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prepared by	Dr Ben Macdonald
co-authors/ contributors/ collaborators	Dr Neil McKenzie
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Contents

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Title	Name	Role	Organisation
Dr	Siosiua Halavatau	Acting Deputy Director and Crop Production and Extension	Pacific Community
Mr	Gibson Susumu	Food Security Officer	Pacific Community
Ms	Maria Elder	Sustainable Land Management Adviser	Pacific Community
Ms	Romika Dayal	Project Assistant	Pacific Community
Mr	Matio Lonalona	Acting Senior Quarantine Officer	Ministry Of Agriculture, Tuvalu
Mr	Tilafono David Hunter	Chief Executive Officer	Ministry of Agriculture and Fisheries Samoa
Mr	Minoneti Vunivesi	Senior Agricultural Officer	Ministry Of Agriculture; Tonga
Mr	Tokintekai Bakineti	Manager of Component 2	Ministry of Environment Land and Development, Kiribati
Mr	Ami Sharma	Senior Research Officer	Koronivia Research Station
Dr	Neil McKenzie	Chief Research Scientist	CSIRO
Dr	Ben Macdonald	Principal Research Scientist	CSIRO
Dr	Mike Webb	Principal Research Scientist	CSIRO
Dr	Jennifer Kelly	Principal Research Scientist	CSIRO
Mr	James Barringer	Scientist	Landcare Research NZ

Executive summary

Inadequate soil knowledge is constraining the sustainable intensification of agriculture in the Pacific Island Countries and Territories (PICTs). Management practices in traditional gardening systems are intensifying and this is depleting the soil's nutrient capital. Comprehensive nutrient budgeting is essential for improving farm productivity and agricultural resilience on volcanic islands and sand atolls. At present, extension officers are unable to reliably ascertain which nutrients (or other factors such as diseases) 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 previous research studies or well-understood farming systems to other locations across the PICTs. Farmers recognize that this lack of soil knowledge is a production constraint. There is a need to increase capacity of all stakeholders participating in relevant value chains (e.g. from farm to market) to overcome this significant threat to livelihoods and natural capital.

A priority for any future work is to enhance soil knowledge and provide a reliable foundation for sustainable intensification of agricultural systems by growers, extension officers and policy makers. The starting point is a strong systems view that ensures nutrient budgeting is a routine part of agriculture throughout the region. This will help identify effective and sustainable interventions. It would involve a move away from the current focus on one or just a few potentially limiting nutrients. The systems view also needs to be framed within a broader pedological and landscape context that ensures more effective generalization of research results (this will represent a change from the current practice where results from field experiments are either assumed to apply to that site only, or at the other extreme, assumed to apply everywhere).

Another priority is to develop improved information systems for delivering practical advice on how to achieve sustainable soil management. Most existing information is inaccessible and this needs to change. Fortunately, the dramatic advances in geospatial technology have opened new possibilities for the development of a Pacific Soil Portal. Experience with such systems in Australia and New Zealand indicates that apart from providing advice on soil management to farmers and advisors, the Portal can meet the needs of other scientific communities (e.g. those involved in simulation modelling, spatial analysis, environmental monitoring), agribusiness and government. The main beneficiaries from the future work outlined in this project will be farmers and the national economies as a whole because of increased profitability resulting from improved farming practices and the resulting multiplier effect throughout the economy.

1 Introduction

Sustainable agriculture is fundamental to the future prosperity of Pacific Island Countries and Territories (PICTs). Diverse farming systems operate across the region and range from traditional bio-diverse gardening systems (Blanco *et al.* 2015) through to commercial mechanized mono-cropping (van der Velde *et al.* 2007). Subsistence farming underpins food security in most rural areas. Commercial farming is an important source of employment and export revenue in several countries (e.g. Fiji, Tonga). While the contribution to gross domestic product is modest (<15%), agricultural development and export markets are high priorities for governments and international development programs across the region (e.g. the Pacific Horticultural and Agricultural Market Access Program (PHAMA)).

While domestic food production from traditional systems is central to the livelihoods of a large proportion of the population in most PICTs (IBSRAM 1989), intensification of production is becoming more important due to population growth and income requirements. The viability of these agricultural systems is under threat, particularly on low-lying atolls in countries such as Kiribati, Tuvalu and the Federated States of Micronesia (ITPS 2015; Plahe *et al.* 2013; Taylor 2016; Wairiu 2016). Climate change and population are primary drivers. However, economic and trade pressures are also important contributors to the land degradation that's occurring across the PICTs. This is causing a range of adverse impacts particularly through the limited availability of nutritious and fresh food.

Sustainable soil management is a prerequisite for long-term success in agriculture. Unfortunately, the recent Status of the World's Soil Resources report (ITPS 2015) presented a disturbing account of the plight of agricultural systems in the Pacific region. Atoll islands are a particular concern because of their poor soils and vulnerable ground water systems. In other parts of the Pacific, nutrient imbalances, a decline in biological function and very high rates of erosion threaten the viability of current agricultural systems and reduced future management options. Large yield gaps persist and soil nutrient imbalances are widespread (ITPS 2015).

These problems are not new, for example, Demeterto *et al.* (1989), IBSRAM (1989), Craswell *et al.* (1996) and Markham (2013) summarize many of the earlier soil nutrition studies undertaken in the PICTs and they each concluded that soil fertility decline was a pressing issue and a barrier to sustainable and productive agriculture. However, nutrient imbalances are a more general problem. Some systems have low inputs and exhibit soil nutrient decline (Craswell *et al.* 1996) while other more commercial high-input systems are causing off-site impacts through leaching and run-off (Van der Velde *et al.* 2004). These problems persist and the limited research impact from past projects has been attributed to lack of basic soil knowledge at the farm, extension and policy levels across most PICTs (Asafu-Adjaye 2008).

