptions occurred during the course of 2020 when project officers from MAF were relocated to SROS, which took over the project administration. As a result, the experimental site at Nu'u 1 (double-cropping taro/taro) and the demonstration site at Tanumalala (commercial farm near Nu'u) were discontinued. Despite this, the rest of the originally planned experimental work was satisfactorily completed and included three field trials (two at the Crop Development Station of the Samoan MAF and one satellite site at a commercial farm in southern Upolu) conducted over two cropping seasons (2018-2019 and 2020-2021). This work made it possible to quantify field-scale nutrient balances and communicate research findings to government agencies (e.g., Samoan MAF), scientific organisations (e.g., SROS, USP), and local growers, extension officers, and agronomists. This report complements the communication effort of in-country partners and CSIRO officers involved in delivering a range of extension activities (e.g., Dr Soils Workshops). Improved nutrient management via field-based experimentation, adoption of rapid soil testing techniques and interpretation of soil tests results were important parts of the work conducted in Samoa.

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7.2.6 Fiji

Phase 1 Field trials

The field trial was designed by the Fiji MOA and local farmers to examine nutrient cycling and budgeting and to test mixed fertilizer applications to increase Taro yield.

Table 9. Phase 1 Taveuni field trial treatments utilising existing rates with different product mixes.

Treatment	Application rates	Application
1	NPK – 40 kg ha^{-1}, Fish meal - 20 kg ha^{-1}, Ag lime - 30 kg ha^{-1}	During Planting
2	TSP - 20 kg ha^{-1}, Urea - 30 kg ha^{-1} (2 splits), Fish Meal - 20 kg ha^{-1}, Ag lime - 30 kg ha^{-1}	During planting except urea which is applied after 4 and 8 weeks after planting
3	TSP - 20 kg ha^{-1}, Ag lime - 30 kg ha^{-1}, Urea - 30 kg ha^{-1} (2 splits)	
4	TSP - 20 kg ha^{-1} , Ag Lime - 30 kg ha^{-1}, Urea - 30 kg ha^{-1} (2 split), Fish Meal - 20 kg ha^{-1}	

Overall, there was no treatment effect on mean corm yield or biomass at either site. It was observed that there were more suckers per plant at the Qila site than the Qarawalu site. The yield difference was greater in Qila in T1 and T2 than in Qarawalu. Severe corm rots were observed in Qarawalu, which may be attributed to over maturity of corms, a dry spell that may have weakened the plants and the observed higher incidence of Mily bugs relative to the Qila site. {Raju, 2019 #10202@@author-year} found that the optimal internal efficiencies of NPK for balanced nutrition were 77.07, 364.07 and 57.23 kg corm kg^{-1} N, P and K removed. It is evident from Table 9 that the current rates that were used in the trial were significantly less than crop requirement.

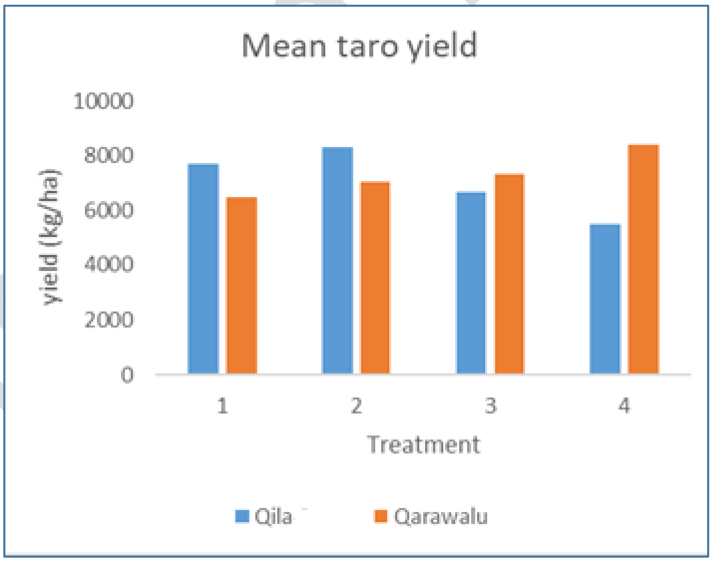

Figure 32 Mean taro yield Phase 1 Taveuni field.

Phase 2 Field trials

The phase 2 field trial was focused on increased rates and mix of fertilizer types which were identified by the extension officers and farmers during project discussions (Table 10). There was no significant difference between the treatments in either corm mass or total sucker mass (Figure 33 and Figure 34). Although it was observed that there was an increase in yield and sucker mass in the Grower's Choice and Carbon treatments. Both treatments had greater amounts of applied (N and P) nutrients and lime were not applied. It was also observed that corm rots occurred in all treatments at both sites.

The nutrient budgeting revealed that the Growers Choice had applied appropriate amounts of K (Figure 36), but excessive amounts of N and P (Figure 35 and Figure 37)Figure 35 Nitrogen balance in each field Phase 2 field trial, Taveuni 2019-2020.. The Carbon treatment applied a balance N and P but under fertilized K. These results indicate that nutrients other than NPK or field management practices were affecting productivity. Taveuni farmers surface apply urea fertilizer and other nutrients and there is a potential for significant run-off losses, this was not accounted for in the nutrient budgeting. However, the atmospheric losses of N through volatilization were accounted for in the nutrient budgeting work. During the discussion with the farmers these loss pathways were highlighted but there was a reluctance to spend money on labour to bury the applied fertilizer.

Table 10 Phase 2 Taveuni field trial treatments utilising increased rates with different product mixes.

Treatments	Fertilizers	Application kg ha^{-1}	Time of application
1. Micronutrients	Urea	34	2 split application (17g) @4 and 7 WAP
	Triple Superphosphate	11	Basal application (during planting)
	Muriate of potash	32	Basal application (during planting)
	Micro- elements (Fe, Mn, Cu, Zn, B)	15	Surface application during planting
	Agricultural Lime	35	Surface application during planting
Control	Urea	34	2 split application (17g) @4 and 7 WAP
	Triple Superphosphate	11	Basal application (during planting)
	Muriate of potash	32	Basal application (during planting)
	Agricultural Lime	35	Surface application during planting
3. Carbon	Urea	34	2 split application (17g) @4 and 7 WAP
	Triple Superphosphate	11	Basal application (during planting)
	Muriate of potash	32	Basal application (during planting)
	Micro- elements (Fe, Mn, Cu, Zn, B)	15	Surface application during planting
	Agricultural Lime	35	Surface application during planting
	Poultry manure/fish meal	35	Surface application during planting
4. Grower's choice	Urea	30	2 split application (17g) @4 and 12 WAP
	Di ammonium Phosphate	30	Basal application (during planting)
	Hydro Complex	30	After 5 weeks of planting

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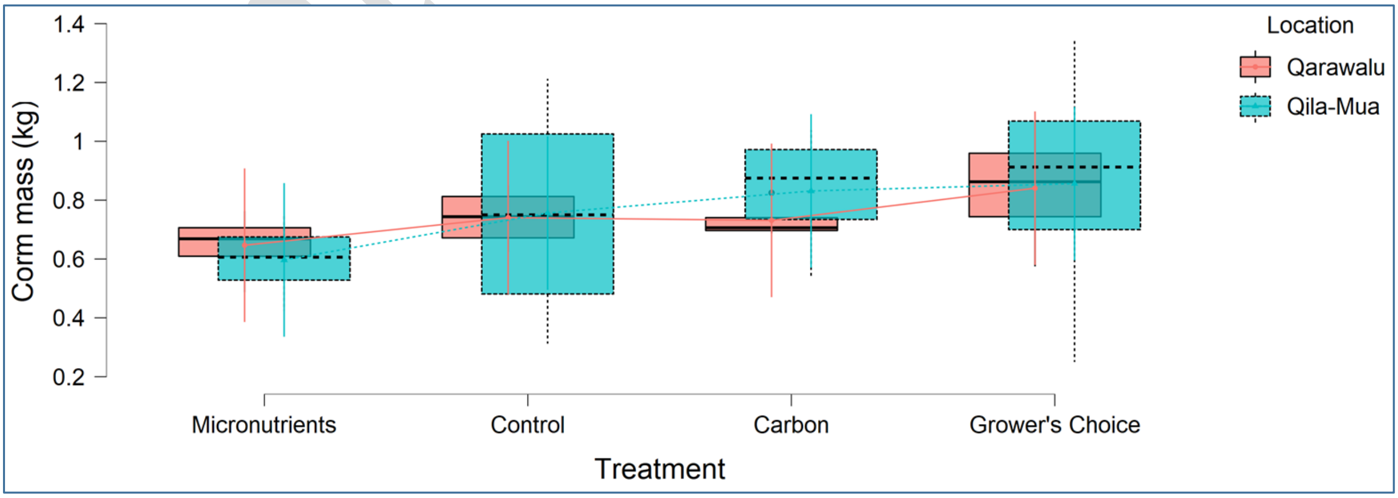

Figure 33. Mean taro yield Phase 2 Taveuni field trial.

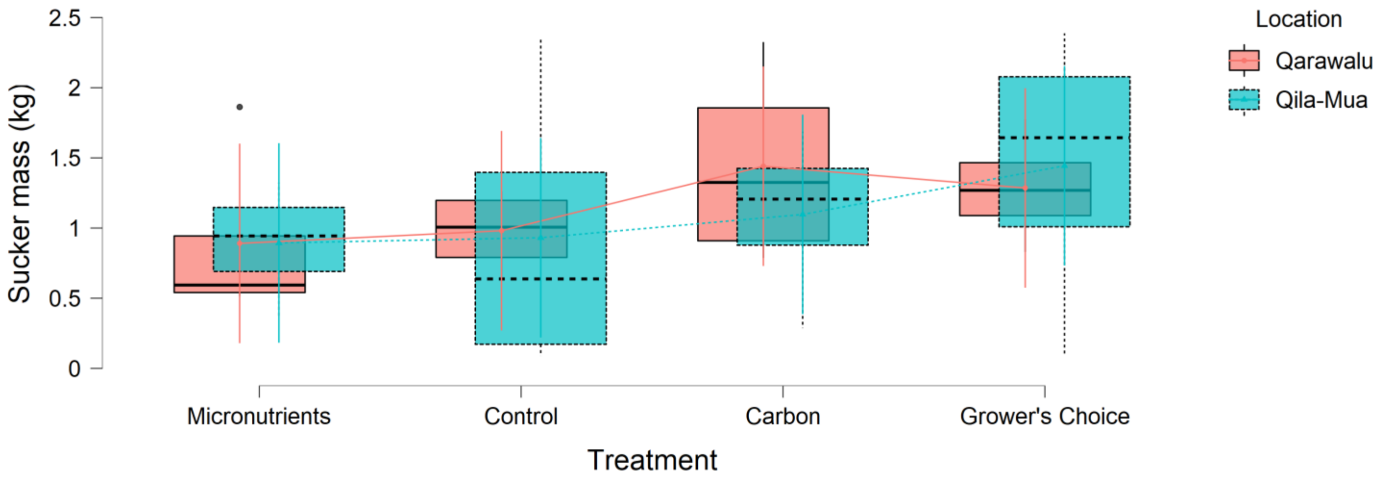

Figure 34 Total sucker mass Phase 2 Taveuni field trial.

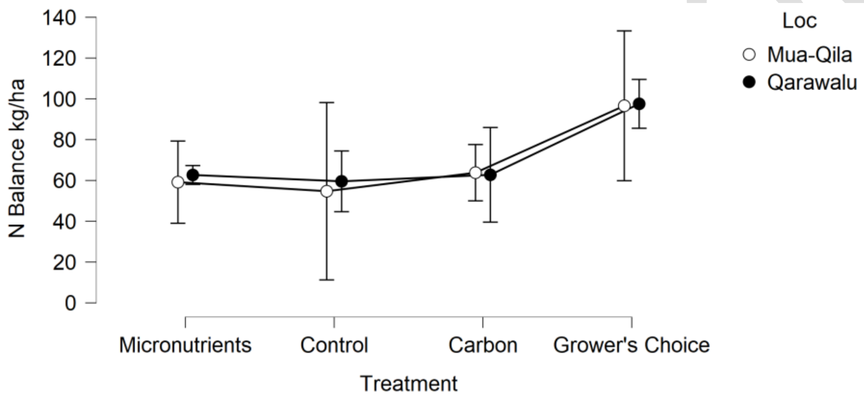

Figure 35 Nitrogen balance in each field Phase 2 field trial, Taveuni 2019-2020.

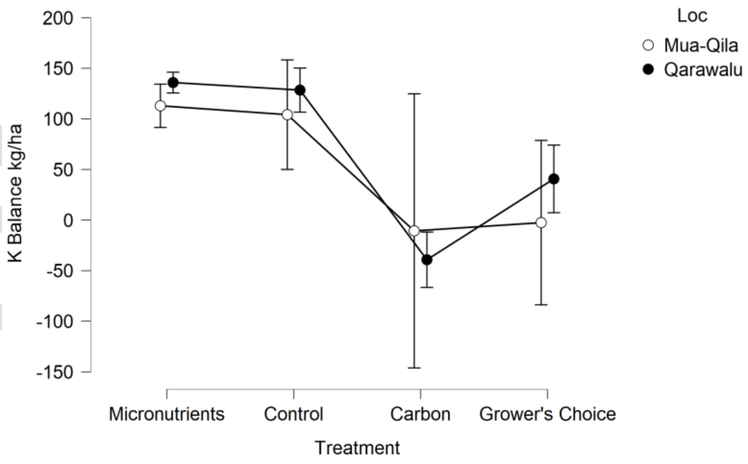

Figure 36 Potassium balance in each field Phase 2 field trial, Taveuni 2019-2020

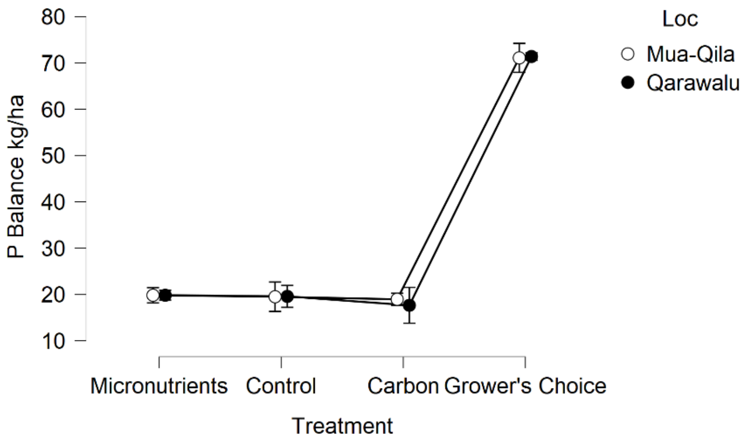

Figure 37. Phosphorus balance in each field Phase 2 field trial, Taveuni 2019-2020

Most growers do not have the time to undertake nutrient budget measurements. The project team found that it was possible to estimate the amount of NPK removed from the taro fields by the *taro and suckers* just from the corm mass. This means that with the development of a simple nutrient replacement system, farmers can just use harvest corm mass to guide NPK replacement.

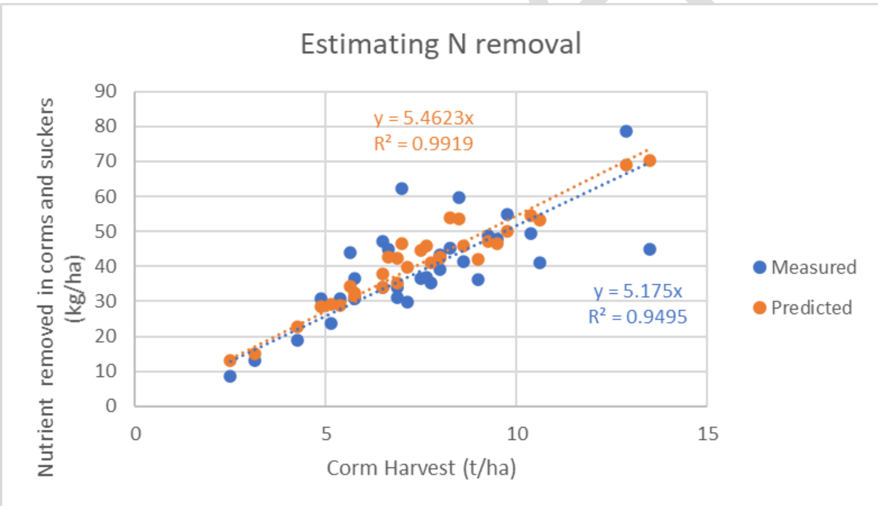

Figure 38. Estimation of N removal from the taro field using literature values {Bradbury, 1988 #4511} and measured values from the field trials.

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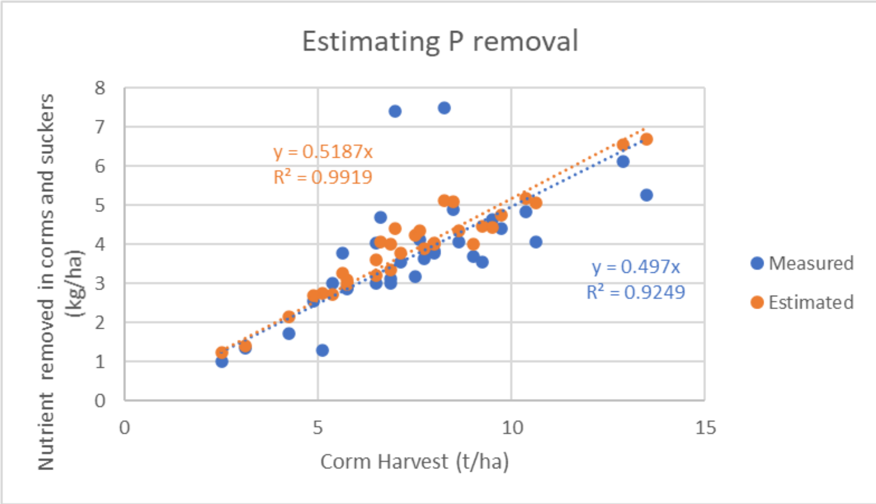

Figure 39. Estimation of P removal from the taro field using literature values {Bradbury, 1988 #4511} and measured values from the field trials.