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.

However, this explanation has to be tested because a range of other factors affect decision-making by farmers, farm advisers, input suppliers, agribusiness and policy makers. While there is general consensus that adoption will be improved through more participative modes of action involving farmers, agronomists, governments and businesses (Craswell *et al.* 2013), it is also apparent that limited adoption of improved agronomic practices can be caused by market inefficiencies, institutional constraints and other risks relating to land, human and production factors (Plahe *et al.* 2013; Sparrow *et al.* 2016; Tittonell *et al.* 2013). This SRA examines soil nutrient management in PICTs with a focus on low input Taro (*Colocasia sp.*) systems. These systems are currently intensifying with shorter rotations, changes in inputs and a greater focus on exports. Our purpose here is to summarize current soil nutrient issues and then identify potential management strategies that farmers and extension officers can implement to improve soil nutrient management and farm profitability.

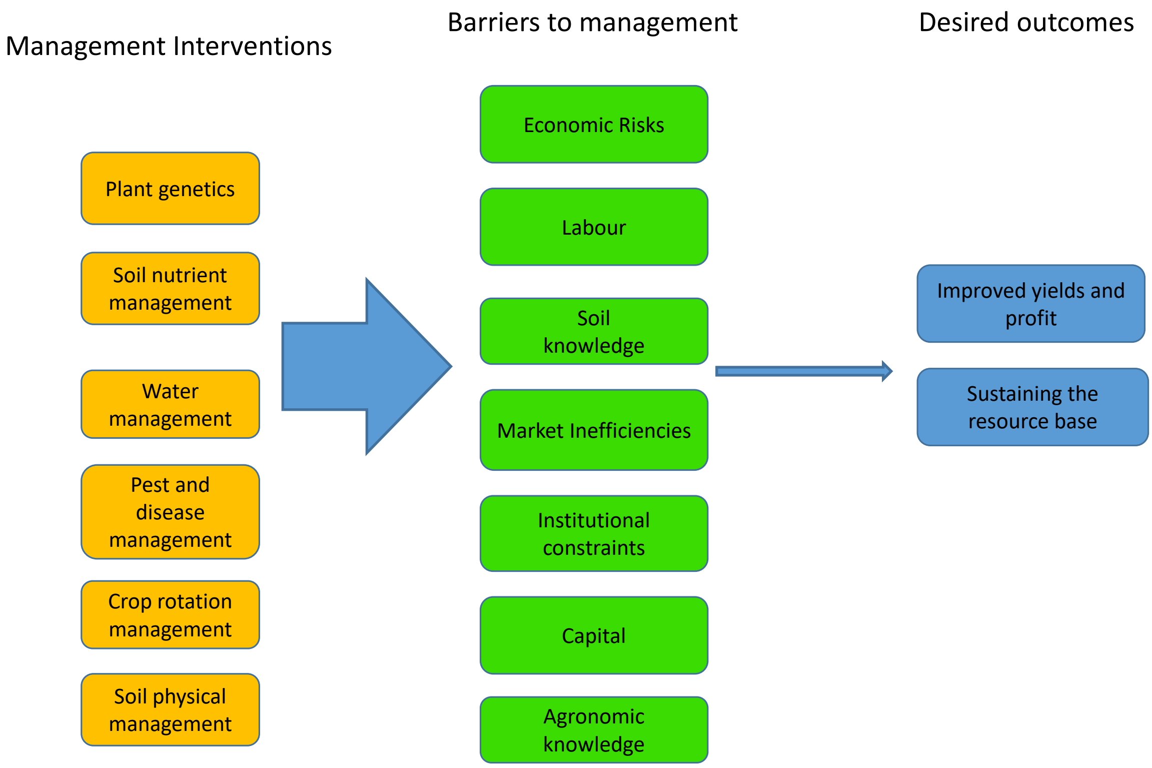

Figure 1. Current identified barriers which are impairing soil fertility management, yields and profit.

2 Declining soil fertility

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 *et al*. 2006). The conversion of traditional agroforestry systems with their typically long fallows (Figure 2A), to systems with shortened fallows (Figure 2B), and eventually to more intensive systems with exports and even shorter fallows (Figure 2C), has resulted in the widespread falling productivity that has been observed in recent decades. The endpoint of this continuum is continuous cultivation of the same piece of land which leads to nutrient loss (via crop harvest, erosion and oxidation of organic matter) and major yield decline (Prasad 2000). Increases in pests and diseases are often associated with the loss of soil fertility.