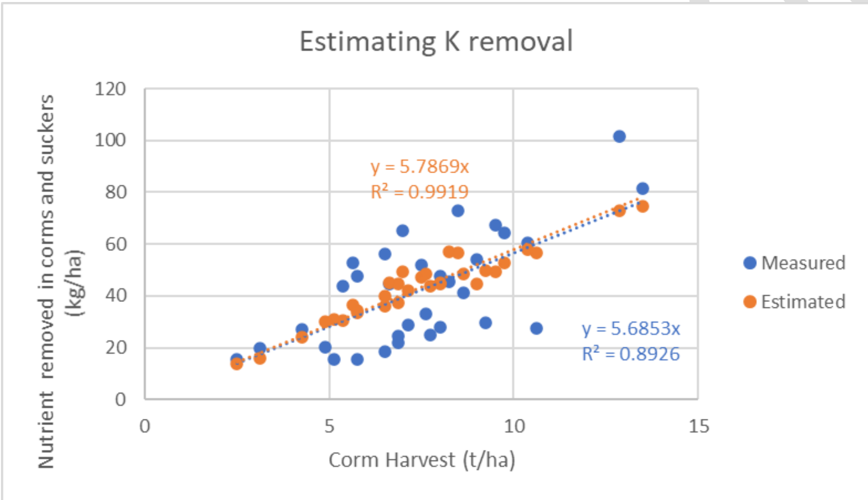

Figure 40. Estimation of P removal from the taro field using literature values {Bradbury, 1988 #4511} and measured values from the field trials.

The effect of soil type can have a significant effect on crude protein in sweet potatoes and variation been observed in taro sourced from the Suva market. {Bradbury, 1988 #4511}. At the Mua-Qila and Qarawalu trials estimated crude protein, calculated from the total N content of the taro corm, does show variation between sites and treatments. This potential shows that consideration of nutritional quality of the taro should be investigated as well as yield. Further work is also needed to refine the measurement of protein content and other nutritional measures.

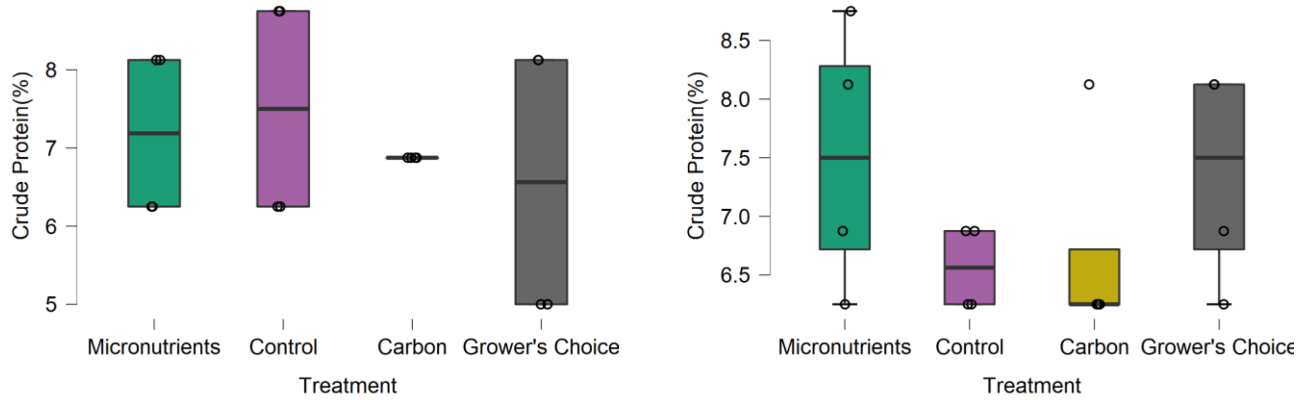

Figure 41 Estimated Taro crude protein (%) Mua- Qila (left) and Qarawalu (right) Phase 2 Taveuni field trial.

Phase 3 Field trials

This field season was disrupted by Cyclone Yasa which struck Fiji in December 2020 and the COVID-19 domestic travel shut down. This nutrient trial was designed to test the hypothesis that boron and micronutrient were limiting yield and organic matter was limiting yield. This trail was recently harvested, and preliminary analysis has been undertaken.

Table 11 Phase 3 Taveuni field trial treatments utilising increased rates with different product mixes.

Treatments	**Fertilizers**	**Application rate (kg ha^{-1})**	**Time of Application**
1.Inclusion of Micronutrients	Urea	34	2 split application 17g @ 4 & 7 WAP
	Hydro Complex	40	1st leaf and @12 weeks
	Micro-elements (Mn, Cu, Zn)	15	Surface application during planting
	Borax	5	Surface application during planting
2. Boron	Urea	34	2 split application 17g @ 4 & 7 WAP
	Hydro-Complex	40	1st leaf and @12 weeks
	Triple Superphosphate	32	Basal application during planting
	Borax	5	Surface application during planting
	Agricultural Lime	34	Surface application during planting
3. Inclusion of Carbon	Urea	34	2 split application 17g @ 4 & 7 WAP
	Hydro-Complex	40	1st leaf and @12 weeks
	Triple Superphosphate	32	Basal application during planting
	Poultry Manure	700	Surface application during planting
4.GrowersChoice	Urea	34	2 split application 17g @ 4 & 7 WAP
	Hydro-complex	40	1st leaf and @12 weeks
	Triple Superphosphate	32	Basal application during planting
5.Organic Matter & Nutrients	Urea	34	2 split application 17g @ 4 & 7 WAP
	Hydro-Complex	40	1st leaf and @12 weeks
	Triple Superphosphate	32	Basal application during planting
	Potash	30	4 weeks after planting
	Poultry Manure	700	Surface application during Planting

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The inclusion of lime reduced the corm mass relative to the other treatments (Figure 42) but the other treatments were not significantly different for the Boron treatment. Sucker mass was not significantly different between each treatment. The effect of the cyclone on the field trial is unclear but experiment was compromised. The inclusion of lime does appear to reduce taro yield.

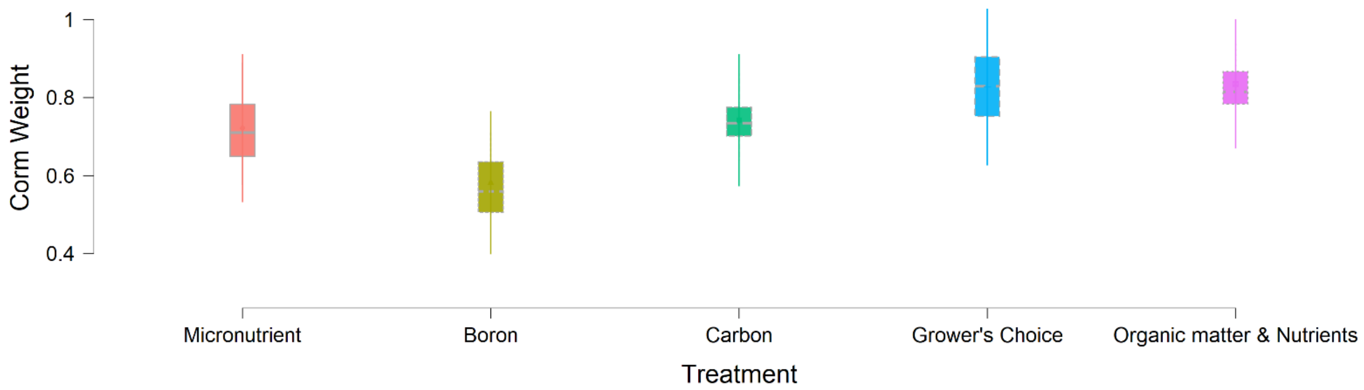

Figure 42 Mean taro yield Phase 3 Taveuni field trial.

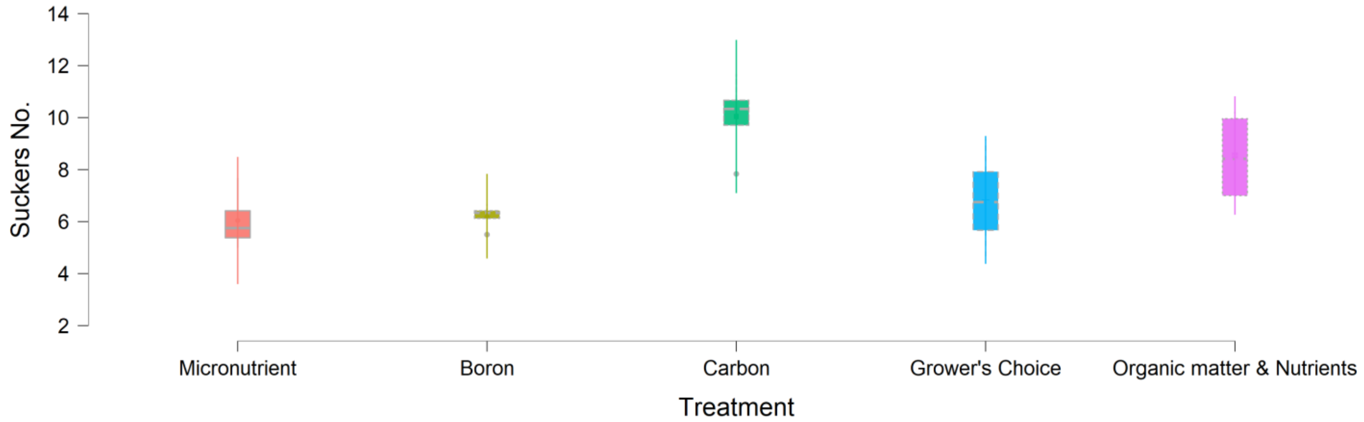

Figure 43. Sucker number Phase 3 Taveuni taro field trial

7.2.7 Tonga

Nutrient budgeting farming system trial was undertaken in 3 different Tongatapu soil types, Fahefa, Lapaha, Vaini. The first phase of the trial, in watermelons has shown that there is a significant over fertilisation of the crop (

Figure 44). The nitrogen use fertiliser efficiency is 38%, which is like other cropping activities. Tonga farmers are similar to Fijian taro farmers by placing fertiliser on the soil surface rather than incorporation. Surface applications of urea in tropical environments, where the soil conditions are warm and wet, upwards of 40% of the urea is lost via volatilization. In the Tonga case this could equate to 116 kg N and the remaining N could be immobilized but the majority would be leached or denitrified.

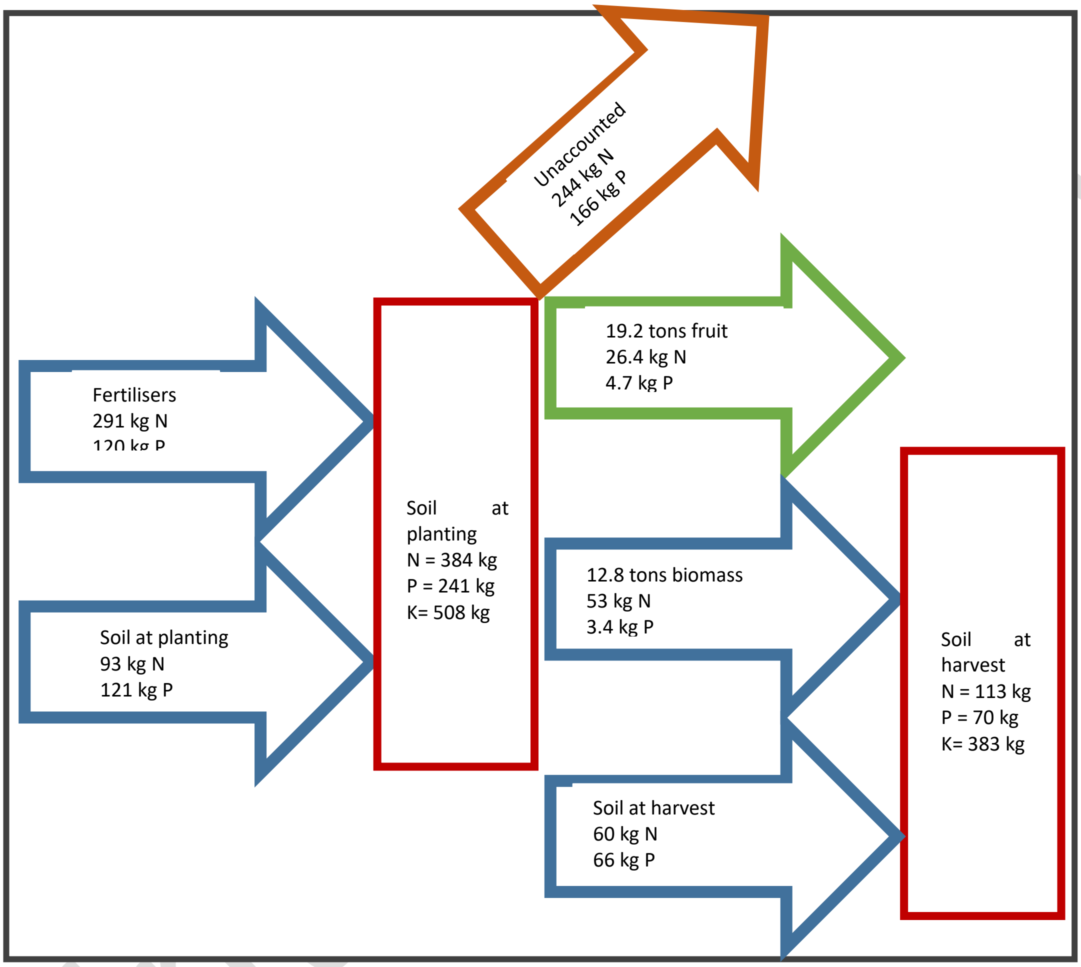

Figure 44. NPK inputs and outputs in a watermelon trial, Fahefa Figure 1. Current identified barriers to improving soil fertility management, yields and profit. **soil type. Blue arrows soil inputs, grower arrow exports, orange arrows losses and red boxes the soil.**

The overall farming system fertiliser trial has been completed and harvest data processed. The soil samples and plant samples have not been analysed due to COVID-19 and laboratory shutdown. We anticipate that the samples should be analysed by February 2022. Overall there was no observed difference in taro yield in between the control and the fertilised treatments. Utilising the relationships developed for Fiji taro Figure 38 to Figure 40 it is possible to estimate the taro crop removal of NPK. It is apparent that NPK is not limiting yield in the trial.

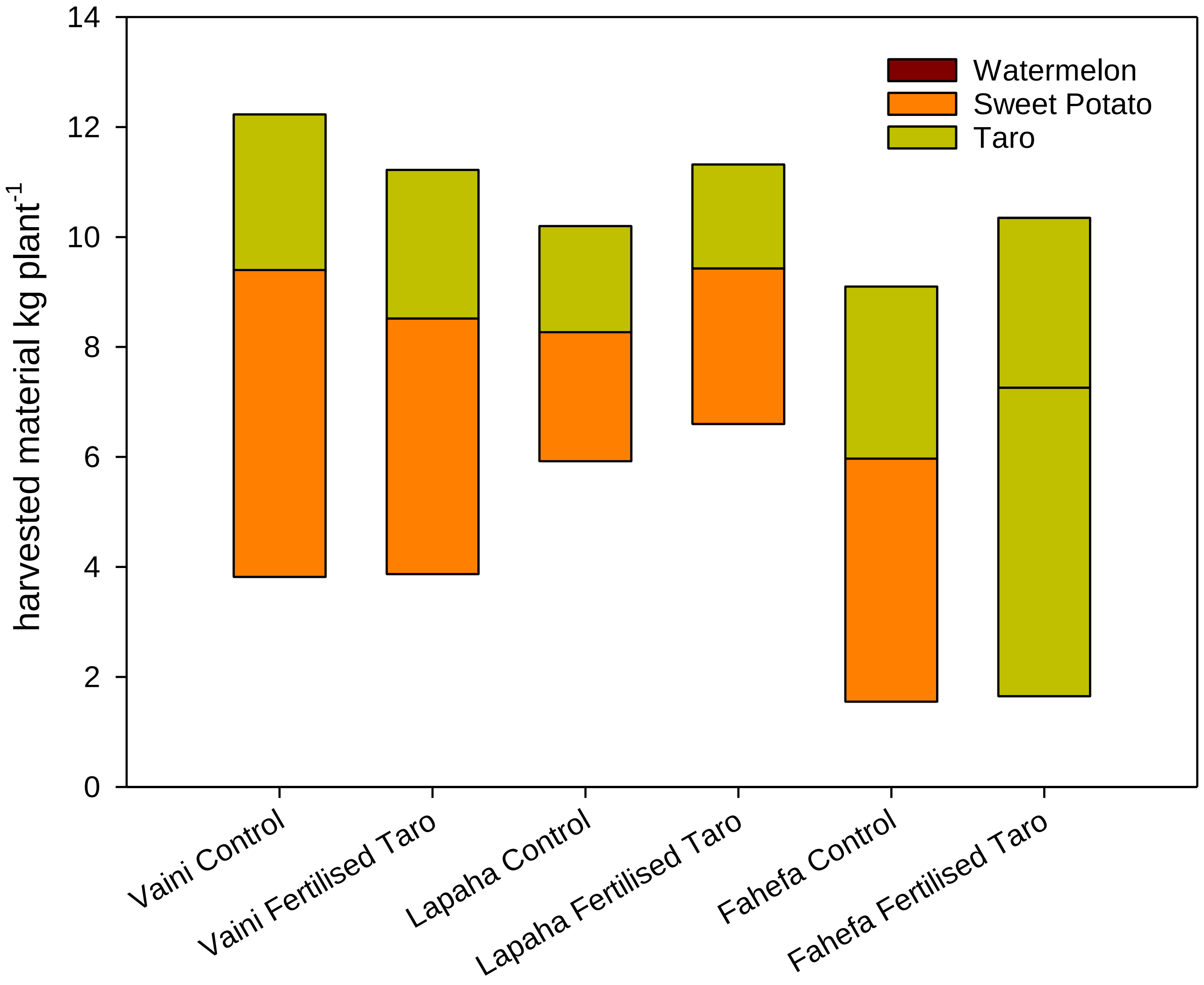

Figure 45 Harvested plant material from the taro, watermelon and sweet potato trials kg plant^{-1}.

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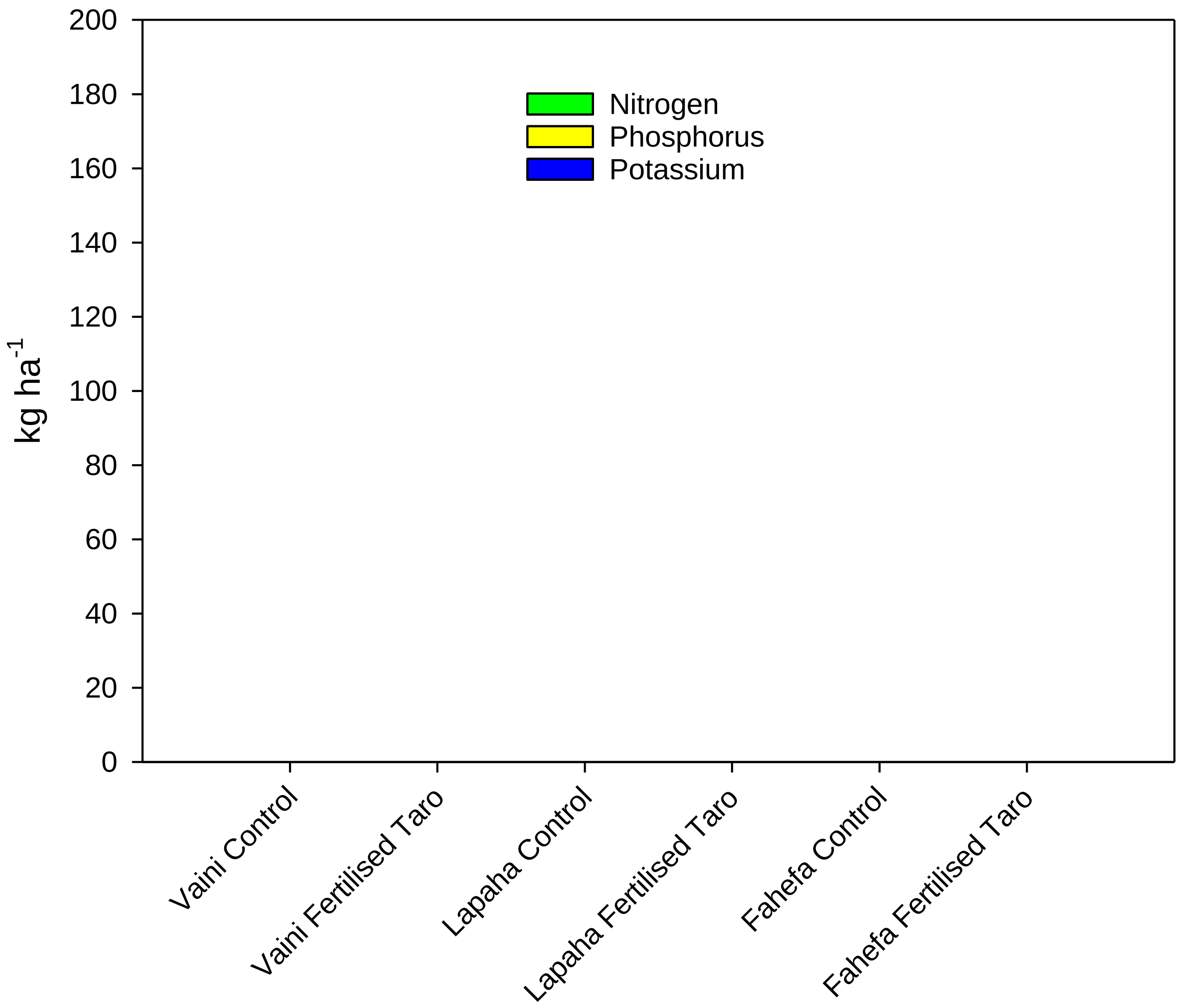

Figure 46. Tonga trial taro corm and sucker NPK removal determined for the relationships in Figures 25-27.

7.3 Objective 3 Testing

7.3.1 Activity 3.1. Review current soil sampling, testing and interpretation protocols used in Pacific Islands.

Addressing soil fertility problems in the Pacific Islands requires effective nutrient management, and therefore needs accurate measurement and interpretation. While this principle is easy to adopt, there are many challenges in developing practical systems of soil sampling, measurement, and diagnosis, especially for complex smallholder systems such as those in the Pacific. Lack of guidelines on soil sampling or outdated soil analysis protocols and the limited knowledge of agricultural research and extension officers to undertake correct soil sampling and analysis need to be assessed and addressed. Under the Soil Management Project, one of the activities was to review the current soil sampling, testing and interpretation protocols currently used in Pacific Island countries.

Soil sampling

The Survey and consultation outcomes showed the three Pacific Islands labs have their own soil sampling protocols which resulted in both similarities and differences in sampling.

- Soil sampled from the surface horizon at 0-15 cm depth when sampling to determine soil fertility for field/root crops.
- Soil is not sampled from the sub-surface horizon (> 30 cm) unless evaluating soil fertility for either tree crops or studying soil profile.
- When sampling soil from a field, the rooting depth of crops for subsequent planting are not considered.
- A commonly used soil sampling tool is the screw auger as a spade and knife are only used occasionally.
- Soil samples are oven-dried followed by sieving with a 2mm sieve. However, they do not have any protocol to discard excess soil being collected.
- Lab staff do not know the maximum size of a uniform land area from which a composite sample can be collected.
- To make up a composite sample, Fiji Agricultural Chemistry Lab collects less than 10 subsamples when sampling, in comparison to SROS and USP labs which use more than 10 subsamples.

- Zigzag and grid sampling methods are used by Fiji Agricultural Chemistry Laboratory to collect subsamples in a uniform area, while SROS and USP labs only use the zigzag method.

- To label soil samples for identification, Fiji Agricultural Chemistry Lab records only the geolocation/GPS readings without inclusion of details such as sampling depth, field history and crop information, village name and the names of farmer or researcher. In comparison, SROS and USP labs record the information which are excluded by Fiji, but they occasionally record the geolocation of soil samples.

Soil testing

The three laboratories analysed their soil samples following the methods of Daly and Wainiqolo (1993), a manual written under a Pacific regional network in the 1990s called South Pacific Agricultural Chemistry Laboratory Network (SPACNET). The USP consultations identified that none of the laboratories followed the soil analysis methods of Rayment and Lyons (2011). Nonetheless, the staff pointed out that procedures in SPACNET manual were simply written but there is interest in using the ASPAC methods of Rayment and Lyons for future soil analysis. However, those procedures can only be adopted if written in simple English that can be easily understood by Pacific Islands lab technicians like the procedures of Daly and Wainiqolo.

Interpretation of results

Staff of Fiji Agricultural Chemistry and USP labs possess knowledge and skills to interpret soil analysis results, however SROS staff lack this knowledge and skills. Consequently, SROS had requested for staff training(s) on interpretation. Currently, interpretation of soil analysis results in Pacific Islands are using interpretation values in the manual by Daly and Wainiqolo (1993)

Gaps

It was pointed out during the consultations that Pacific Island labs have a renewed interest in reviving SPACNET due to its role in addressing the need for quality assurance and soil analysis in the Pacific region. When SPACNET was functional, lab technicians in the region had undergone trainings to build their capacity on simple procedures in documenting standard methodologies for soil and plant analysis and quality control, strengthening soil and plant

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exchange network, and sharing of knowledge and skills among the soil laboratories in Pacific Islands. Services mentioned have been identified as existing gaps in the Pacific Islands laboratories consulted in this review.

Based on the outcomes of the survey and consultations, the following recommendations are made:

1. There is a requirement to develop a soil sampling protocol that can by Pacific Island laboratories to allow the lab technicians, extension workers and farmers to correctly sample, prepare, bag and tag soil samples to achieve uniformity in soil analyses results. Further, this will also address the differences in sampling protocols in Pacific Island countries which causes inconsistency in results.

2. An urgent need exists to simplify the methods such as those of Rayment and Lyons (2011) by writing them in a format and language that Pacific Island Soils Lab technicians and managers can easily comprehend.

3. The Pacific Soil Laboratory Network (ASPAC) was established under the existing Australasian Soil and Plant Analysis Council (ASPAC) in 2019. The inclusion of Pacific Island and Papua New Guinea laboratories in ASPAC ensures the long-term sustainability of the network, granting laboratories local technical assistance and increasing their possibility to improve their performance by participating in extra-GLOSOLAN activities. The project has promoted the Pacific Soil Laboratory Network. None-the-less extension and outreach are needed to inform all sectors of the existence of the body. Further development is needed to improve laboratory performance

i. Enhance the quality of soil and plant analysis of the region's participating laboratories with specific objectives of developing quality assurance programmes.

ii. Document standard methodologies for soil and plant analysis and quality control.

iii. Organise training of technicians of Pacific Soil Laboratories, where and when required.

iv. Strengthen soil and plant exchange network if ASPAC does not cover this area. At present ASPAC is sending soil and plant samples to the Pacific Soil laboratories which are their members with subscription.

v. Develop links with a laboratory in a metropolitan country to support the quality assurance programmes.

vi. Identify laboratories within the Pacific region to serve as centres for the provision of regional analytical services; and

vii. Co-ordinate laboratory upgrades and capacity building with government, aid schemes and NGOs.

7.3.2 Activity 3.2. Utilise MIR to make rapid assessment of calcareous and volcanic soil fertility

Key MIR capacity building activities at FACL MOA

The in-country team at FACL MOA independently set up protocols and workflows of soil sample preparation, MIR soil sample scanning, soil spectral inference and MIR soil property estimation and quality control assessments based on what they learnt during the "MIR spectroscopy" hands-on training and utilizing also the extensive step-by-step training materials, and online troubleshooting and refresher training provided by the CSIRO team (refer to Section 5.1.3 Activity 3.2). Introducing MIR operations at FACL MOA provided the opportunity for FACL MOA staff to gain new skills in soil sample preparation and rapid analysis with MIR. Three FACL MOA staff are now proficient in the preparation and measurement of samples with the Bruker MIR. In addition, Ms Radeshni Singh obtained new skills and responsibilities through taking on the role of leading the MIR soil spectral inference analysis and calibration model building activities at FACL MOA.

Table 12 shows a summary of soil samples analysed through MIR at FACL MOA during the duration of the project (447 in total). In the table it is also shown which samples and datasets were used for building of MIR spectral

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reference libraries and thus for which data sets wet chemistry analysis was also conducted at FACL MOA or for which wet chemistry analysis existed from archive data.

Table 12**. A summary of soil samples analysed with MIR at FACL MOA.**

Location	Soil samples	Wet chemistry	Spectral library	Comments
Fiji – Taveuni	121 samples Topsoil (0-15 cm)	Yes	Regional	FACL MOA archive
Fiji – Taveuni (Mua, Qila, Qarawalu)	6 samples Topsoil (0-15 cm)	No		ACIAR field trial
Fiji – Ovalau (Levuka)	142 samples Topsoil (0-20 cm)	Yes	Regional	Soil health card
Fiji – Viti Levu (Koronivia)	82 samples Topsoil (0-15 cm)	Yes		Soil health card
Fiji – Viti Levu (Sigatoka)	48 samples Topsoil (0-15 cm)	In progress		Soil health card
Tonga	48 samples Mixed topsoil and subsoil	Yes	Local	ACIAR field trial

In the first instance the FACL MOA team prepared and scanned soil samples from the FACL MOA archive that originated from various farms across Taveuni to form the basis for a 'Taveuni' island soil spectral reference library. The calibration models derived were then applied by the FACL MOA team independently to estimate soil chemical properties from MIR soil sample spectra stemming from ACIAR field trials based at Taveuni (Mua, Qila, Qarawalu). The FACL MOA staff also used soil samples from ACIAR field trials in Tongatapu, Tonga, to build a local calibration for these soils. In addition, FACL MOA staff, analysed soil samples collected under the new Soil Health Card program with MIR and wet chemistry methods to expand soil spectral libraries for Fijian islands. For example, the FACL MOA team travelled to Levuka and independently planned out and conducted a soil survey across Ovalau island, collecting 142 soil samples and their geolocation and established an Ovalau island regional calibration.

Using MIR for soil property estimation of PICT calcareous and volcanic soils

In the following, results are presented for volcanic soils only. Obtaining and analysing samples from calcareous soils was impacted by the Covid-19 pandemic and results are not available at present.

Volcanic soils of Fiji and Tonga soil sample locations

Figure 47 shows the overall locations of sampling of Fijian island soils of volcanic origin on Taveuni, Viti Levu and Ovalau, with Figure 48 showing the geo-located sampling locations of the detailed soil survey of Ovalau island, Fiji. The sampling locations of volcanic soils of Tonga, i.e. Tongatapu island are shown in Figure 49Figure **48**. Figure 49 shows the locations of ACIAR field trials at which soils were sampled for the generation of a local calibration (highlighted through blue circles). It also shows sampling locations of a regional survey conducted by MAFFF and a Monash University student (Krawitz 2019) during which historic soil sampling sites across the island with soil legacy information were revisited and re-sampled with their geolocation recorded. Soil samples were sent to Australia and analysed by the CSIRO team through various spectroscopic techniques and subsamples were also analysed for a range of soil properties in the laboratory {Appendix 2`, \Stockmann, 2019 #10203}.

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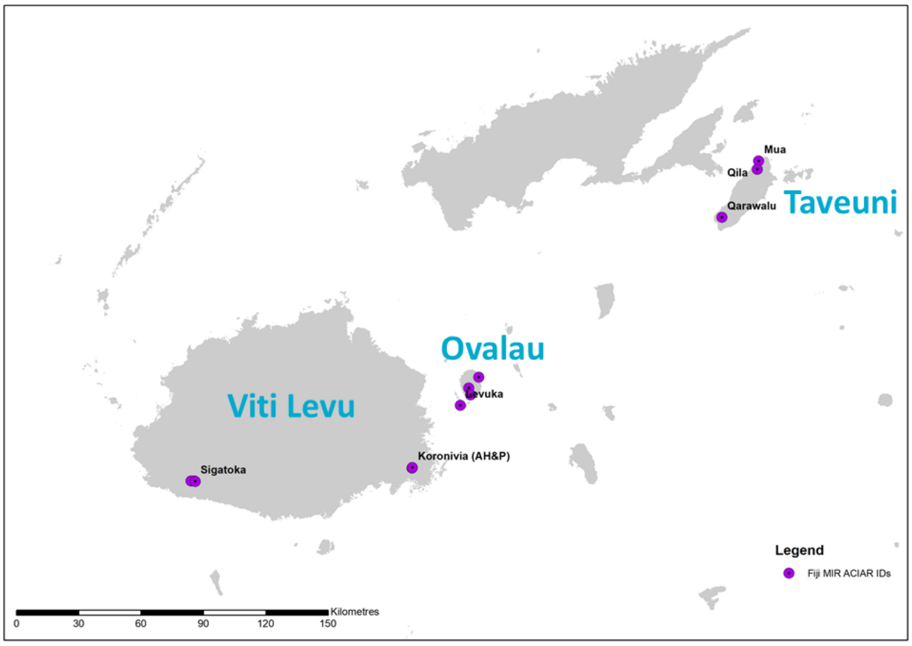

Figure 47**. Fiji islands volcanic soils sampling locations.**

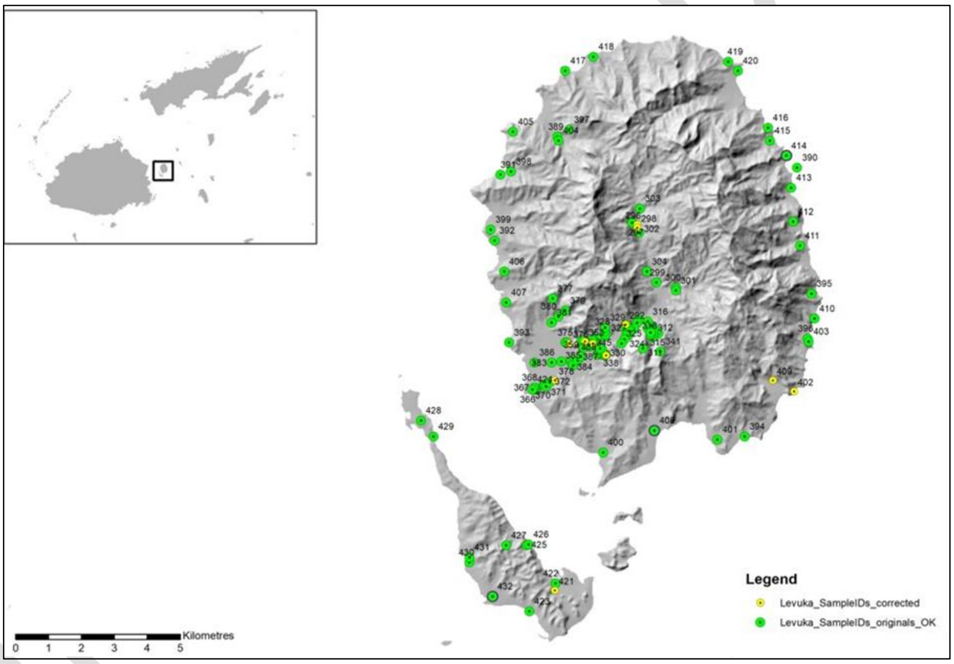

Figure 48**. Sampling locations of the detailed soil survey of Ovalau island, Fiji.**

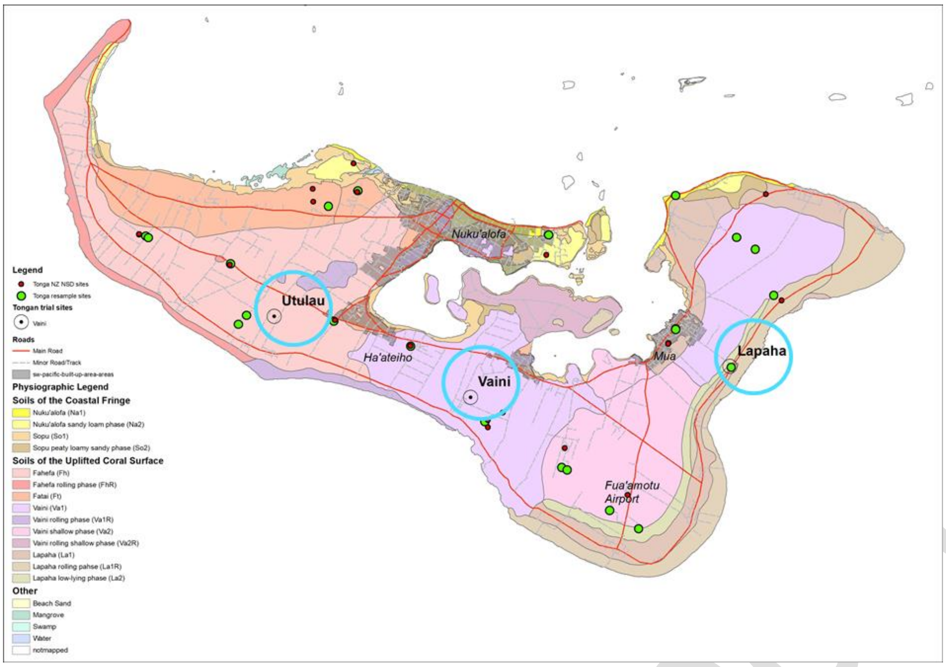

Figure 49**. Locations of ACIAR field trials on Tongatapu island, Tonga (blue circles) in respect to the soils of volcanic origin. Trials locations coincide with the Fahefa (Utulau), Vaini (Vaini) and Lapaha (Lapaha) soils of the uplifted coral surface. Locations of the historic (red dots) and revisited 2018 (green dots) soil sampling locations are also shown.**

Volcanic soils of Fiji and Tonga MIR spectroscopy calibration model results

Soil chemical properties (i.e. soil organic carbon content (%), pH in water, electrical conductivity (dS/m), total nitrogen content (%), exchangeable cations of Ca, Mg, K, Na (me/100g), extractable Fe, Mn, Cu, Zn (mg/kg), and Olsen available P (mg/kg)) were estimated from MIR soil spectra and calibration models (refer to Figure 4), and prediction results were assessed against soil laboratory analytical results (see Table 13 to Table 15 for statistics of measured soil chemical properties using wet chemistry of the regional and local calibration datasets).