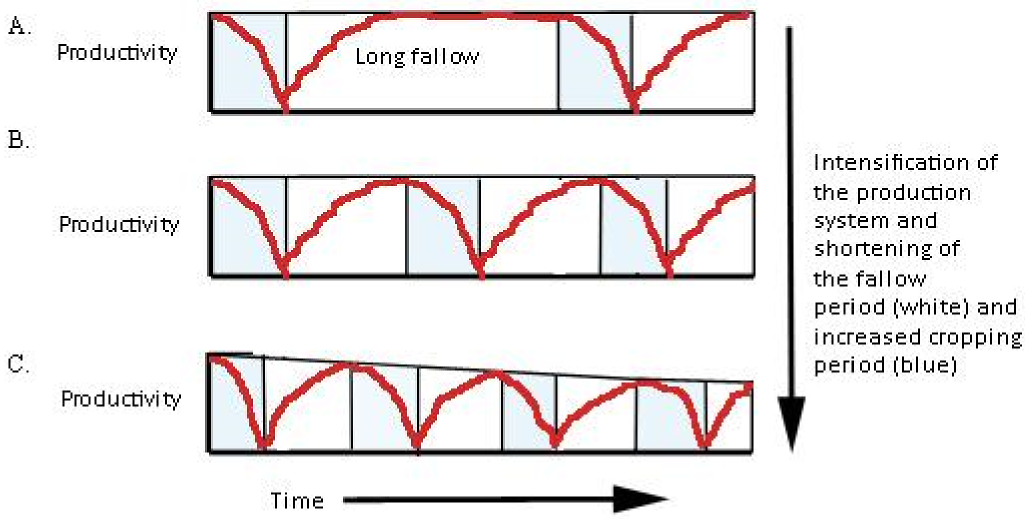

Figure 2. Generalized decline of productivity in Pacific Island farming-systems. Increasing intensification without appropriate nutrient management for different soil types leads to declining productivity.

In reviewing nutrient inputs into Pacific Island agricultural systems (e.g. rock weathering, biological N-fixation, organic amendments, fertilizer, atmospheric inputs), it was evident that nutrient inputs from sea birds play an important role in terrestrial food webs by transporting marine-based energy and nutrients to islands (Anderson *et al.* 1999) and fertilising low-input farming systems (Figure 2a) and terrestrial ecosystems more generally. There appear to be no detailed studies on the effect of guano on PICTs but on Californian Gulf Islands, productivity is 13 times greater on islands visited by seabirds (Polis *et al.* 1997). The settlement and agricultural intensification 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). In agricultural systems on PICTs where fertilisation is minimal, nutrients supplied by seabirds have most likely underpinned soil nutrient supply. A better understanding is needed of the significance and extent of disruptions to this input pathway across a range of PICTs.

Nutrient decline has been clearly documented in semi-intensive farming systems such as sugarcane (*Saccharum officinarum*) in Fiji. Morrison *et al.* (2016) document substantial topsoil fertility decline over 30 years caused by inadequate soil conservation and poor nutrient management practices. They conclude that *soil and farm nutrient budgets* have to be developed to assist farmers in their management decisions. As noted above, the problem is not confined to cane production but occurs more broadly across farming systems in the Pacific, especially where intensification and crop export from the field are occurring. These problems are further exacerbated when land is leased for agricultural production. The tenants will favour technologies and investments that will return benefits within the period of secure land access (Chand *et al.* 1997). Soil management is a long term option and is not favoured, which leads to soil nutrient mining and yield decline on leased land (Ward 1995).

The current situation facing producers of taro (*Colocasia esculenta*) in Taveuni, Fiji, is a prime example of the issues facing all Pacific Island nations as they move towards more intensive farming systems. The young soils of Taveuni are formed from volcanic parent materials and in their natural state are very fertile. It is estimated that since 1990, when intensification began, approximately 150,000 tonnes of taro have been exported from Taveuni (Kjaer 2015). The net elemental export can be estimated using the taro composition data of Bradbury and Holloway (1998). On this basis, there has been a net export of nutrients from the soil system (Figure 3a) leading to nutrient decline (Figure 3b).

The fertility decline in combination with soil organic N and C loss, shortened rotations, pests and diseases and other agronomic issues have caused a fall in productivity. The approximations provide only a partial budget because the garden production system involves a complex web of nutrient flows (Figure 4).

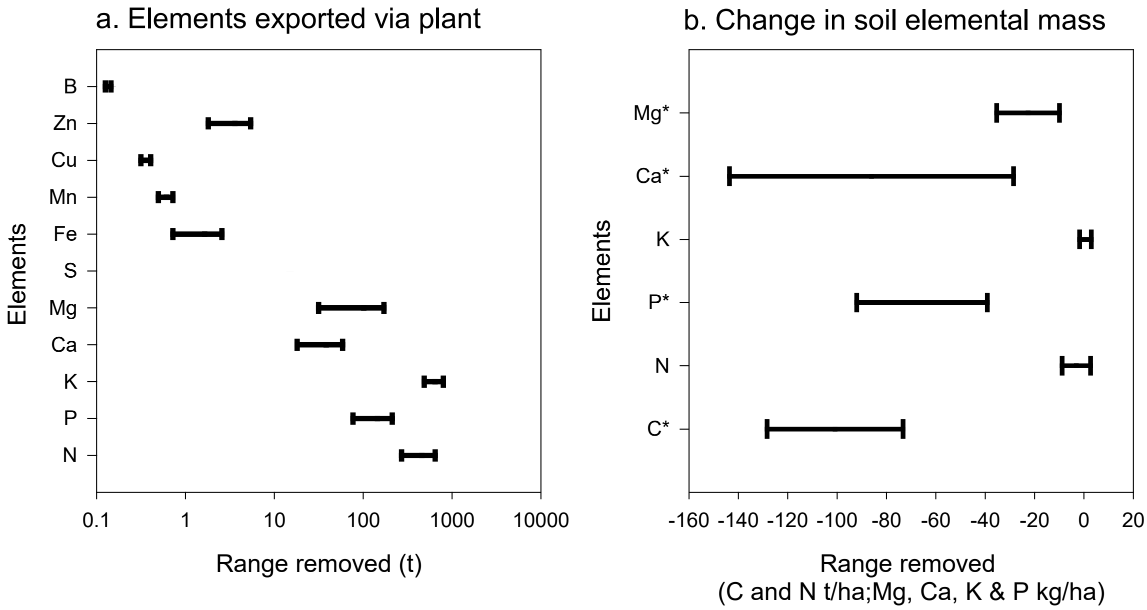

*Figure 3. A. Initial approximation of the average range of elements removed by crop exports from Taveuni taro production systems (1990-2015, t. Taro elemental composition sourced from Bradbury and Holloway (1988). B. Initial approximation of the average loss of elements in the topsoil (0-20 cm) in Taveuni taro production systems (data from Sharma, 2016). * indicates a significant difference between the measurements 1990 and 2012.*