Table 13. Statistics of MOA FACL laboratory measured soil chemical properties using wet chemistry methods – Regional calibration Fiji – Taveuni Soil Archive samples.

	N	Mean	Std. dev.	Median	Min	Max
pH H_2O	121	5.8	0.45	5.8	4.6	7
EC (ds/m)	121	0.17	0.11	0.14	0.01	0.46
OC (%)	121	7.27	4.69	6.79	0.1	20.6
TN (%)	121	1.03	1.61	0.77	0.03	11.63
Avail P Olsen (mg/kg)	121	6.29	6.08	4	0.25	35.6
Exch Ca (me/100g)	121	11.46	8.60	10.18	0.29	50.03
Exch Mg (me/100g)	121	4.84	2.66	4.61	0.12	13.26
Exch K (me/100g)	121	0.44	0.41	0.28	0.01	2.25
Exch Na (me/100g)	121	0.28	0.36	0.21	0.01	2.93
Extr Fe (mg/kg)	121	56.45	43.52	42.79	5.24	301.154
Extr Mn (mg/kg)	121	26.35	36.57	10	0.96	189.87
Extr Cu (mg/kg)	121	3.01	2.14	2.35	1	15
Extr Zn (mg/kg)	121	7.48	21.44	3	0.3	227

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Table 14. Statistics of MOA FACL laboratory measured soil chemical properties using wet chemistry methods – Regional calibration Fiji – Soil Health Card program – Ovalau island.

	N	Mean	Std. dev.	Median	Min	Max
pH H_2O	142	5.37	0.81	5.25	4	8
EC (ds/m)	142	0.06	0.07	0.06	0.02	0.8
OC (%)	142	2.35	1.17	2.2	0.5	7.7
TN (%)	142	0.38	0.16	0.35	0.02	0.83
Avail P Olsen (mg/kg)	142	4.11	9.39	2	0.2	87
Exch Ca (me/100g)	142	20.88	15.14	18.6	1.94	115.15
Exch Mg (me/100g)	142	22.94	32.99	9.98	0.01	162.36
Exch K (me/100g)	142	0.83	1.50	0.41	0.01	12.05
Exch Na (me/100g)	142	0.26	0.31	0.19	0.01	2.54
Extr Fe (mg/kg)	142	21.86	11.11	21	5	63
Extr Mn (mg/kg)	142	29.41	22.08	24.5	2	94
Extr Cu (mg/kg)	142	2.82	1.44	3	0.3	11
Extr Zn (mg/kg)	142	2.82	1.44	3	0.1	209

Table 15. Statistics of MOA FACL laboratory measured soil chemical properties using wet chemistry methods – Local calibration Tonga – ACIAR field trials – Tongatapu island.

	N	Mean	Std. dev.	Median	Min	Max
pH H_2O	48	5.83	0.29	5.9	5.10	6.30
EC (ds/m)	48	0.09	0.02	0.08	0.06	0.16
OC (%)	48	1.82	0.99	1.75	0.40	3.80
TN (%)	48	0.19	0.09	0.14	0.09	0.40
Avail P Olsen (mg/kg)	48	9.13	8.64	6.5	0.01	42
Exch Ca (me/100g)	48	23.96	5.13	24.07	14.70	35.61
Exch Mg (me/100g)	48	7.24	1.32	7.35	4.04	10.05
Exch K (me/100g)	48	0.95	0.76	0.76	0.11	3.07
Exch Na (me/100g)	48	1.62	0.96	1.43	0.41	4.57
Extr Fe (mg/kg)	48	58.97	31.41	53	9	126
Extr Mn (mg/kg)	48	68.89	51.66	51	14	232
Extr Cu (mg/kg)	48	6.71	3	6	1	13
Extr Zn (mg/kg)	48	3.9	2	3	1	8

Table 16 to Table 18 show results for the goodness of fit of MIR predictions against analytical results for Taveuni island Fiji (regional calibration), Ovalau island Fiji (regional calibration) and Tongatapu Tonga ACIAR field trials (local calibration).

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Table 16 Goodness of fit – Regional calibration Fiji – Taveuni Soil Archive samples (N = 121), R^2 – R squared coefficient of determination.

Soil property	R2	OK		Soil property	R2	OK
EC	0.79	ü		TN	0.14	û
Organic carbon	0.59	~		Extractable Fe	0.12	û
Exchangeable Mg	0.43	~		Extractable Zn	0.09	û
Extractable Mn	0.33	û		Extractable Cu	0.08	û
pH H2O	0.30	û		Available P (Olsen)	0.03	û
Exchangeable Ca	0.29	û		Exchangeable Na	0.02	û
Exchangeable K	0.18	û				

Table 17 Goodness of fit – Regional calibration Fiji – Soil Health Card program – Ovalau island (N = 142), R^2 – R squared coefficient of determination.

Soil property	R^2	OK		Soil property	R^2	OK
Exchangeable Ca	0.81	ü		Available P (Olsen)	0.08	û
Organic carbon	0.73	ü		EC	0.06	û
pH H_2O	0.73	ü		Extractable Fe	0.05	û
TN	0.40	~		Exchangeable K	0.04	û
Extractable Mn	0.36	û		Extractable Cu	0.04	û
Exchangeable Mg	0.28	û		Extractable Zn	0.03	û
Exchangeable Na	0.16	û				

Table 18. Goodness of fit – Local calibration Tonga – ACIAR field trials – Tongatapu island (N = 48), R^2 – R squared coefficient of determination.

Soil property	R^2	OK		Soil property	R^2	OK
Exchangeable K	0.96	ü		Exchangeable Ca	0.77	ü
Extractable Cu	0.96	ü		Exchangeable Na	0.73	ü
Organic carbon	0.94	ü		pH H_2O	0.73	ü
Exchangeable Mg	0.93	ü		Available P (Olsen)	0.72	ü
Extractable Fe	0.89	ü		TN	0.64	~
Extractable Mn	0.89	ü		EC	0.56	~
Extractable Zn	0.89	ü				

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Goodness of fit results show that MIR spectroscopy can be used successfully to estimate a range of soil chemical properties important for soil fertility assessments for allophanic soils in Fiji and Tonga. Results show, however, that the predictive power of calibration models varies depending on the dataset used for calibration model building. In Table 16 to Table 18 predictions with R^2 between 0.4-0.7 are marked with the ~ symbol and are considered to show promise that analytical data can be related to the spectral features from this calibration dataset, with predictions of $R^2 < 0.4$ marked with a cross (û) and considered unreliable from this calibration dataset.

There is a noticeable difference between the predictive power of the calibration models built in relation to their geographic extent (small farm plots to island wide surveys), and distribution of soil chemical properties of the datasets tested for calibration building (refer to Table 13 to Table 15). Results are consistent with the general rule that local calibrations generally give more accurate estimates than regional or national calibrations. Results are also consistent with that more extreme soil property distributions are more difficult to predict. Soil chemical properties of interest here, related to the amount of individual exchangeable cations (macronutrients) and extractable micronutrients in the soil are generally also harder to predict from spectral data, and thus consistent soil sampling and processing methods, analytical laboratory standards and protocols used are particularly important.

Some datasets considered in this project were not suitable for calibration model building. Continued building of soil spectral reference libraries of representative soil types in the Pacific Islands together with analytical laboratory standards and protocols will improve predictive power of calibration models.

The FACL MOA laboratory joined the Australasian Soil and Plant Analysis Council (ASPAC), the formal body for promoting excellence and standards in soil and plant analysis. The laboratory passed the proficiency test achieving satisfactory performance standards when analysing the required set of blind samples sent by ASPAC through a range of wet chemistry laboratory methods. During the project a set of samples from the ACIAR trials in Tonga and some samples also from Fiji that were analysed through wet chemistry methods at the FACL laboratory were also sent to Australia for analysis at the Chemistry Centre, Department of Environment and Science, Queensland Government. Whilst some properties analysed at both labs such as SOC matched very well, we saw some discrepancies with others, particularly exchangeable and extractable cations. Sample preparation differences may be impacting these results and need to be reviewed in the future.

7.4 Objective 4 The Portal

7.4.1 User needs Results

Initially 12 personas were developed with three primary personas (agricultural extension officers in Fiji, Tonga, and Samoa), and nine secondary personas ranging from a Head of Extension, an Agricultural Research officer, an Agricultural Field Researcher, a Policy Maker, a Scientist, a Fertiliser Salesperson, and a semi-Subsistence Farmer). Five additional personas were recorded during discussions at the project inception meeting, these included a larger commercial farmer and a Donor representative. These personas were developed by small groups of potential users with different backgrounds inventing a hypothetical user based on a known role (e.g., agricultural extension officer). The group develop a user story based on this personas job or role, and then define what their information needs will be and then how these might be serviced by the portal.

As an example, this is the profile for an Agricultural Extension persona:

50 years old

Government employee

Bachelor of Applied Science

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General agriculture expertise: economics, crops, soils, farming, livestock management. Worked up through the ranks over 25 years from Labourer to Principal Agricultural Officer, early mid-career university education

Accesses soils information from reports in library 1-2 times per year – wants something easier, faster, more focussed, and useful for showing less educated users.

Deliver soils data to laptop first, smart phone second

Needs information that will help explain why the differences in soils that are well known occur – what is it about the soil that makes this happen.

Focus on crops suitable for different soils.

Facilitate preparation for meetings and bring printed materials to share

Who were the key stakeholders and what were the key data needs?

From these personas we identified the Agricultural Extension Officer as the key user type, followed by individual farmers.

How were these user needs translated into the Pacific Soils Portal?

To simplify the presentation of mapped soil information we chose to present a generalized crop suitability rating via the web map services rather than trying to represent soil classification which requires a significantly more complex colour legend and a basic understanding of the classification to make visual sense of the colour scheme.

Originally through MapServer on the LRIS website (https://lris.scinfo.org.nz), but later through a specific GeoServer instance established for the Pacific Soils Portal, we used Styled Layer Descriptors (SLD) to generate a crop suitability view of the soil maps for each country. The result was a small number of classes and simplified cartographic symbology targeting the user requirement to focus on crop suitability while still permitting queries and discovery of deeper information about soils.

Why soil profile data?

Demand for the inclusion of soil profile data came through most strongly from the GSP and the soil science stakeholders but we also chose to incorporate this data in the Pacific Soils Portal because it represented a key opportunity to secure this “raw” soils data for the future. Currently much of that data is very hard to access, but it represents an important baseline for soil properties in the region.

7.4.2 Data Discovery, Harmonization and Upload Results

Best available Data

Each of the country portals has best available data displayed on its map interface. The references for those data are recorded in the “Resources” section of each countries sub-portal in the Pacific Soils Portal (e.g., https://samoa-psp.landcareresearch.co.nz/resources/gis-resources/) including geospatial data, soil survey and map references and scientific publication references.

The data for all 5 countries is variable in quality and source (including in terms of funders and practitioners who carried out the mapping).

Fiji, Samoa and Tonga were all originally mapped in the 1960s at small scale (>=1:100,000 scale) by the New Zealand Soil Bureau, but in all cases these early maps were later updated to larger scale more accurate maps in the 1980s and

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1990s. In all cases, again by the New Zealand Soil Bureau, or in the case of Samoa the DSIR Land and Soil Sciences (effectively the same agency but in transition to the Crown Research Institute Manaaki Whenua Landcare Research). Fiji and Samoa were mapped at 1:50,000 scale, but in the case of Tonga with smaller islands and total land mass, the map scale was 1:25,000 scale.

In all three cases, as national soil maps, these represent good quality data, certainly for the time at which they were mapped.

The atoll countries have soils that are very weakly developed on young, porous and highly calcareous sands and gravels, and characterized by high alkalinity, immature profile development, low water retaining capacity and a lack of clay and natural fertility. This along with the much smaller, widely spread, very low relief land masses and lack of commercial agriculture, has resulted in relatively little soil survey.

In the case of Kiribati, very little soil mapping has ever been attempted except the 1:10,000 scale soil map for the 73ha Abatao Islet on Tarawa. Hammond (1969) also created a crude soil map for Christmas island as part of an MSc in Soil Science, but the quality was too poor to digitize.

For Tuvalu all atolls have soil maps prepared as part of the FAO Land Resources Survey which covered all nine atolls in the group at an approximate scale of 1:10,000. However, this project did not employ a specialist pedologist. Soil series definitions were not attempted, and the completeness of soil profile descriptions and nature of soil sampling were inadequate for soil classification by Soil Taxonomy. Morrison (1990) states that:

"The soils of Tuvalu have received limited study as part of a Land Resources Survey (UNDP, personal communication). The soils have been classified according to the FAO/UNESCO (1974) Legend mainly as Calcaric Regosols; data available in some cases is insufficient to fully classify the soils by Soil Taxonomy. Tuvalu soils have udic soil moisture regimes in the absence of groundwater influence, and most are Tropopsamments (Regosols) or Troporthents (Lithosols). Insufficient detail on colour and structure prevents the confirmation of mollic epipedons and hence the presence of Mollisols".

Despite these shortcomings these soil maps and associated profile descriptions and laboratory analyses are the only available data, and therefore included in the Portal as the best available data for Tuvalu.

Digital maps

With the target audience identified as agricultural extension officers and farmers, and with user needs having identified (previous section), we represented soils in terms of general suitability for cropping using only four classes except in the case of Fiji. Since Fiji had a land use capability classification (classes 1 to 8) we used that alternative view|.

Fiji, Samoa and Tonga all had geospatial versions of soils maps available through previous projects and archived a MWLR. For Kiribati and Tuvalu, the paper maps available in reports were digitized into ArcGIS Geodatabase format utilizing the ESRI World Imagery WMTS as a base mapping layer. Each map was scanned, and then the scanned image georeferenced to the coastline in the World Imagery dataset as far as possible accounting for coastal change. Digitizing was carried out heads-up on-screen.

Once in digital form the datasets were uploaded to MWLR's LRIS Portal (https://lris.scinfo.org.nz) which utilizes Mapserver (https://mapserver.org/) and provides functionality to deliver web map tile services (WMTS) to be consumed by suitably configured web portals. These services are all OGC standards compliant, with ISO and Dublin core metadata and Styled to display a generalised crop suitability. The WMTS image service is used in preference to web feature service (WFS) as it delivers a faster response, particularly to users in the bandwidth constrained settings

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typical of the Pacific Islands. The LRIS Portal also has a user login and private groups functionality that allows the Pacific Soil Portal to access the WMTS service but restricts access to only registered users who have been given permission to access the data. Permissions can be easily opened to the public, or some restricted groups, or even individual users as required.

The WMTS services were transferred to a dedicated GeoServer (http://geoserver.org/) instance at Amazon Web Services (AWS) to support independent delivery of Web Map Services. Both the LRIS Portal and AWS are commercial arrangements, but the AWS is deemed much more stable long-term and in addition the most likely longer-term host, SPC, have experience with GeoServer but not with MapServer.

Collating profiles

Collating soil profile locations and associated data is an on-going process. While locations for some 664 profile locations have been identified (Table 19), it is the process of correctly matching these locations to soil laboratory data that is still ongoing. Some of the remaining 200 legacy profiles identified may not be retrievable in terms of matching a good location to good data. But additional legacy data may also still come to light, and new data, particularly now in the form of proximally sensed data will be the next step in adding to a combined dataset of measured soil data.

Most soil reports and publications from which soil profiles are drawn as included in the ancillary documentation attached to the data layers and stored in the LRIS Portal, and for each country listed in the Pacific Soil Portal static content pages (e.g., https://fiji-psp.landcareresearch.co.nz/resources/)

Table 19 Soil Profiles with geolocation per country

Country	Legacy profiles loaded	Legacy profiles to process	Total
Fiji	133	180	313
Kiribati	48	20	68
Samoa	52	0	52
Tonga	69	2	71
Tuvalu	162	0	162
Total	464	200	664

Harmonization and Upload

Due to the small number of total profile locations and the largest group being just over 150 samples (Tuvalu) but more typically 10-25 profiles from any single source harmonization of soil profile data was to a large extent carried out manually, as there was insufficient economy of scale to try to implement a data loading tool that could manage the diversity of laboratory data, and particularly laboratory methods used across all this legacy data.

Because the core data for Tonga as well as some profiles for Fiji and Samoa were already in the New Zealand National Soils Data Repository (NZ NSDR) that is stored in a database schema that is compliant with international standards and with an Application Programming Interface (API) implemented in the NZ Soils Portal (https://viewer-nsdr.landcareresearch.co.nz/) to generate on-the-fly soil profile reports using Frag (https://observablehq.com/).

For data not currently already stored in a suitable database schema, harmonization was achieved through manually entering the data from into a consistent Excel spreadsheet template and utilizing a database schema for laboratory methodology metadata modified the one used for the NZ NSDR.

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So, using the Pacific Soil Portal API (psp-query-service) and front-end code already delivering reports from Pacific Soils Portal for the data held in the NSDR, we wrote processing scripts to copy the harmonized spreadsheet data into SQLite databases with the same database schema. This allowed us to reuse the existing API (psp-query-service) and front-end code without modification to read profile data from the SQLite database and serve it to the web application as GeoJSON.