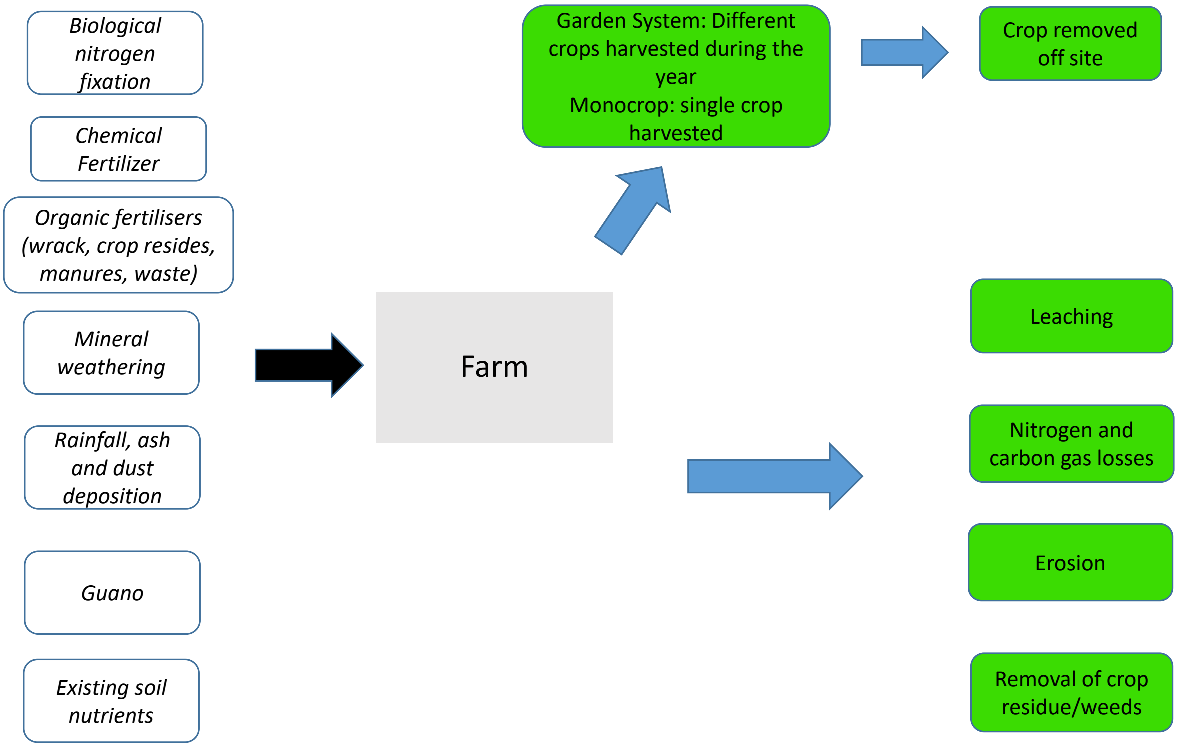

Figure 4. Potential nutrient inflows (black arrows) and outflows (blue arrows) for a typical garden system on islands such as Taveuni. The difficult aspect in quantifying nutrient flows is the multiple harvests from different crops from the bio-diverse garden.

Better information on yields (t ha^{-1}) is required to quantify nutrient export from each farming system. Nonetheless, the decline in topsoil nutrients and base cations are strong indicators of fertility decline. In Taveuni, farmers have become aware of the importance of nutrient inputs for taro production (especially K) because of research and extension activities supported by ACIAR (e.g. SMCN/2009/003). SMCN/2009/003 has shown yield responses to fertiliser applications in conjunction with fish meal relative to NPK applications only. These results point to the importance of organic N (and biological processes) in meeting nutrient requirements of crops. It also indicates that a more integrated response is needed to address all relevant macronutrients and micronutrients, and in particular, to rebuild stocks of soil organic carbon.

On atoll islands, such as Tuvalu and Kiribati, the naturally occurring soils are very infertile compared to those on volcanic islands. This has been compounded by the loss of nutrients due to manual tillage, deep drainage and domestic crop consumption. 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 for smallholder farmers (White *et al*, 2007).

A further issue on these islands is the maintenance of groundwater quality for domestic supply. Agriculture is a key source of nitrogen and faecal contamination of groundwater lenses (White and Falkland 2010; van der Velde *et al*, 2007). 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 household wastes but material is also collected from other locations such as forest and ground water reserves, harvested sea-weed and driftwood and tide wrack. The harvesting of these source areas needs to be carefully managed so that nutrients are not mined.

The soil nutrient imbalances evident on Pacific volcanic and atoll islands occur in smallholder farming systems elsewhere in the world. For example, in Africa (e.g. Stoorvogel *et al*., 2003; Smaling *et al*., 2003) district-scale losses are in the order of 112 kg N, 3 kg P and 70 kg K ha/yr. The risk for smallholder farmers in the Pacific is to be caught in a poverty trap similar to those experienced by many African farmers (McCown and Jones 1992, Giller *et al*. 1996, Tittonell and Giller 2013) where crop intensification and declining soil fertility leads to a downward spiral of lowering yields, falling incomes and a decreasing ability to afford the necessary inputs.