7.4.3 Portal Technical Design

The Pacific Soils Portal platform uses common Open Source (OS) technologies, frameworks and libraries. There are three fundamental components that are created as independent modules that can be developed independently, and that comply with Open Geospatial Consortium (OGC) standards. This facilitates for an update of one component without necessarily having to update the other two. The three components are shown diagrammatically with the OS software platform dependencies in Figure 50. The backend servers (Web Server and Map Server) use Ubuntu Linux operating system. The web server is installed with the common configuration of an Apache web server, PHP, and a PostgreSQL relational database. The PostgreSQL database is used to store content and configuration relating to the website.

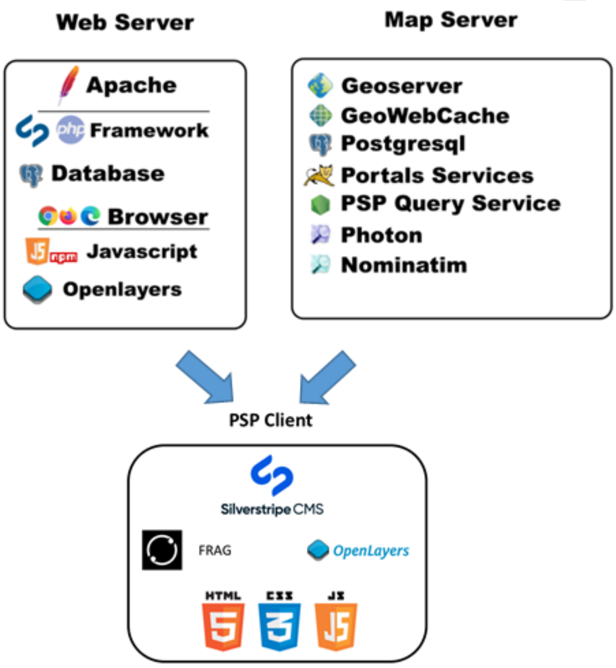

Figure 50 Schematic representation of Pacific Soils Portal architecture

The map server uses a PostgreSQL relational database with the PostGIS extension and is used to store the spatial soil data. This database is connected to by a Geoserver instance which is used to create, store and publish the soil maps. The map layers are configured using the Geoserver web administration page, with the styling set using the open standard Styled Layer Descriptors. Geowebcache is used to pre-generate the map tiles, allowing for faster retrieval / load times by the Pacific Soil Portal map application. Additionally, Geoserver is installed with the Metadata module, which allows creation, storage and publication (via the ISO metadata standard) of metadata for each of the soil layers. All aspects of map layer creation, including associated metadata, is carried out via the Geoserver web administration page. This allows maintainers of the Pacific Soils Portal system easy web-based layer configuration and metadata administration, all from one central place.

The website (Pacific Soils Portal client) is built using the Silverstripe content management system (CMS) which provides a framework for creation of the web site itself and includes a web-based administration panel for creating and maintaining the site content.

The Pacific Soils Portal map page uses the common OS web mapping library, OpenLayers, to provide web mapping functionality. It consumes map tiles served by Geoserver, via the open standard WMTS protocol (e.g. Web Map Tile Service request). The metadata panel is populated via the open standard Catalogue for the Web Service (CSW) protocol.

7.4.4 Portal Infrastructure

An important component of the Pacific Soil Portal Dev-Ops infrastructure (Figure 51) is outlined in this section. Having developed the technical design outlined in the previous section, it is also critical to have a well organised Dev-Ops infrastructure within which to manage ongoing portal development, testing and releases so that users experience minimal impact from unexpected downtime during site maintenance or release of new data or functionality.

This Dev-Ops environment involves instances of the Pacific Soils Portal and Web Services operating both locally and on AWS, so that developers can carry out programming and web site development locally and using local map and web services in a Dev environment until ready to carry out testing and any further iterations of bug fixing and further testing in the development and Test instances.

Once the Portal is ready for launch the Test instance is duplicated but this time in the AWS environment where all dependencies can be tested, and the developers and testers can be assured that the portal is functioning correctly.

The final change over from Stage to Production essentially involves the Stage instance of the Portal in AWS becoming the new Production version with the roll-back option of the old Production version being reinstated should there be any unexpected failure at this late stage.

This is a formal process, following a detailed checklist, for transitioning any new version of the Portal though the Development, Test, Stage and Production stages to ensure that users are not impacted negatively when the new release reaches Production. Releases are timed carefully to ensure there is time to roll-back when key staff are available to implement a retreat, and warning notices on the site inform users of the impending change and outcome.

At this time care also needs to be taken to ensure that Google Analytics and any other logging activities are correctly updated to track usage across these changeovers.

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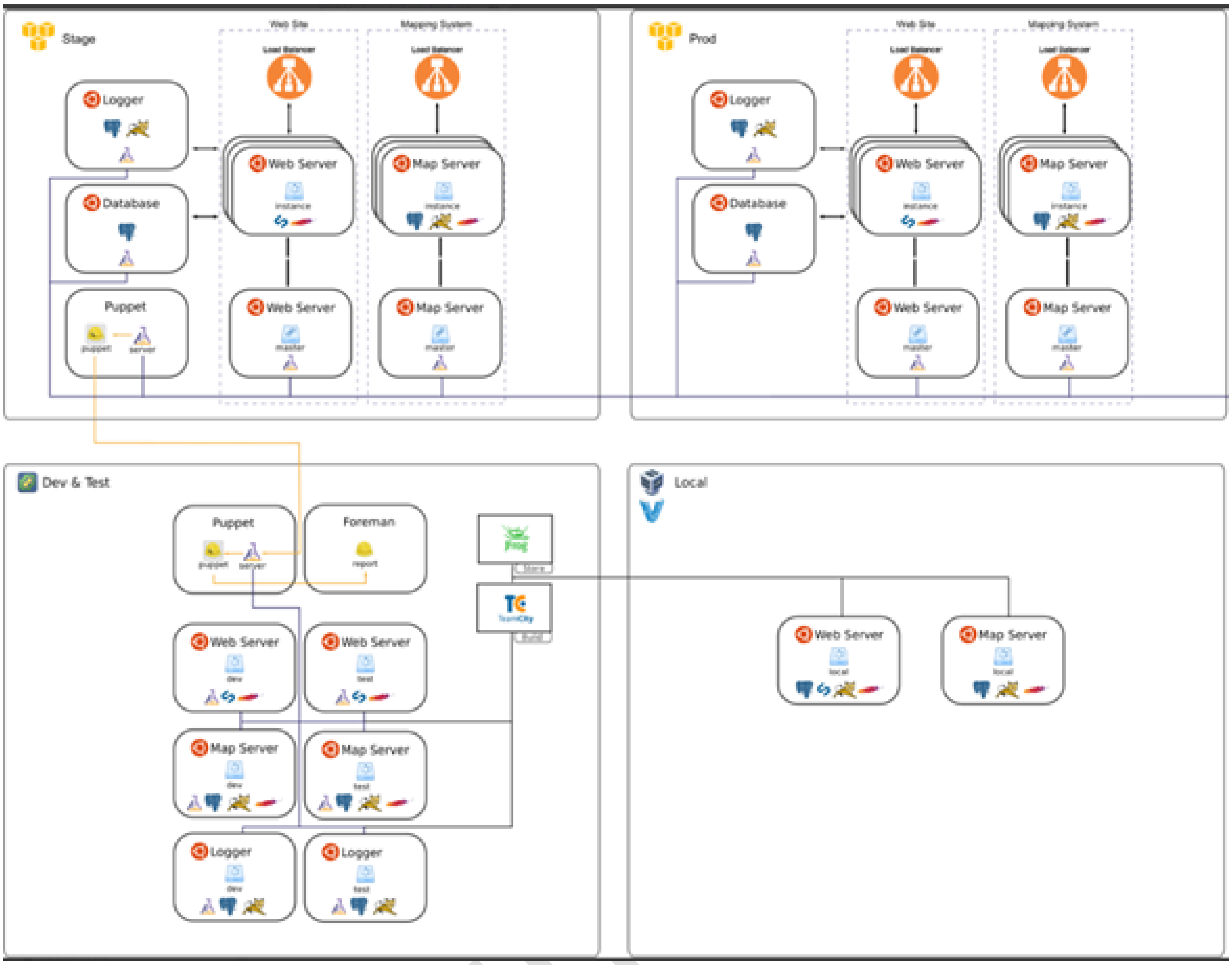

Figure 51. The Pacific Soil Portal Dev-Ops infrastructure

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7.4.5 Analysis of Pacific Soils Portal Usage

The following summary is based primarily upon Google Analytics which provides a wealth of information about how users interact with a website. Note however, that analytics need to be interpreted carefully as they represent a statistical summary of all users, and while they can be filtered to focus on more specific groups of users, these groupings can be crude depending on how well they can be identified, and varying degrees of interpretation is required to draw conclusions from this data.

In 2 years the Pacific Soils Portal has had 1950 users of soils data involved in 4500 sessions making 26,000 pages views and spending an average of almost 7 minutes 45 seconds on the site.

We can unpack these numbers to some degree. Beyond the relatively modest total of 1950 users, we can see that users average 2.35 sessions, so some users do make more than one visit and those users visit on average 6 pages on the web site during each session. Another statistic commonly quoted is "bounce rate" – meaning the number of users who land on a site/page and immediately "bounce" away having not found what they want, or not found something interesting enough to draw them further into the site. The Pacific Soil Portal has a bounce rate of 2.3% meaning more than 97% of users explored beyond the first landing page on the Pacific Soil Portal (most probably the main home page).

In terms of total user numbers, we have no real data regarding engagement with soils data prior to the portal being online but can estimate that users of Pacific soils data from written reports, maps, databases of GIS data for the 5 countries currently in the portal was probably in the order of <300 users per year. This group of educated scientists, tertiary students, consultants and government officials are still likely be accessing soils data from these sources but may also have found the portal. But we can conservatively estimate that 1950 users are about a 4-to-5-fold increase in people engaging with soils data in the region.

Further in terms of user engagement, what is a good bounce rate? And is a low bounce rate a good thing? Generally, bounce rates from 25% to 30% are considered excellent and likely to be as low as you'll see with everything working correctly. Anything under 40% that's not the result of a broken Google Analytics installation is excellent, and indicative of a well-built, professionally designed website that is meeting its users' needs. However, very low bounce rates might be a concern. They might for example reflect a web site design that forces users into more than one interaction before leaving, and this could be the case with the Pacific Soils Portal where users may well land on the Home Page, click on a country button and then, say, on the map button before deciding this site isn't of interest. However, considering the average number of pages visited (6) and the average time on site (8 minutes) this is unlikely to be the case. This evidence points to excellent user engagement.

Google Analytics can analyse use patterns geographically based on IP addresses from which users access the portal. Virtual Private Networks and some security gateway software can confound this information, but it can certainly provide a broad overview of where portal users are based. About 30% of the users who accessed the Pacific Soils Portal in the last 2 years are from Fiji, Tonga, Samoa, Kiribati or Tuvalu. From help desk enquiries we know that some Pacific Island users are accessing the site from New Zealand, Australia and further afield, and there is also steady interest from academics and consultants from other countries.

User registration was not made compulsory to avoid discouraging users from visiting the site. As a result of this relatively few users have chosen to register at this stage. However, we already have examples of Government departments (Ministry of Agriculture and Fisheries, Samoa and Tonga); Industry Groups (e.g., Samoa Federated Farmers) and academics (e.g., from New Zealand and Australia). Unless approached directly via help desk, we cannot know if users accessing the portal from New Zealand, Australia or other international origins are in fact Pacific Islanders studying or working from those countries, or other foreign nationals with an interest in the Pacific.

In terms of technology, overall, 75% of users are accessing the Portal from a computer (desktop or laptop), 22% from a mobile, and only 3% from a tablet (Table 20). As expected, mobile use is greater in Tonga (45%), Fiji (36%) and Samoa (26%). User numbers in Kiribati and Tuvalu are currently too low to evaluate.

Table 20. Portal user numbers and distribution.

	Desktop	Mobile	Tablet	Total	Desktop	Mobile	Tablet
Total	1443	441	55	1934	74.42%	22.74%	2.84%
Fiji	218	119	3	339	64.12%	35.00%	0.88%
Tonga	92	90	3	185	49.73%	48.65%	1.62%
Samoa	61	20	0	81	75.31%	24.69%	-
Kiribati	7	4	1	12	58.33%	33.33%	8.33%
Tuvalu	4	3	0	7	57.14%	42.86%	-
Pacific	246	155	6	624	61.12%	37.76%	1.12%

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Although the 407 users

Although the 624 users from Pacific Islands over this 2-year period may seem modest, we conservatively estimate, like total numbers of users, is likely to represent a 4-to-5-fold increase in access to soils data during this period.

In terms of within site user behaviour, the 4,500 sessions and 26,500 pageviews generate about 62,000 events within the portal. A request might include within page requests like a pan or zoom on a map. And in fact, a minimum of 60% of those events involve accessing or using the mapping interface. Others are events triggered from the map interface like bringing up reports. Perhaps not surprisingly, as the largest land mass and largest population, Fiji, represents nearly 44% of total events and mostly since November 2020.

Only 3% of users are visiting the soil descriptions pages, and other static data resources are being visited even less. While it is good to see that the primary method for disseminating soils data is being well used, it does suggest scope for encouraging more use of ancillary information held elsewhere in the portal.

7.4.6 User testing results

An opportunity for user feedback while demonstrating the new PSP Tonga website to the Tonga MAFFF and agricultural sector representatives ("primary customers") attending an event to “soft launch” the Tongan component of the pacific Soils Portal at the end of November 2019. We ran a user testing session on the Beta website. This involved asking a group of approximately 15 users to follow a 30-minute user-testing session and answer a simple questionnaire that related to the 5-10 simple tasks carried out on the Pacific Soils Portal and evaluating their user experience (UX) using the System Usability Scale (SUS) score (https://uxplanet.org/how-to-measure-product-usability-with-the-system-usability-scale-sus-score-69f3875b858f).

The System Usability Scale (SUS) questionnaire contains 10 statements. Participants were asked to respond on a scale of 1–5 according to how they agreed with each statement regarding their user experience. A score of 1 means strongly disagree while 5 means strongly agree with the statement. A total score is then calculated.

Table 21 Results of system usability testing.

	Statement	Average Ratings	SUS Score
1	I think that I would like to use this website often	4.6	3.6
2	I found the website unnecessarily complex	1.8	3.2
3	I thought the website was easy to use	4.2	3.2
4	I think that I would need the support of a technical person to be able to use this website	2.8	2.2
5	I found the various functions in this website were well integrated	4.1	3.1
6	I thought there was too much inconsistency in this website	2.05	2.95
7	I would imagine that most people would learn to use this website very quickly	4.05	3.05
8	I found the website very awkward to use	2.05	2.95
9	I felt very confident using the website	4.3	3.3
10	I needed to learn a lot of things before I could get going with this website	2.75	2.25
Total			74.5

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The Pacific Soil Portal beta site score of 74.5 represents GOOD (grade B) usability. Given the relatively complex information being presented and use of a map interface, the use of smart phones as well as laptops during the evaluation, and the diversity of age and experience amongst the Tongan testers, this is a satisfactory outcome. Some minor improvements were made to the portal prior to full release to respond to specific feedback received during this evaluation.

Table 22: SUS score classification.

SUS score	Grade	Rating
> 80.3	A	Excellent
68-80.3	B	Good
68	C	Okay
51-68	D	Poor
<51	E	Awful

7.4.7 Governance

A Governance group was established during the HOAFs meeting in Samoa in October 2019. This group was made up of a country representative, usually the Head or Secretary of Agriculture in each country, or a suitable high-ranking alternative. Membership of the Governance Group is necessarily fluid as changes are made in who holds these positions from time to time. ACIAR, CSIRO, SPC and MWLR all have non-voting observer status in this group, as do the project leads in each country.

The Governance group were given some preliminary briefing notes, prepared by MWLR, regarding:

- Terms of reference for the group
- Data sharing agreements/protocols
- Hosting options

The meeting requested that MWLR work these up into final drafts for consideration at the next meeting of the governance group.

This group was unable to meet again due to the Covid pandemic. Once it became apparent that the pandemic would preclude any in-person meetings the group were consulted vias email and agreed to conduct business via briefing documents, email exchange and on-line voting to make any important decisions. Following this process the draft Terms of Reference and Data Sharing Agreement were ratified and the Hosting Options document tabled. The governance group directed MWLR and SPC to establish how best to proceed with a hosting transfer and this process is now underway. Due to the capability required, it seems likely this will be a stepwise transition, and may leave highly technical web development functions in the hands of MWLR.

7.4.8 Maps

Fiji soil portal within the Pacific Soils Portal incorporates mapped soil data for four of the main islands in the Fiji Group (Viti Levu, Vanua Levu, Taveuni and Rotuma; Figure 52). In addition soil data for some 87 soil profiles from Fiji has so far been collated and included in the portal. There are 313 known profile locations, and work continues discover and load this additional profile data.

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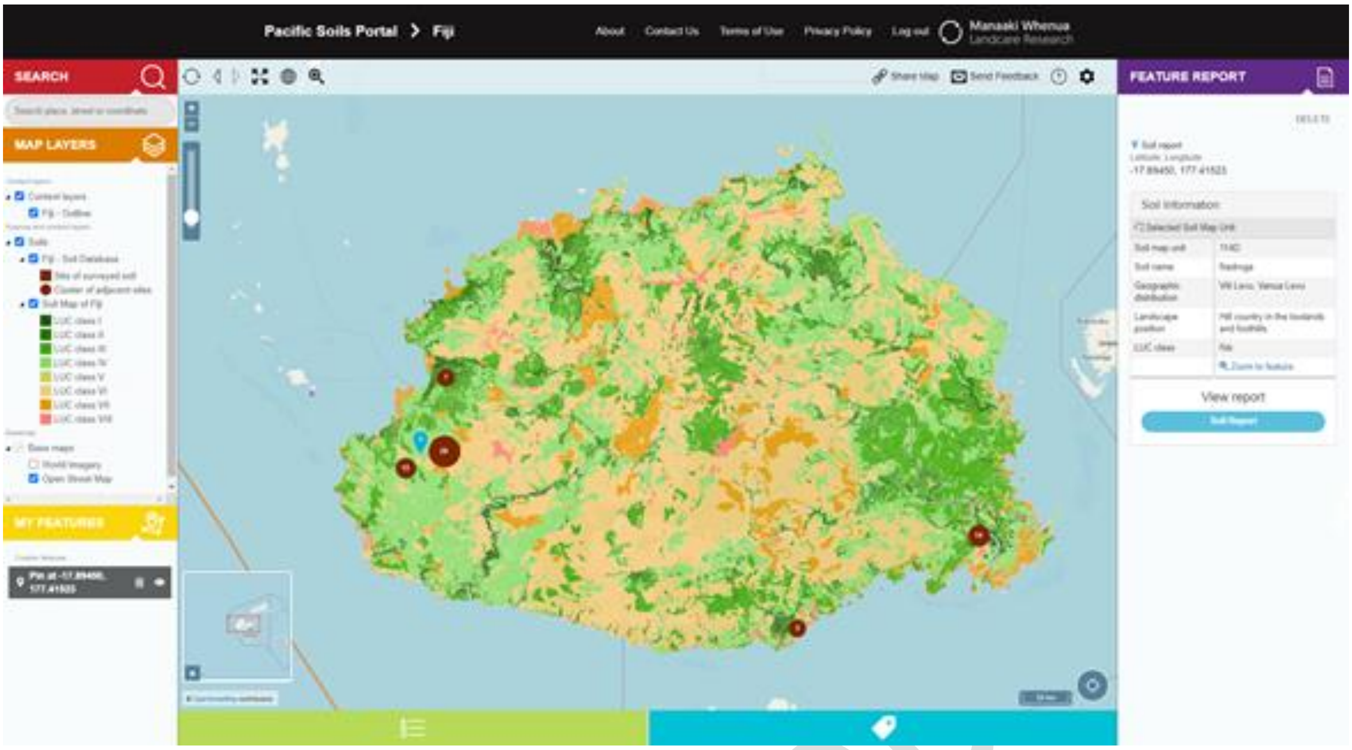

Figure 52. Screen shot of the Viti Levu, Fiji soil information https://fiji-psp.landcareresearch.co.nz/maps/

The Tongan soil portal within the Pacific Soils Portal incorporates soil map data for all of the main islands in the Tongan Group (Tongatapu, 'Eua, the Ha'apai group, Va'va'u, Niuatopotapu and Niuafo'ou). In addition soil data for some 69 soil profiles from the Tongan soil survey carried about by DSIR New Zealand Soil Bureau have been imported from the New Zealand Soil Data Repository and included in the portal.

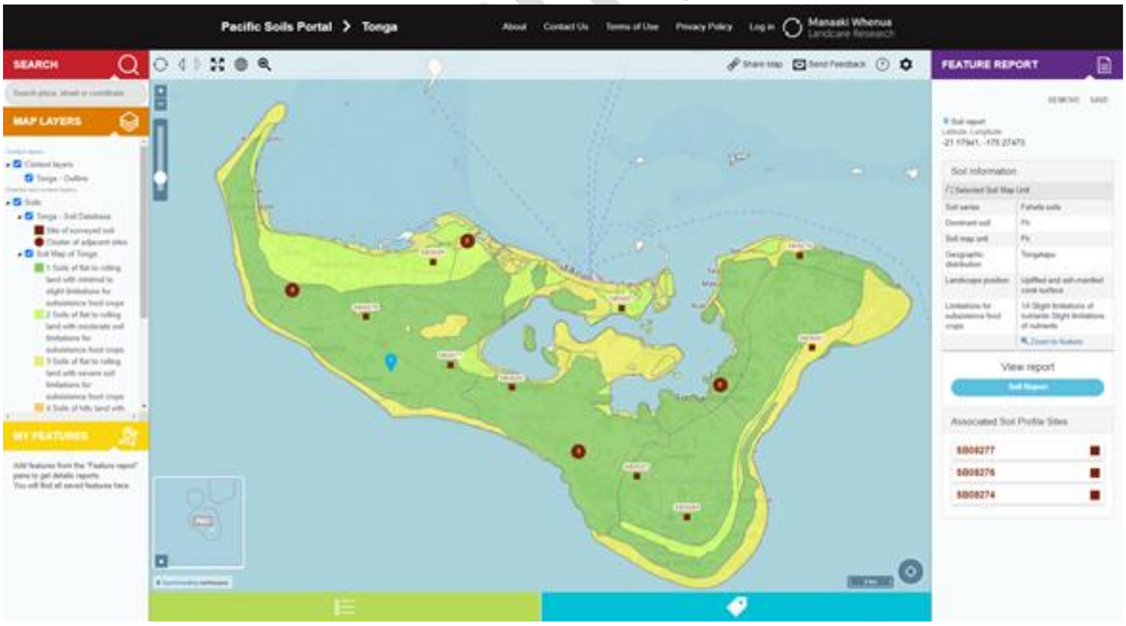

Figure 53. Screen shot of the Tongatapu, Kingdom of Tonga, soil information https://tonga-psp.landcareresearch.co.nz/maps/

The Samoan soil portal within the Pacific Soils Portal incorporates soil map data for both main islands (Upolu and Savai'i). In addition, limited soil sample data for some 39 soil profiles from the original 1963 survey soil survey carried about by DSIR New Zealand Soil Bureau and 9 profiles from Lanoanoa Farm have been included in the portal. Profiles from a Soil Taxonomy training course will be added at the next data release.

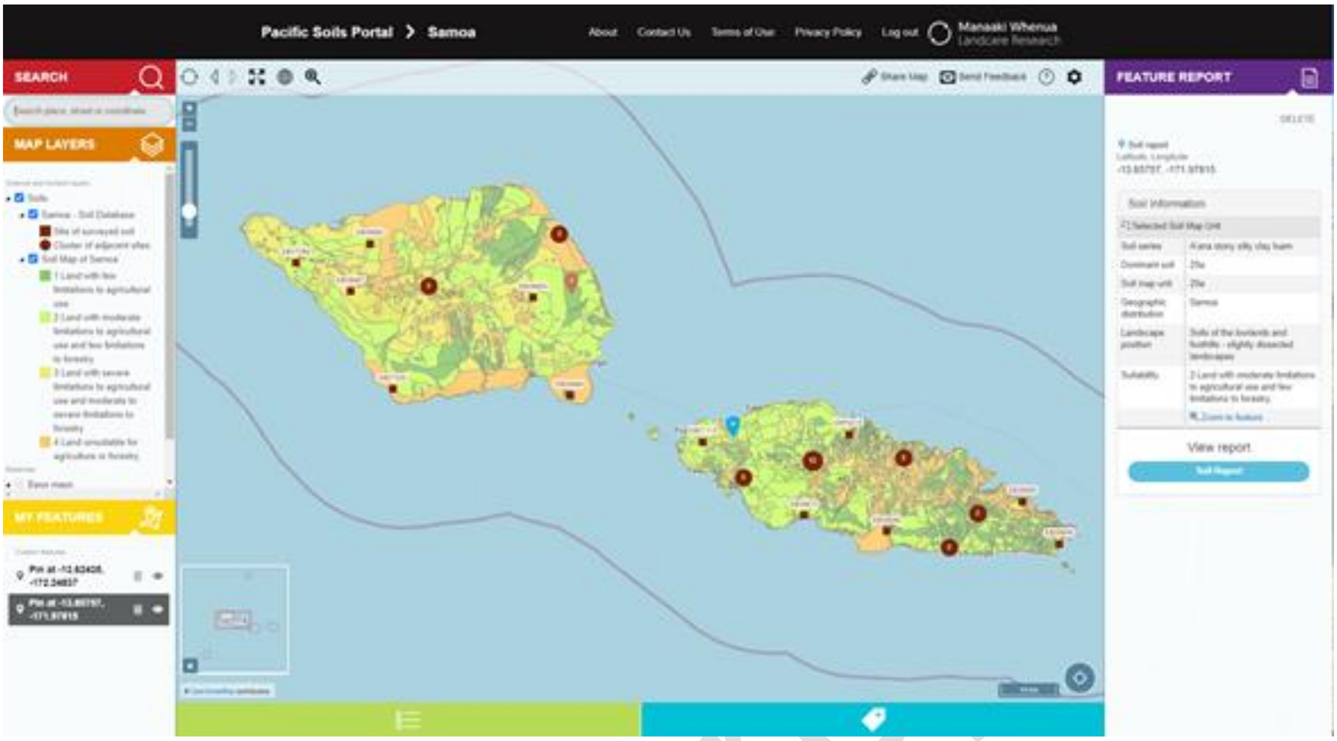

Figure 54. Screen shot of the Samoan soil information https://samoa-psp.landcareresearch.co.nz/maps/

There is very little soil mapping for Kiribati, only one small motu on the main atoll of Tarawa (Abatao islet) has had a soil map prepared to evaluate Kiribati soils (Figure 55). This limited area has been included in the Kiribati soil portal component of the Pacific Soils Portal. In addition limited soil sample and profile description data for some 48 soil profiles or sample locations from multiple sources (mostly published scientific papers) have been included in the portal.

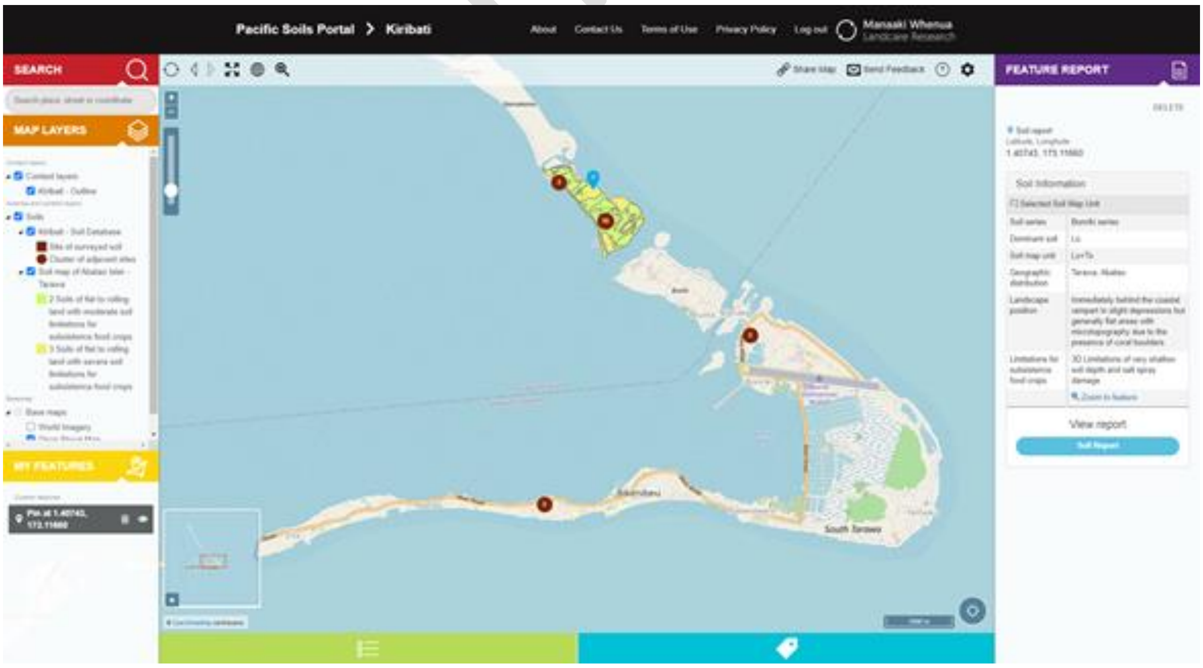

Figure 55. Screen shot of the Kiribati soil information https://kiribati-psp.landcareresearch.co.nz/maps/

Tuvalu has poorer quality soils data (Figure 56. The FAO Land Resource Study prepared soil maps for the whole group and collected soil samples at 162 sites on all the atolls except Funafuti. However, it is important to note that this soil mapping and soil data was not carried out by a specialist soil scientist/pedologist.

Tuvalu soil maps from these reports have been georeferenced to contemporary coastlines and included in the Tuvalu soil portal component of the Pacific Soils Portal. In addition the limited soil sample and profile description data for some 162 soil profiles or sample locations have been included in the portal. These soil descriptions are insufficient for classifying soils in Tuvalu, and the field samples are not all well documented (depths vary in relation to horizons and are not always recorded) and were not processed at an established soil laboratory. As the only data available for Tuvalu this soils data is included, but their data quality and therefore fitness-for-purpose should be carefully evaluated before use.

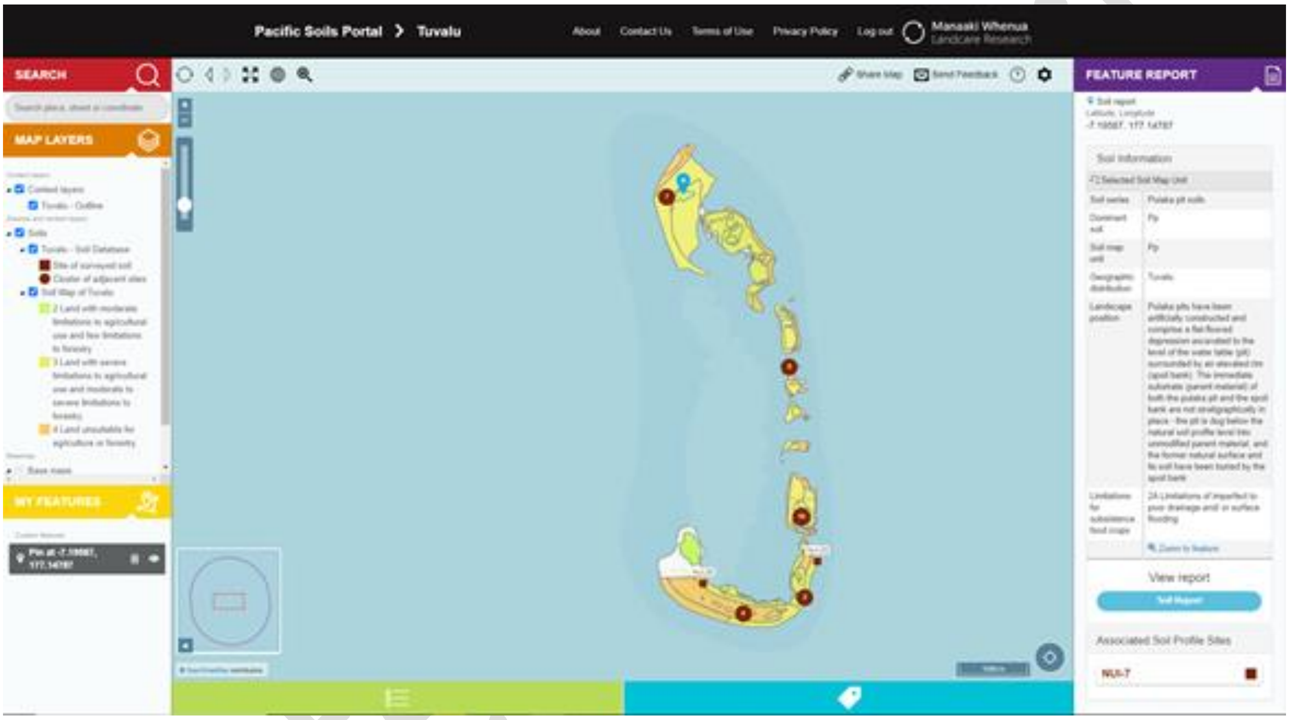

Figure 56. Screen shot of the Tuvalu soil information https://tuvalu-psp.landcareresearch.co.nz/maps/

8 Impacts

8.1 Scientific impacts – now and in 5 years

- Soil portal has enabled the rediscovery of the different spatially scales soil information for the Pacific Islands. This information has been used to guide field sampling and to quantify the change in soil carbon stocks in Tongatapu, Kingdom of Tonga. It is now possible to repeat this exercise in Fiji and Samoa.
- The project has helped improve the Fiji soil health card design and delivery. This monitoring and evaluation program will be used to determine the state and trend of soil resource base, and in five years time will enable valuable scientific analysis to the effect management interventions on soil health
- The use of proximal sensing NIR, MIR and pXRF has been shown to the rapidly predict of soil properties and field portal spectrometers have worked effectively. These tools will be able to greatly improve the monitoring and evaluation of soil state and trend and enable the provision of timing advice to land managers.

8.2 Capacity impacts – now and in 5 years

8.2.1 Project Management

Project staff were empowered to design, manage, and deliver on-ground activities, as well as project management and reporting. This will strength future work programs and enable project staff to develop and design research activities.

8.2.2 Farming Extension

The capacity of research and extension services to understand soil health concepts and practices, as well as their ability to use participatory methods to communicate these messages to farmers has been strengthened in Tonga, Fiji, Samoa, Kiribati, and Tuvalu. Indeed, the strategy of performing on-farm trials has improved the ability of government and community services to connect with the farming community. The repeated visits to the farming sites have enabled serendipity extension activity through regular discussions with the land holder. The follow-on effect from the embedding the research into the community was not quantified. Workshops and dissemination of soil knowledge at workshops has built understanding of relevant nutrient management, an awareness of the soil portal and monitoring and evaluation. For example, a training participant in Tonga reported that sometimes they got confused between the symptoms of plant disease and soil nutrient deficiencies, but the training helped to develop their skills to the point they can now tell the differences between nutrient deficiencies in soil and plant diseases". Just over 775 people participated in the project's training programs across the 5 countries. Over 70% of these participants were reported to be farmers and youth.

In addition to this, a first draft of a Dr Soils train-the-trainer program has been developed. This concept of this program builds on the Dr Plant train-the-trainer program that has been successfully implemented across the Pacific. The Dr Plant program has identified a need for soil and plant health information to be combined for farmers, as several plant pest and disease issues are soil related. This was also recognised in the projects training program. In response to the needs of participants, the topics covered in the trainings supported by the project ranged from soil testing to crop health and pests and diseases. Discussions are currently underway to merge the two programs to create a community of experts for both plant and soil health that can both train farmer and help problem solving issues and challenges with them.

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8.2.3 Field Survey and Nutrient Management

The project trained in-country staff in various methods of collecting soil and plant sampling, data management and interpretation and the development of farming system fertilizer recommendation. The team now uses GPS, either Garmin or a phone application, to record sample location to enable trend analysis of areas. This has been an important development because previously only cadastral or village location was recorded which prevent site revisit and development of soil database. The recently launched Fiji soil health card (Figure 57) is evidence the importance of recording sample position and the nutrient management advice is a combination or either synthetic or organic fertilisers. The formulation is based on literature understanding and project experience.