3 Focal Crop System: Taro

Taro is grown across a range of soil types and climates in all the Pacific Island nations. It is one of the most important staples of the region. The versatility of taro and its cultural importance and resilience makes it an ideal focal crop to address the aim of improving soil knowledge. Onwueme (1999) states that taro is able to grow in ecological conditions which other crops may find difficult or adverse. There are at least three such situations.

1. Waterlogged and hydromorphic soils.
2. Saline soils: some taro cultivars can tolerate salinity, and can grow in 25-50% sea water. Such saline conditions would prove lethal to most other crops.
3. Shady conditions: taro's tolerance to shade enables it to grow well as an intercrop between tree crops (e.g. coconuts), because it can profitably exploit the diffuse light reaching the plantation floor.

Soil fertility decline is a major production constraint and has been identified as a high research priority in taro agricultural systems (Guarino *et al*. 2003). The resilience of taro to climate change and extreme weather events further strengthens the case for selecting it as a focal crop system (Wairiu 2016).

Interaction with plant diseases

Besides directly affecting crop yields variations in soil biological, physical and chemical properties can cause soil fungal diseases. In Cameroon, soils classified as Andosols (similar soils are found on young volcanic islands in the Pacific) have higher contents of organic matter, calcium, potassium, magnesium and nitrogen which are negatively correlated with disease incidence (Adiobo *et al.* 2007). Adiobo *et al*. (2007) found that soils that have lower organic matter contents have increased root rot possibly due to the poorer soil structure, nutrient supply and lower microbial biomass and activity. These conditions stress the plant and the resulting increase in soil wetness promotes fungal growth.

Increased compaction and the application of organic matter to correct nutrient deficiencies may also increase the risk of rot root due to changed soil moisture dynamics (Miyasaka *et al.* 2001). Leaf material in some instances is added at depth to allow water to flow freely into the soil, avoiding collection on the surface and run-off into the taro planting holes which can lead to corm rot (Spriggs 1981). Further, intensification and resulting modification of planting dates may have also contributed to increased rot-root incidence (Miyasaka *et al.* 2003). In some instances root rot has meant that the farmers have switched from an 8 month growing season to a 5 month season to avoid the disease. In Taveuni root-rot has become a problem in the latter stages of the crop causing significant rejection rates and mortality.

The decline in Taveuni taro production

Despite significant financial returns from taro exports, Taveuni farmers have not adequately fertilised their soils (Figure 2) and, as noted earlier, this has probably contributed to falling production (Figure 5). In Taveuni, the taro production area was increased in the early 1990's due to increased demand and appeared to stabilise in 2000. Average yield fell from 30 to 9 t/ha between 1990 and 2012 and this has been attributed to fertility decline, increased pests and diseases (Sharma, 2016), and shortening of the growing season to avoid root rot (Halavatau per comm). It is alarming if the yield collapse in Taveuni is due in part to soil nutrient decline because the soils involved are the most fertile in Fiji (Denis 1979). Improved understanding of the causes of the yield decline is essential. This requires gathering data on basic attributes such as planting density and area planted.

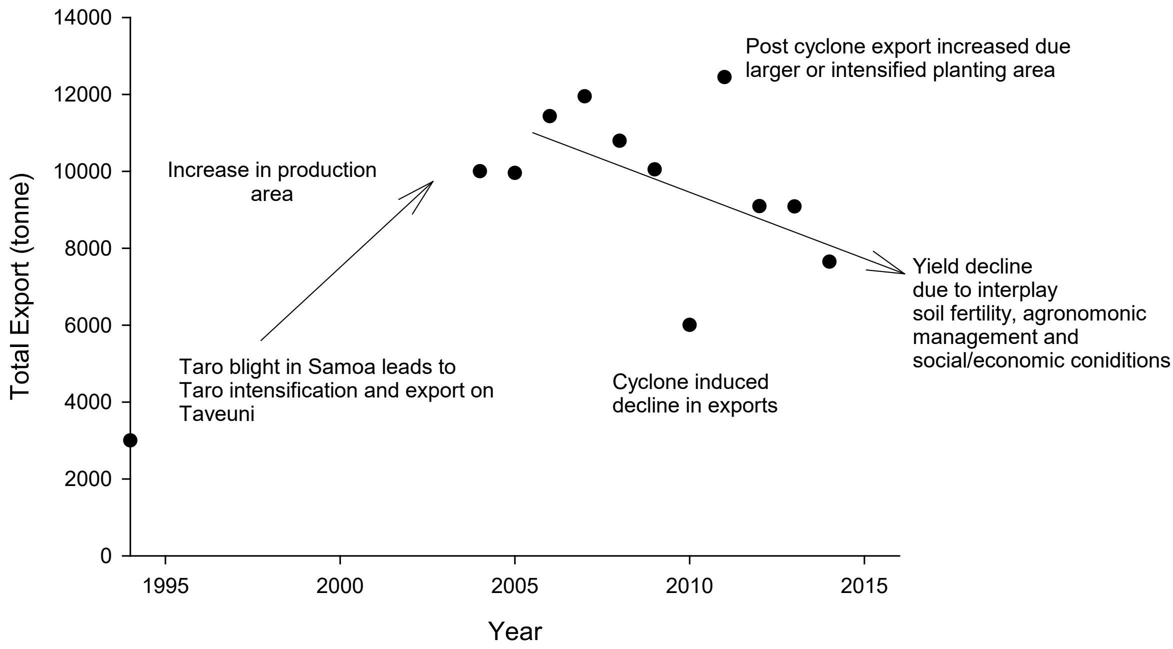

Figure 5. The rapid rise and decline in taro exports from Taveuni (1994-2015). This appears to be a classic example of rapid agricultural expansion with subsequent exhaustion of soil nutrients and increased plant disease causing yield decline.