The soil health card initiative is a government initiative through the Ministry of Agriculture to provide every registered farmer a soil health card detailing the nutrient and fertility status of their soil and other relevant information relating to fertilizer recommendation and long-term soil health and management. This scheme is intended to facilitate farmers for better understanding of soil and Integrated Nutrient Management (INM) through to provision of information regarding the status of his/her soil as well as providing advice on fertilizer usage and other nutrient recommendations that maintain soil health in the long run. It is well known fact that soil is the basis for agriculture and protecting the soil is the basic responsibility of every farmer to sustain agriculture. Unfortunately, the quality and yields of agriculture produce is not at expected level due to deficiency of various nutrients. At the same time, there is excessive usage of certain nutrients. All this is happening as farmer is not fully aware of various physical, chemical, and microbial activities in soil and due to this, farmers are unable to apply fertilizers in balanced and required quantities.

The SHC is intended to provide each farmer with information regarding the status of his/her soil as well as providing advice on fertilizer usage and other nutrient recommendations that maintain soil health in the long run and provide nutrient recommendations to farmers based on local soil health tests, with expectation that it will promote balanced nutrient management practice to help improve productivity. This ACIAR project has enabled the collection of 127 Levuka, which were analysed in the laboratory, fertility reports were prepared with fertiliser recommendations which was then used to provide guidance to farmers. In the soil health card initiative a total of 272 cards were prepared, out of which 83 soil health cards had been distributed to Levuka, and 6 to Beqa farmers.

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SOIL HEALTH CARD

Soil Health Card Number: ____________________

Name of Farmer: ____________________

Validity from: __________ To __________

Fertilizer Recommendation		
Si No	Parameter	Recommendation
1	Urea (Kg/ha)	
2	Ammonium Sulphate (Kg/ha)	
3	Triple Superphosphate (Kg/ha)	
4	Sulphate of Potash	
5	NPK (13:13:21)	
6	Copper sulphate	
7	Zinc Sulphate	
8	Ferrous Sulphate	
General Recommendation		
1	Organic Manure (t/ha)	
2	Biofertiliser (L/ha)	
3	Lime / Gypsum (tons/ha)	

SOIL HEALTH CARD			
Farmer's Details			
Name			
Address			
Village			
District/Province			
Farm Size (ha)			
Phone contact			
Email Contact			
MoA Officers			
Soil Sample Details			
Soil Job Number			
Laboratory ID			
Date of Collection			
Soil Depth (cm)			
GPS Position	Latitude:	Longitude	

Name of Laboratory				
SOIL TEST RESULTS				
S No.	Parameter	Test Value	Unit	Rating
1	pH			
2	EC			
3	Organic Carbon			
4	Available Nitrogen			
5	Available Phosphorous			
6	Available Potassium			
7	Available Sulphur			
8	Available Zinc			
9	Available Boron			
10	Available Iron			
11	Available Manganese			
12	Available Copper			

Fertilizer Recommendations for Reference Yield (with Organic Manure)						
SI No.	Crop & Yield	Reference Yield	Fertilizer Combination - 1 for N P K		Fertilizer Combination—2 for N P K	
1						
2						
3						
4						
5						
6						

Figure 57. The Fijian Ministry of Agriculture soil health card

A similar SHC initiative is being proposed for Tonga. Project and associated staff were trained in the importance of undertaking rapid soil testing and diagnosis of the soil constraint while in the field.

8.2.4 MIR spectroscopy – Rapid soil testing

The project established laboratory-based MIR spectroscopy analytical capability at the Fiji Agricultural Chemistry Laboratory, Ministry of Agriculture, based at Koronivia research station. Three FACL MOA laboratory staff have been trained and can prepare soil samples for MIR analysis and are able to independently operate the Bruker Alpha-II-FT-IR (MIR) instrument. One laboratory staff member, Ms Radeshni Singh has also become proficient and took on a leading role conducting the MIR soil spectral inference analysis using the Bruker OPUS software. Further training is required in the data analytics and quality assurance and quality control. The FACL MOA team has utilized the MIR outside the project and have independently included the National Soil Health Card program soil samples to build spectral reference libraries for regional soils in Fiji. MIR spectroscopy has the prospect to help develop rapid and robust laboratory-based soil analysis at FACL MOA, which will complement existing wet chemistry methods and reduce analysis costs and time.

8.2.5 Next generation researchers

The project has enabled Dr Ellen Iramu, who recently join SPC, to rapidly develop networks across the Pacific Island Countries and Territories. This includes work closely all project partners to deliver project activities, a clear understanding of the Pacific Soil portal and nutrient management issues and soil knowledge barriers to sustainable production. The project has developed linkages to Dr Kader, USP and enable him to join project and Pacific Soil Partnership meetings, undertake reviewer on soils testing and to deliver a Dr Soil program in Apia, Samoa. This helped

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Dr Kader, who joined USP after the start of the project, develop a network across the Pacific Island Countries and Territories. This ACIAR project has also enabled Dr Uta Stockmann and Dr Dio Antille to gain experience in undertaking research for development work; to develop networks in the Pacific Island Countries and Territories and New Zealand and gain an understanding of the potential impact pathways in soil and land management and associated research needs in the Pacific Islands. The project enabled Mr Shaun Krawitz (Monash University) to undertake his honours thesis research on Tonga soil carbon status (Appendix 1) and Ms Mikayla Hyland-Wood to undertake a special topic on nutrient cycling and budgeting (Appendix 1).

8.2.6 Irrigation management

The project introduced chameleon and wetting front detectors to in-country partners to monitor soil water status. Kiribati has successfully utilized the detectors to monitor solute flux and water use.

8.3 Community impacts – now and in 5 years

The project has created scientific, capacity and community impacts benefiting NGO, Faith Based organizations, individual growers and government agencies and services. During the inception till conclusion of this project, the project delivers information that meets the needs of landholders and to improve livelihoods of communities through more sustainable and secure food production.

8.3.1 Economic impacts

The development of soil management systems to overcome soil constraints is expected to improve livelihoods of smallholders as better knowledge is developed on how to manage the soil constraints to increase agricultural production without eroding the natural resource base. The current and on-going extension about managing soil health and improving soil carbon should improve the productivity in the longer-term. However, the recent announced ban on paraquat in Fiji and discussions in other countries will result in a rethink on tillage to enable the management of weeds. Further follow up work will be needed to ensure that soil health is maintain as farm management is altered.

The development of the soil portal and associated data infrastructure removes a significant barrier and enables streamlined access to soil information. This information underpins the development of new business opportunities and reassess of land capability mapping and associated policy development. Further the development of rapid soil testing MIR to quantify soil organic C will enable the development of new revenue streams for Pacific Island communities through participation in voluntary soil carbon markets.

8.3.2 Social impacts

A major focus of the project is centred on pilot sites and their farming communities and a capacity building and communication strategy has been formulated to achieve wider impact and adoption. The project has sought to create social impact through several interventions centred at different scales.

- Local: On-farm trials and surveying. The project has used on farm trials and soil surveying to directly connect on-ground land managers with the importance of gaining and applying soil knowledge for sustainable agriculture. The close participation and active engagements of our key stakeholder clearly demonstrate that they are keen to learn and adopt the new technologies or ideas to improve on their current practices, thus gradually making significant impact on production, livelihood, and environment.
- Regional: Workshops. The project has organized workshops that have included government, commercial and non-government extensions agents, growers, research and development

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practitioners, students and any other interested party using soil knowledge for sustainable agriculture.
- Country Scale: The project has partnered with the relevant ministries in each country, and actively engaged with HOAFs and via PIRAS. The aim is to develop policies that enable the development of sustainable agricultural policy and develop which in turn achieves social impact
- International Scale: The project has enabled team members to discuss their findings to others via international workshops (e.g., FAO) and Global Soil Partnership.

The goal of these intervention is to enable improved food security through the management of the soil resource base and resilience to the farming system to future challenges. 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.

8.3.3 Environmental impacts

Nutrients. Improving our understanding of island nutrient budgets will enable targeted management to improve soil health and long-term sustainable production systems. The project has endeavoured to improve the capability of growers and extension agents to management farming system nutrient management and to quantify nutrient leaching and water use in atoll systems.

Soil organic carbon: The project has revealed that soil organic carbon has declined in Pacific Island soils which has strong correlation to farming system yield decline, especially in low input systems. These results have begun discussions among the project partners, and the policy committee about the next steps in agricultural practice and research.

Monitoring and Evaluation of soil state and function: The research team in Fiji, Tonga and Samoa understand the importance of sample geolocation and recording of data into digital infrastructure to enable quantification of soil state and function. This is key to utilising monitoring and evaluation to direct soil management and policy and achieve sustainable agricultural production.

Fertiliser Policy: Tonga and Fiji. The soil analysis and interpretation data and expertise build in the Chemistry Laboratory of Fiji's Ministry of Agriculture (MoA) has influenced Fiji's national fertiliser policy. Specifically, the Government's policy was changed to respond to soil deficiencies identified. In Tonga the multi-stakeholder national workshops enabled by the project on Sustainable Soil Management resulted in agreement to develop a policy brief and/or voluntary guidelines around fertiliser use. The outcome built on the changes in awareness and knowledge reported by farmers about the importance of managing their soil health in line with specific nutrient deficiencies, including the potential use of single nutrient fertilisers. Something the private sector led farmer network will experiment with going forward.

8.4 Communication and dissemination activities

In December 2019, COVID-19 CSIRO travel restrictions and more broadly implemented travel restrict commenced in March 2020 affect the projects' ability to travel and implement project activities in person for between for the last 2 years of the project. While the project team was able to switch to online communication to continue the project there still was a significant impact on person-to-person communication and dissemination. It is critically important

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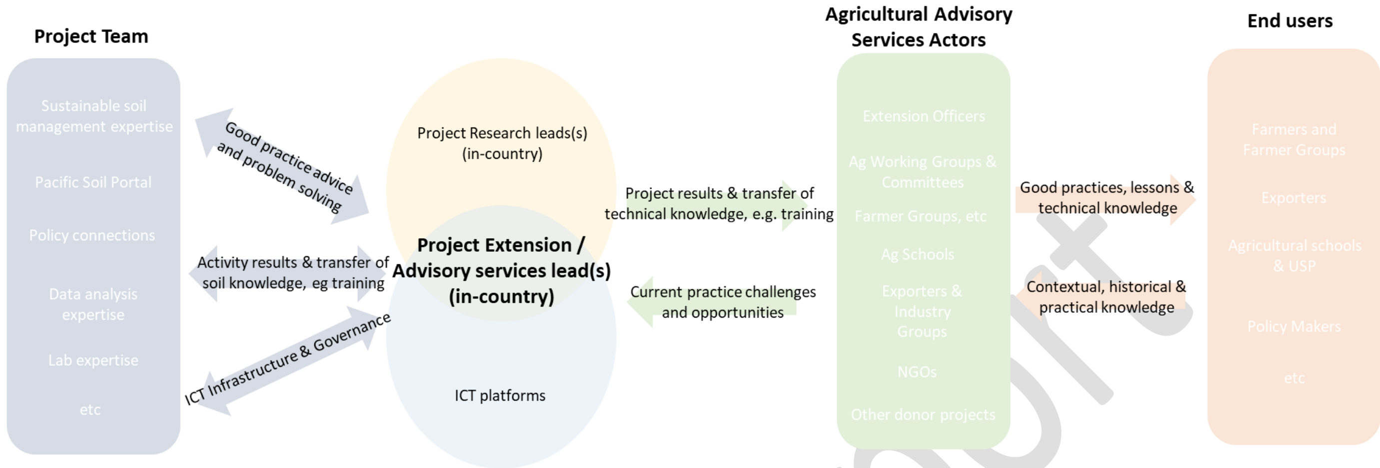
for all parties to get to the field and discuss results, problems and issues and observe. Since the March 2021 Fiji has been in lockdown and planned communication and dissemination activities have been postponed.

Figure 1. Proposed conceptual knowledge sharing framework for Pacific Soil project



This framework attempts to recognises that many ICT platforms are efficient ways of broadcasting information, but for effective knowledge sharing and extension services it needs to be more than broadcasting information. Effective communication also requires interpretation, analysis and listening. There is no one ideal communication method. To overcome these barriers the project team from objective 1 & 3 worked with the identified project extension/advisory services to build and or strengthen relationships with key advisory services actors and end user groups to act as a broker of knowledge to and from the project.

On-farm trials continued in Tonga and Fiji throughout the project . This was a key pathway to train local growers and extension officers. Many of the farmers are relying on synthetic agro-inputs for crop production. Farmers are applying fertilizers without any know- ledge of soil nutrient availability and follow historic recommendations for individual crops. This behaviour is slowly changing as farmers are closing adhering to advice from the Ministry in Fiji, but also other sources. The project team had many informal sessions, in Fiji these sessions are called *talanoa,* with the growers and discussed real-time soil data, nutrient management and avenues to increase the scale of production. In Fiji, famers are slowly blending composts to current fertilizer regime and keeping the leaves and petioles in the field.

Since this project is participatory based farmers engaged in the projects were trained on soil sampling, interpretation and fertilizer calculations. Farmers were also demonstrated on the procedures for carrying out soil sampling, and on the installation of field equipment such as the Chameleon, full stops, nitrate tests conducted on field. During the trial phase, farmers and extension staffs were trained on soil and plant sampling techniques.

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Figure 58 Setting up the field experiments with Taveuni farmers.

Figure 59 Ms Anteera Ititaake testing for soil iron during "Youth in agriculture workshop", Kiribati.

Figure 60 Dr Mike Webb (CSIRO) with the "Youth in agriculture workshop" participants, Kiribati

Figure 61 MELAD Workshop session on soil and plant sampling, Kiribati

Figure 62. Iron deficiency identified during Tuvalu field school in sweet potato in compost treatment

Figure 63. Nutritional value of compost identified and discussed during Tuvalu field school

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Regional

Location	Date	Audience	Topic
HOAFs-Online	October 2021,	21 Heads of Agriculture and forestry services and supporting staff.	Pacific Soil Portal
FAO KJWA Webinar-Online	June 2021	FAO Pacific Webinar 2-All members of the Pacific Chapter	Improved nutrient use and manure management towards sustainable and resilience; Use of soil test; results to guide; fertilizer use (Sharma); Nutrient balance sheets in a Tongan cropping system -Tonga (Minoneti)
FAO, SPC and SPREP-Online	May 2021	PSP, FAO SPC and SPREP members; National Focal Points for Convention on Biological Diversity (CBD); National Focal Point for Biodiversity for Food and Agriculture (NFP BFA)	Soil biodiversity, an important topic for the Pacific Islands (Iramu)
HOAFs/Samoa	October 2019	21 Heads of Agriculture and forestry services and supporting staff.	Nutrient budgets and soil health; Pacific Soil Portal

Fiji

Location	Date	Audience	Topic
Nawaisomo, (Beqa Is)	April 2021	Farmers	Soil health training
Dakuibeqa (Beqa Is)	April 2021	Farmers	Soil health training
SPC Narere	December 2020	SPC LRD staff	World Soil Day - soil biodiversity and organic farming systems
Taveuni	February 2022	Farmers and extensions officers	Nutrient budgets and soil health

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Tonga

Location	Date	Audience	Topic
'Utulau	January 2021	Nishi Trading growers	Nutrient budgets and soil health
Vaini Experimental Farm	February 2021	MAFFF staff	Nutrient budgets and soil health
		Eastern District Watermelon farmers	Nutrient budgets and soil health
‘Utulau		Nichi Trading growers	Soil test training
Éua,		Government and growers	National Workshop on soil health
‘Utulau	March 2021	Nichi Trading growers	Soil test training
Vaini Experimental Farm		MAFFF staff	
Nuku’alofa		Representatives from research, government, growers’ groups NGOs and other key stakeholders	National Workshop on soil health
Haápai		including representatives from government and growers.	National Workshop on soil health

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Samoa

Location	Date	Audience	Topic
MAF Crop Research Station at Nu'u	12 March 2020	MAF Field and Laboratory Technical Officers (attended by 14)	Dr Soil Workshop covering the use of quick diagnostic tools for assessing soil nutrients and soil pH, measurement of soil density and water infiltration rates
MAF Crop Research Station at Nu'u	13 March 2020	MAF Extension Officers and local growers (attended by 11)	Dr Soil Workshop covering the use of quick diagnostic tools for assessing soil nutrients and soil pH, measurement of soil density and water infiltration rates. Discussions about fertiliser (including organic manures) decisions with farmers and extension officers were at length. Two elements were central to these discussions: (1) Use of synthetic fertilisers is generally perceived as non-economical; however, there appears to be no recent research demonstrating the potential economic return from fertiliser application, and (2) The use of the Hannah® test kit for 'quick' assessments of NPK status was well-received, and likely to be adopted for decision-making if the service could be provided by MAF Personnel.
USP Campus	November 2021	SROS, MAF and USP	Nutrient budgets and soil health, Dr Soil
Savaii	October 2021	MAF and farm extension	Hannah test kits and nutrient testing

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Kiribati

Location	Date	Audience	Topic
Tarawa	2021	277 (108 Females, 169 Males) Youth in Agriculture	Nutrient, water and soil management
North Tarawa	2021	134 (66 Females, 68 Males) Farmers at North Tarawa	Trained on soil management, simple drip irrigation, crop and agroforestry, plant health.
Tarawa	2021	23 (6 Females, 17 Males) Agricultural Assistants	Simple soil test soil samples collection
Tarawa	Feb 2019	10 Youth; 6 farmers and 6 MELAD staff	Soil sampling, Chameleons and FullStops, Pacific Soil Project and nutrients, Nutrient management of garden wastes, why become an agricultural scientist?

Tuvalu

Location	Date	Audience	Topic
Funafuti	December 2020	25 Extension, farmers and landholders.	World Soil Day-Nutrient management
Funafala	Feb 2019	3 extension staff	Fullstop and chameleon training, noting plant response to deficiencies

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9 Conclusions and recommendations

9.1 Conclusions

COVID-19 has been an ordeal across the world and the project has had to adapt and respond to the changing social environment. The project's aim was to improve soil knowledge to enable sustainable agricultural production and despite the COVID-19 challenges the project team has delivered the majority of the intermediatory outcomes. A key barrier for the development of sustainable production systems is the fractured and contradictory advice that clouds the broad extension system. Individuals do not know which advice should be trusted, scientifical robust and should utilised. Soil knowledge is a limiting factor within a complex problem space, compounded by the lack of effective extension services and multiple competing information sources. This is compounded because there is an on-going disconnection between extension services, exporters and growers, which inhibits the development of sustainable, profitable and productive farming systems. Alarmingly the next generation of agronomic advisors/experts is not evident.

Country scale nutrient budgets for agriculture lands showed that on average the soils are exporting more NPK than what is returned to the soil via fertilisers. This is clear evidence of nutrient imbalance and "soil mining" in island food production systems. A potential solution is to utilise island waste streams, augmented with macro- and micronutrients to correct this imbalance. Local level nutrient budgets (Tonga) indicate that excessive nutrients are being applied and further refinements are needed to improve management.

Soil organic carbon content has declined in Fiji and Tongan farming systems. This indicates that a rethink of farming system management is needed to reverse this trend. It may be possible to develop mechanisms for small-holder farmers in the Pacific to participate in the voluntary carbon market and earn additional revenue from building soil carbon and woody biomass carbon. The decline in soil organic matter, as evidence by the decline in soil carbon also means that there has been a reduction in soil nitrogen, sulphur, and phosphorus. The reduction of this "nutrient bank" reduces the crop yield potential in these low input systems. Differences in SOC, soil pH and nutrient levels (especially total N and Olsen's P) between these sites suggested high vulnerability of soils to fertility rundown; particularly, when soils are used for cropping without significant C and nutrient inputs

Legume intercropping is not a quick fix. The amount of nitrogen (N) supplied via fixation (40-60 kg ha^{-1}) was insufficient to meet taro crop demand for N. Temporary immobilisation of P in-crop biomass is likely to be significant and may therefore reduce P availability to the taro crop during the growing season. This can compromise N and K uptake and affect crop water-use. These effects can be more significant in lower fertility soils and soils with low water holding capacity. When legumes are intercropped with taro, the fertilisation program should account for the nutrient demands of both crops. However, this will require careful optimisation of the system to ensure increased water use by legumes (due to increased biomass in response to applied fertiliser) does not limit water and nutrient uptake by the growing taro crop.

The nutrient balance was negative when legumes were used. Apparent surpluses of N, P, and K at when either compost or fertiliser were used were explained by low corm yields and therefore poor

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nutrient use efficiencies (recovery in corm biomass), and lack of weed control over the season. Despite this, corm yields were higher in amended (compost or fertiliser) treated taro compared with legume intercropping. The attainable yield (6150 kg DM ha^{-1}) may not be achieved without application of nutrients and proper weed control.

In Samoa corm yields were lower than the national average and the estimated yield gap (difference between actual and attainable yields) was wide. Yields obtained with surface application were like soil incorporation, which suggested different nutrient loss mechanisms may be driving such effects (e.g., increased volatilisation, and possibly runoff, when applied on the surface, and increased leaching when incorporated – this is possible because of the high permeability and infiltration rates observed in these soils). Appropriate fertilisation coupled with 'good' crop husbandry (weed control, crop protection) can significantly narrow current yield gaps. Overall the farming system trials revealed that NPK on the volcanic islands did not increase yields. The micronutrient trials were disrupted by COVID-19 and cyclones which may have potentially effected yields. It was observed that farm management, such as weeding and planting, and access to quality planting material may have impacted on the farming system experiments.

A conceptual framework for developing nutrient recommendations for taro was presented and discussed. This framework proposes that recommendations for N be derived from the yield-to-N response function and that for other nutrients (P, K, Ca, and Mg) recommendations be based on replacement. Knowledge of the yield-to-N response relationship will enable derivation of the most economic rate of N (MERN). The economic return from N applied at this rate will be maximised. The replacement strategy for the other four nutrients will require the development of soil Indexes. These indexes can be used to define the long-term nutrient management policy at a given site or field. This long-term policy is informed by soil analyses, and it will determine whether there is a need to build-up or maintain soil nutrients levels, or whether application can be omitted because nutrient levels exist within a satisfactory range.

In the atoll environments the use of compost and irrigation management tools improve yield and labour costs. Further work is required to develop fortified composts that overcome micro-nutrient yield constraints. Prior to any further expansion of micro irrigation and food cube systems careful accounting of available water is needed and the utilisation of solar desalination options should be investigated.

The introduction of laboratory-based MIR spectroscopy at Fiji Agricultural Chemistry Laboratory, Ministry of Agriculture, based at Koronivia research station, built capability to analyse PICT soils rapidly and cost-effectively for soil properties of agronomic importance, together with introducing new rapid soil analysis skill sets to the FACL MOA team. MIR calibration results showed that future training needs to be focussed on the refining of MIR spectral and wet chemistry processing and analysis protocols underpinning the establishment of soil spectral reference libraries for the PICTs, including robust calibration model building and quality assurance and control. There is a need for conducting regional surveys of representative PICT soils to build spectral reference libraries and extend and improve the predictive power of the calibration models generated from these. There is also the need to extend the soil spectral reference libraries to soil samples collected deeper than 20 cm, as the libraries are currently biased towards surface samples, except for the soil samples collected at ACIAR field trial sites in Fiji and Tonga.

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The Hannah® test may be used by growers as a quick and inexpensive method to pre-assess the overall fertility status of their soils. Depending on the outcome of this test, accurate laboratory analyses may be also needed to formulate fertiliser recommendations and establish a long-term nutrient management policy. The nutrient management framework developed as part of this work may be used to that effect.

There is potential for rapid MIR analysis together with traditional wet chemistry laboratory analysis to contribute towards building a soil information system for the PICTs embedded with the Soils Portal. The Pacific Soil Portal brings together lost soil information into one central repository. To archive impact the soil portal needs to be utilised by policy development and the commercial sector to identify land capability and management options.

9.2 Recommendations

The project recommends the following:

1. In Fiji, Tuvalu and Kiribati the project was greatly hindered from pandemic and in Fiji cyclones. Further follow-up four-year trials undertaking farming system nutrient management should be formulated and implemented. Additional training and awareness should be made to key stakeholders on nutrient budgeting work especially on commercial crops.
2. Continued capability improvement of in-country staff not only in sustainability farming system but also project management, communication, information technology and research extension
3. Improved connections with USP and FNU to development environmental science graduate students and staff research and training either through higher education opportunities or collaborative research projects.
4. Soil carbon data from Tonga and Fiji shows that there has been a significant decline in stocks since the 1990s. It is critical for on-going agriculture production to develop farming systems, a consumer base and policies that build soil carbon. Current Australian research has shown it is possible to build soil carbon in dry land cropping systems through appropriate nutrient management. Voluntary carbon markets may be a mechanism to improve farm income through international carbon sequestration purchases. SMCN-2020-139 will need to undertake briefings with Government agencies and others about the soil carbon findings and to enable the develop of a policy platform and research strategy to improve soil carbon sequestration. This co-developed strategy and platform should be tested within the SMCN-2020-139 field trials.
5. Organic farming systems are being promoted in all Pacific Island Countries and Territories. There is a need to develop a sustainable compost industry for agricultural production systems and ensure that composts are tailored to the specific soil contrasts.
6. GxExM research. There is an opportunity to investigate GxExM interactions for important Pacific Island Countries and Territories crops. Current research has utilised typically market available varieties this is limits our ability to determine genetic traits that may be suitable for different soil types and climate and associated farming system management. This research should also include nutritional quality of the harvested materials.

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7. MIR spectroscopy has been successfully used to augment soil laboratory analysis at the Fiji Agricultural Chemistry Laboratory, Ministry of Agriculture. During the project pilot soil spectral reference libraries for Fiji and Tonga have been developed but need to be expanded and built upon facilitated through conducting soil surveys of representative PICT soils. Recommended next steps at FACL MOA are to refine and establish protocols/standards for applying existing calibration models to new spectral data including the selection of a set of sub-samples for wet chemistry analysis to improve existing calibration models, together with the development of a soil database capturing the soil information collected following standard methods and protocols. Rapid infrared spectroscopy-based analysis should be further expanded to other PICT countries, and the use of infrared spectroscopy offerings capable to be taken to the field should be explored, such as near-infrared (NIR) and portable X-ray fluorescence (pXRF) spectroscopy. MIR, NIR and possibly pXRF should also be explored within a broader Pacific Island Countries and Territories laboratory impact and business plan.
8. Pacific Soil Portal needs to be transferred to SPC to improve linkages to users and decision makers. The Portal should also be used to develop new soil mapping and land capability mapping in subregions for land use planning.
9. Development of nutrient recommendations for taro:
    a. The proposed conceptual framework needs validation, and soil nutrient indexes for major elements established for taro as well as other crops used in rotation. Yield-to-nitrogen response relationships need to be determined at key locations and information combined with climatic and nutrient input cost data to be able to provide annual fertiliser (N) recommendations. The communication effort may be coordinated by extension officers, and information delivered to farmers on an annual basis to assist with their nutrient decisions.
    b. The relative effects of nutrient source (organic amendment, mineral fertiliser) and placement (surface-applied, soil incorporation) on the crop agronomic performance require further investigation. There is a need to quantify pathways of nutrient losses and better understand the mechanisms involved. These are important considerations to ensure nutrient recovery in harvested plant material (use efficiency) is maximised and the risk of environmental losses of nutrients is minimised.
10. Nutrient balance and intensification of taro production systems:
    a. There is a need to refine the field-scale nutrient balance calculations reported in this work to assist the development of long-term nutrient management policies aimed at maintaining the productivity of taro soils. Establishment of permanent experimental sites, carefully designed for long-term monitoring of soil nutrient dynamics and agronomic performance of taro, could serve to that purpose. Information derived from these sites can be then used to develop nutrient advice.
    b. Intensification of taro production may be possible through the establishment of double taro cropping systems whereby a second taro crop is planted (intercropped) before the main crop has been harvested. The main objective of this planting system would be to be able to harvest two crops in for example 12 months instead of 16 months, which is more common. This approach would require adjusting plant nutrition to ensure any adverse impacts on soil fertility and crop productivity are

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avoided. It will also require careful management of soil water, particularly regarding weeds control, and optimisation of the planting window for the second crop. Virtual trials in APSIM could be used to inform the design and management of double taro cropping systems and assist the establishment of future experimental work.

   c. Interest in reducing herbicide and manufactured fertiliser use, particularly to produce food crops, could increase adoption of tillage for weed control and application of organic amendments to meet crops demand for nutrients. This will require the development of best management practices for tillage and understanding of the fertiliser replacement value and nutrient release characteristics of organic amendments. Tillage management protocols will ensure adverse effects on soil are minimised; namely: (a) increased rate of oxidation of soil organic matter due to manipulation of soil for weed control and seedbed preparation, (2) increased risk of soil compaction due to tillage (most soil) and traffic (low bearing capacity), (3) soil structural damage, and (4) reduced rate of infiltration (reduced surface cover) leading to increased runoff and erosion, and therefore nutrient and sediment transport to surface waters.

11. Further development of the taro module in the APSIM modelling framework:
   a. The taro module in APSIM was developed by Crimp et al. (2017) using data collected in Fiji, Vanuatu, and Tonga. The existing module has limitations as it is site and variety specific. Further development of this module will improve its capability to simulate the response of taro to projected changes in climate in the Pacific and to identify strategies for farming systems adaptation.
   b. If this model could be developed for release, then they would be useful given the importance of taro (and cassava) as staple for large numbers of people globally.
   c. Significant savings in field-based experimental work could potentially be realised if this was, in part, replaced by virtual trials, leaving field trials for verification of modelling outcomes.

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9.4 List of publications produced by project

1. Antille, D. L., Uelese, A., Tugaga, A., Webb, M. J., Tauati, S., Kelly, J., Stockmann, U., Barringer, J., Palmer, J., Macdonald, B. C. T. (2022). Agronomic response of rainfed taro to improved soil and nutrient management practices in Samoa. ASABE Paper No.: 2200065. St. Joseph, MI.: 2021 ASABE Annual International Meeting, American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/aim.202200065.
2. Halavatau, S 2021. Building and strengthening connections and relationships between actors for better soil management in Tonga. Report.
3. Iramu, E. Beqa Island Training on Soil Health for Farmers: 7 – 8 April 2021. Report
4. Kader, M 2012. Soil doctors programme: guidelines for implementation in PICTs. Report
5. Kader, M 2021. Dr Soil Day training in Samoa. Report
6. Kader, M 2021. Present status of soil sampling and testing protocols employed in key regional soil laboratories in the Pacific. USP Report.
7. Kader, M 2021. Soil Sampling guidelines. Strengthening regional collaboration on soil sampling.
8. LRD 2021. Soil analysis methods and results interpretation manual. A guide for soil laboratories in the Pacific Island Countries and Territories. Report.
9. Stockmann, U., Farrell, M., Carter, T., Tuomi, S, Krawitz, S., Small, B, Macdonald, B. Utilizing rapid spectral techniques to assess impacts of agriculture on soil function in pacific soils. In: 7th International Symposium on Soil Organic Matter in a stressed world; 6-11 October 2019; Adelaide, South Australia. som.org; 2019. 1 p.
10. Susumu, G, Sharma, A, Halavatua, S., Antille, D.L., Webb, M.J., Barringer, J, Kell, J, Macdonald, B (under review) Pacific Island countries are losing nutrients: this will affect crop productivity and human nutritional health. Pacific Science.
11. Tausi, S., 2020. World soil day Report December 2020.
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10 Appendices

10.1 Appendix 1:

Project resources – Pacific Soils Project (csiro.au)

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10.2 Appendix Testing – Objective 3.2

Stockmann, U., Farrell, M., Carter, T., Tuomi, S, Krawitz, S., Small, B, Macdonald, B. Utilizing rapid spectral techniques to assess impacts of agriculture on soil function in pacific soils. In: 7th International Symposium on Soil Organic Matter in a stressed world; 6-11 October 2019; Adelaide, South Australia. som.org; 2019. 1 p.

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Utilising rapid spectral techniques to assess the impacts of agriculture on soil function in pacific soils

An example from Tongatapu island, Tonga

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Introduction

Anthropogenic activity, notably land intensification and climate change, has had a dramatic impact on the status of the soil resource. The soil's ability to deliver crucial ecosystem services, including soil organic carbon storage, soil nutrient delivery and soil water holding capacity has been affected. At present, little is known, however, about the impacts of land intensification in remote pacific island agroecosystems. The state of the soil is a key factor in farm value on pacific islands and therefore warrants monitoring to ensure the sustainability of the soil resource for future generations. However, traditional soil laboratory techniques are expensive to use for high resolution soil monitoring purposes and also hard to access at times, because of remoteness of the islands and limited laboratory capacity. In turn, soil spectroscopic techniques, in particular devices that can be taken to the field, offer local land managers a means for rapid and cost-effective soil analysis with minimal sample preparation. They have the ability to predict a range of soil properties of agronomic importance, including soil organic matter, soil texture and nutrient contents.

Aim

The purpose of this study is to assess the suitability of soil spectral devices to quantify aspects of soil fertility for allophanic soils of agricultural sites on Tongatapu island, Tonga. Here, we present results for measuring total carbon (TC) and soil organic carbon (SOC) utilising vis-NIR spectrometry.

Methodology

Sampling locations across Tongatapu island were chosen at agricultural sites with soil legacy information (Potter, 1986; Cowie et al., 1991) to also allow for comparison of the impact of management practices on the soil's status.

Figure 1: Sampling locations across agricultural plots on Tongatapu island, Tonga.

Soil Data

Five soil core samples were taken from the corners and centre of 1 ha plots at each site using a hand-corer; representative of the top- and subsoil (i.e. 0-15, 15-30, and 30-60 cm) (Figure 1 and 2). The centre soil core of each plot was analysed for TC and SOC in the laboratory (81 samples) using the dry combustion method (Leco), whereas all 382 soil samples were scanned using portable vis-NIR; in field and air-dried ground (<2mm) condition (Figure 2).

Figure 2: Soil sampling in the field, and spectral analysis using a Panalytical ASD LabSpec vis-NIR spectrometer.

Table 1: Statistics of measured TC and SOC content (mg/g) of the calibration dataset (Leco, dry combustion).

	n	Mean	Std. dev.	Median	Min	Max
Total carbon (mg/g)						
Calibration	61	43.19	33.10	32.39	12.51	136.52
Validation	16	39.43	24.15	31.7	11.66	118.61
Soil organic carbon (mg/g)						
Calibration	61	29.67	11.93	28.33	9.38	64.3
Validation	16	31.99	10.33	29.36	11.66	53.41

Prediction method

Spectral data obtained from air-dried and ground (<2mm) soil samples were converted from reflectance to absorbance, trimmed, filtered (using the Savitzky-Golay filter with a window size of 10 nm and a polynomial degree of 2), baseline corrected using the standard normal variate technique and resampled for data reduction purposes. Three prediction methods were tested for spectral calibration, partial least squares regression (PLSR) with no external validation, PLSR with internal and external validation (20%), and bagging PLSR, which generates multiple PLSR models and averages the predictions (50 realisations were used here).

Results and Discussion

Soils of Tongatapu

Dominant soils on Tongatapu are allophanic soils derived from volcanic ash, with younger-reddish brown tephra over older browner and finer textured tephra deposits. These in general fertile soils are well drained with clayey textures and deep dark-coloured A horizons. Smaller areas also have occurrence of soils formed from coastal coral sands. These soils tend to be nutrient deficient with high pH and levels of calcium, which makes them less desirable for cropping (Cowie et al., 1991).

TC and SOC vis-NIR measurements

Models were trained on normalised data (sqrt) and bagging PLSR resulted in the most robust model on this relatively small dataset (Figure 3). The bagging PLSR model was then applied to the whole spectral library (302 spectra).

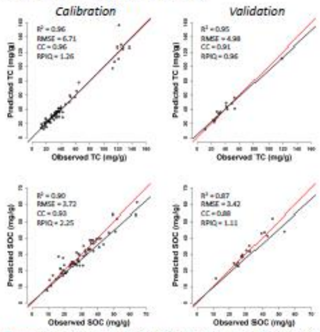

Figure 3: Goodness of fit showing the relationship between vis-NIR predicted TC and SOC as compared to laboratory measured values, for the bagging PLSR prediction method (Goodness of fit of back transformed data are presented here). R^2 – R squared coefficient of determination, RMSE – root mean square error (mg/g), CC – concordance correlation coefficient which measures the closeness to the 1:1 line, RPIQ – ratio of performance to inter-quartile distance.

Our results show that vis-NIR spectrometry can be used successfully for allophanic soils for traditional soil fertility measurements, and in upcoming work we will also examine its capability for other soil quality indices and soil properties. Furthermore, for this data-set, we will also test algorithms to enable in-field measurement of soil attributes.

Conclusions and Future work

Our preliminary results indicate that the introduction of rapid spectroscopic techniques can play an important role for means of soil measurement of pacific island soils.

This study contributes to the building of a soil information infrastructure for pacific island soils, including soil spectral reference libraries, and data for baseline soil attribute assessments; which will contribute towards enabling informed land management decisions in the pacific island region, and monitoring their status towards ensuring soil resilience.

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