Fertiliser practice

Current fertiliser application rates for taro vary widely across the PICTs and where taro is grown as a subsistence crop no fertiliser at all is applied (Blamey 1996). Recommended NPK fertiliser rates for taro range from 60-140 kg N/ha, 25-125 kg P/ha and 80-340 kg K/ha (de Geus 1967). More recent results have indicated similar rates to be appropriate, viz. 40-80 kg N, 10 kg P and 40-80 kg K per hectare for high corm yield, with split applications of N and K (Mohankumar and Sadanandan 1989; Mohankumar *et al*. 1990). At rates of between 40-80 kg NPK per hectare and a spot fertiliser price of $US 388 per tonne farmers would need invest $16-31 per hectare. This investment is beyond many smallholder farmers.

4 Better soil sampling, measurement and diagnosis

Responding to the problems outlined in the previous section requires effective nutrient management and this in turn requires accurate measurement and interpretation. While this principle is easy to espouse, 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

Figure 3a shows that in Taveuni large amounts of nutrients are removed annually with the taro crop. These are not completely replaced by inputs and this leads to soil nutrient run-down (Figure 3b). Some of the exported nutrients may simply be those that have been added previously to the soil in the form of organic and synthetic fertilisers. However, such inputs in taro production systems are low so it suggests that the nutrients must be coming from another source. In many nutrient studies, sampling is often confined to upper 0-30 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 is between 0-60 cm (HORT/2012/011), thus some of the large amount of nutrient export in Figure 3 could be coming from below 30 cm. Further, leached nutrients may be accumulating deeper in the profile. 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. This is especially important if nutrient declines are occurring deeper in the soil profile because amelioration is far more difficult.

Nutrient pathways

A second important issue in managing soil nutrients in these systems is the quantification of nutrient pathways in the mixed-crop system and, in particular, the losses (e.g. soil adhered to the root, erosion, leaching and gas) and inputs (Figure 4). For example, if we assume that approximately 50 g of soil is lost with every 2 kg taro root exported, then approximately 225 kg/ha of soil is removed each year with exports compared to losses caused by soil erosion by water that may range between 10 to 1000 Mg/ha), it highlights that a comprehensive systems-view is necessary for understanding nutrient stores and fluxes at multiple scales (e.g. plant, soil profile, field, farm, catchment, island, nation). Soil testing alone will not provide the critical information that is needed if taro production is to be sustainable.

Soils with variable charge and calcareous soils

A third important issue in the Pacific is the prevalence of soils with variable charge. These are most commonly soils derived from volcanic ash (Andosols) or strongly weathered soils dominated by the oxides and oxyhydroxides of aluminium and iron. Apart from being more vulnerable to nutrient decline, these soils require specific testing procedures. 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 *et al*., 1991) leading to the risk of faulty recommendations on nutrient management. The manipulation of pH is fundamental to the successful management of variable charge soils. Liming and organic matter are key ingredients but careful analysis using appropriate analytical methods is essential to avoid unintended deficiencies (Curtin *et al*., 1991). Further, the form, placement and timing of synthetic and organic fertilisers needs to be optimised for each soil type.

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). Most tests for calcareous soils have been developed for semi-arid conditions where soils contain significant amounts of clay but minimal organic carbon (i.e. <1-2%). In contrast, the soils of atolls are often sandy, free draining and contain appreciable organic carbon (3-5%).

Soil biological function

Soil microorganisms play a major role in the decomposition of soil carbon and the cycling of nutrients and water in tropical island soils (Leo *et al.* 2014). However, there are significant knowledge gaps in our understanding of diversity and function of these microorganisms in the Pacific Islands (Leo *et al.* 2014). A key gap is an inventory of soil biodiversity across the major soil types and land management systems.

Many diagnostic tools have been used to assess gross biological function in soils. These include soil respiration, substrate induced respiration, N-mineralisation rate (Visser *et al.* 1992), the amino-N mineralisation (Khan *et al.* 2001), biological indicator species (e.g. worms or nematodes) and DNA barcoding. The application of one or more of these tests in the Pacific Islands will enable an assessment of the gross biological function and provide information to growers and extension officers about sustainable land practices. There is also a need to understand the epidemiology of diseases affecting taro and in particular, the role of soil pathogens as a function of soil type and management.

Fertiliser Practice

Improving fertiliser practice to maintain soil fertility is critical, but the use of synthetic fertilisers sits within a complex social, biophysical and political landscape. The use of synthetic fertilisers is beyond the reach of many farmers due to the capital investment required. Further, some PICT states have banned the use of synthetic fertilisers to prevent groundwater contamination. However, a solution may be to adopt a micro-dosing strategy where small amounts of fertiliser are applied to move crops up the initial and steepest part of the yield-response curve (Okebalama *et al*., 2016). This may ensure economic returns, prevent off-site pollution and provide a feasible longer-term fertiliser management strategy.

There is a complex interplay between soil organic nutrient pool and crop yield. In Taveuni, farmer fertiliser trials have only shown yield responses to fertiliser applications in conjunction with fish meal relative to NPK applications only. Further mass balance soil C data from Taveuni indicate that large stocks of soil C have been removed from the surface soil. This points to the interaction of organic nutrient pool and crop yield and indicates that a more integrated response is needed to address all relevant macronutrients and micronutrients, and in particular, to rebuild stocks of soil organic carbon.

Rapid and cost effective soil and plant analysis

The need for efficient methods to quantify soil chemical properties at large scales is acute in many low-income regions such as Sub-Saharan Africa (Towett *et al.* 2015). Similar to Sub-Saharan Africa, the Pacific Island Countries have sparse, dated and inadequate data to guide soil fertility management and conservation strategies. Many Pacific Island nations do not have the capital to invest in the establishment of soil and plant testing laboratories and currently samples are either not collected due to cost or sent to an off-shore laboratory. Direct soil spectral methods developed by the Africa Soil Information Service (AfSIS) project (www.africasoils.net) and by SMCN/2009/031 hold promise for providing rapid low cost and reproducible soil characterization (Towett *et al.* 2015) for the Pacific Island Countries.

Spectroscopy in the mid-infrared range (i.e. wavelengths from 600–4000 cm^{-1}) can now be used to estimate soil physical, chemical, and biological properties with sufficient accuracy and precision for practical soil management. These properties include total and organic C, total N, cation exchange capacity (CEC), extractable Ca and Mg, clay content, sand content, Fe, K, P, S and soil pH. MIR instrumentation is cost-effective and with protocol development and training is a cost-effective approach to soil analysis.

Direct spectral methods have been used successfully on variable charge soils in Hawaii and Columbia (Bonett *et al.* 2016; McDowell *et al.* 2012). The AfSIS initiative has also used direct spectral methods and sampling protocols to develop methods for monitoring land and ecosystem health (Shepherd *et al.* 2015). Portable X-ray fluorescence has also been used to characterise soil and plant elemental content.

The development of rapid and inexpensive methods such as those above overcomes one significant barrier to improved soil nutrient management. One of the main causes of low use of fertilisers has been that the farmers do not know the fertility status of their farms and the majority are also not fully aware of various low-cost organic methods of maintaining the soil fertility of their farms (Nisha *et al.* 2015).

4.1.1 Knowledge Transfer

Soil information systems

The ITPS (2015) recognized that a key barrier to sustainable soil management in most regions is the lack of access to relevant information on soils. Some of the most important soil changes take place over decades and they can be difficult to detect, especially by unaided human observation. As a result, farmers, communities and institutions may not respond until critical and irreversible thresholds have been exceeded.

Dalal-Clayton and Dent (2001) reached a similar conclusion when they stated that while soil and land resources are prized by almost everyone, the paradox of ongoing and serious land degradation is largely due to ignorance rather than wilful neglect. Information counters ignorance but it needs to be provided in a way that recognizes the questions at hand, the economic drivers and the individuals involved. In short, expertise is needed to provide guidance and advice for a range of economic situations, not just maps and data.

The distribution and characteristics of the soils across the island nations of the Pacific are neither obvious nor easy to monitor. As a consequence, understanding whether a farming system is well-matched to the qualities of the soil requires some form of diagnostic system both to identify the most appropriate form of management and to monitor how the soil is functioning. Four important components of the diagnostic system necessary for sustainable land use and management are:

- an understanding of spatial variations in soil function (e.g. maps)
- an ability to detect and interpret soil-change with time (e.g. via soil testing, field experiments, long-term monitoring sites, environmental proxies)

- a capacity to forecast the likely state of soils under specified systems of land management and climates (e.g. through the use of simulation models);
- an understanding of the soil requirements of plants within the cropping system of interest.

At first sight it would appear that good soil information is available for most Pacific nations (often much better than in Australia). Soil surveys have been completed for most countries (Barringer et. al., 2006; Leslie, 2010) and these were intended to support better land-use planning and improve soil management. However, they have been under-utilized. There are a range of possible factors:

- the information is not directly relevant to farming (e.g. the maps show soil types or land capability classes rather than information on how soils function when farmed (e.g. specific nutrient deficiencies, guidance on erosion control))
- those doing the surveys did not always liaise closely with potential users and information products did not directly assist decision making (e.g. a key barrier being the use of excessive technical language)
- some of the most important types of information (e.g. nutrient availability) are difficult to measure and map
- most surveys were done on a project basis by teams from other countries (e.g. New Zealand, United States, France, Australia) but ongoing funding for curating and upgrading information systems has been lacking

Opportunities to improve soil information in the Pacific

The surveys and soil information noted above represents a large and prolonged investment by many organizations. On the basis of Leslie (2010), a conservative estimate of the investment by New Zealand indicates that approximately AU$20M was expended and this suggests the total amount for the Pacific would easily exceed AU$50M over several decades. It is highly unlikely that new programs of soil survey and monitoring will be undertaken to overcome the problems listed above. However, there is a significant opportunity to reanalyse much of the 'legacy data' and take advantage of some of the new technologies that have arisen from the digital information revolution. This could involve the following.

- Upgrade conventional field and laboratory measurement systems with readily deployed proximal sensing technologies that can be used to directly diagnose the status of crops and soils. This is in line with the ACIAR soil health project which recommended that provision should be made to ensure that the farmers' soils are tested and test results are conveyed to them in a meaningful way (Nisha *et al*., 2015). A key issue identified was an urgent need to improve awareness among the farmers about the soil fertility management practices. Furthermore, research experiments should be carried out on farmers' fields with combined efforts of both the farmers and researchers, to ensure that the researchers are able to combine farmers' traditional knowledge and experience into their modern research techniques to evolve the best farm management practices.
- Reanalyse and repackage the legacy information collected by the soil surveys and deliver integrated land resource information via web-services (rather than physical maps and reports) to government extension officers, agri-businesses and other decision makers.
- Use cloud computing to overcome infrastructure barriers in national agencies and take advantage of the sophisticated analytical systems provided by service providers in the geospatial industries (e.g. Google Earth Engine).

Much of the legacy information resides in government hard copy data, soil reports and scientific publications which are neither easy to obtain, nor easily interpreted by agricultural extension officers and farmers. Local data needs to be incorporated where available. For these reasons, reanalysis and repackaging via a ‘Pacific Soil Portal’ has been proposed as a solution to the soil information problem (Barringer *et al*, 2006; SPC, 2008a) and considered to be required (SPC, 2008b). The main functions that would assist agricultural extension officers and farmers are those that would enable:

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

5 Regional Priorities

Soil experts from 12 Pacific countries met in Suva, Fiji in October 2014 and again in Nadi, Fiji Dec 2015 to review the soil problems and opportunities across the region. They identified the following priorities for action:

1. Share and develop appropriate soil management solutions noting the particular challenges for atoll islands
2. Increase soil literacy
3. Build local and regional capacity, grounded in the appropriate cultural context
4. Design efficient and effective methods for soil analysis that are locally appropriate and robust
5. Enhance coverage of soil information and collate new and legacy soil data into more useable forms.
6. Ensure soil information security to protect regional data assets against loss
7. Share capacity including laboratories, portals and extension resources.
8. Research should occur on volcanic islands, raised atolls with ash and calcareous soils and atolls with calcareous soils.

The meeting concluded that large improvements in plant nutrition and soil fertility should be possible but it will require a collaborative effort across the region using emerging networks such as the Pacific Regional Soil Partnership (affiliated with the Global Soil Partnership) and Pacific Islands Rural Advisory Services (PIRAS). However, a prerequisite is to examine the underlying causes of poor soil fertility, identify the solutions and overcome the barriers to adopting agricultural practices that build farm resilience.

The group proposed that a nutrient management investigation be untaken and that the main sites for the proposed work be located in Taveuni, Fiji (volcanic island, ash and basaltic soils), and Tonga tapu, Tonga (raised atoll, volcanic ash and calcareous soils), with the satellite sites in Samoa (volcanic island, ash and basaltic soils) and Kiribati and Tuvalu (atoll, calcareous soils). This would cover the following taro export production systems:

- Taveuni *Colocasia esculenta* production system;
- Tonga tapu *Xanthosoma sagittifolium*; and
- Samoa *Colocasia esculenta* production system.

On Kiribati and Tuvalu, *Colocasia esculenta* production systems are of minor extent.

As stated at the outset, taro is culturally important across the PICTs and is therefore a key crop for understanding soil fertility. The different sites listed above are representative of island types and environments that are widespread across the Pacific Island taro growing communities and would make the findings generally applicable.

6 Soil nutrient work in PICTs

There have been more than 30 years of research undertaken in the region by Pacific Island, Australian and New Zealand governments. This includes a significant program of soil survey across the region by NZ DSIR (estimated value $AU20-50M) and detailed studies of soil formation, soil nutrition and contaminants involving Australian (e.g. the large body of work by Professor John Morrison (University of Wollongong, formerly University of the South Pacific (USP)) and various ACIAR projects) and Pacific Island organisations (for example SPC, USP).

The following ACIAR soil-related projects have been undertaken

1. FST/9114 and FST/9685 identified N, P, K, S, B and Zn deficiencies in forestry plantations the volcanic islands Fiji (Viti Levu), Solomon Islands (Kolombangara) and Samoa (Upolu and Savai'i); and the atoll Island Niue (Vaiea).
2. Developing cleaner export pathways for Pacific agriculture commodities HORT/2007/118
3. Towards a sustainable oil palm industry in Papua New Guinea FR2009-47
4. Overcoming magnesium deficiency in oil palm crops on volcanic ash soils of Papua New Guinea FR2009-11
5. Analysis of nutritional constraints to cocoa production in Papua New Guinea FR2009-09
6. E T Craswell, C J Asher & J N O'Sullivan (eds) (1996) Mineral deficiencies in root crops ACIAR PR065
7. Diversification of seaweed industries in Pacific island countries FIS/2010/098
8. Accelerating economic development through engagement and development of local industry institutions in Pacific island countries FR2011-09
9. Identifying pilot sites and research methods for soil health research in the Pacific region FR2011-03
10. Improving soil health in support of sustainable development in the Pacific SMCN/2009/003
11. Management of animal waste to improve the productivity of Pacific farming systems SMCN/2001/038
12. Improving soil health, agricultural productivity and food security on atolls SMCN/2014/089
13. Diagnosis and correction of nutritional disorders of yams SMCN/1998/028
14. O'Sullivan J.N. 2010. Yam nutrition: nutrient disorders and soil fertility management. ACIAR Monograph No. 144. Australian Centre for International Agricultural Research: Canberra. 112 pp.
15. Understanding the responses of taro and cassava to climate change HORT/2012/011
16. Implementing sustainable soil management in the Pacific to achieve improved crop yields and resilience to climate change SMCN/2016-252
17. Asher C., Grundon N. & Menzies N. 2002. How to unravel and solve soil fertility problems. ACIAR Monograph No. 83. Australian Centre for International Agricultural Research: Canberra. 139 pp.
18. Webb M.J., Reddell P. & Grundon N.J. 2001. A visual guide to nutritional disorders of tropical timber species: *Swietenia macrophylla* and *Cedrela ordorata*. ACIAR Monograph No. 61. Australian Centre for International Agricultural Research: Canberra. 178 pp.

19. O'Sullivan J.N., Asher C.J. & Blamey F.P.C. 1997. Nutritional disorders of sweet potato. ACIAR Monograph No. 48. Australian Centre for International Agricultural Research: Canberra. 136 pp.

20. Nelson P.N., Webb M.J. et al. 2010. Environmental sustainability of oil palm cultivation in Papua New Guinea. . ACIAR Technical Report No. 75. Australian Centre for International Agricultural Research: Canberra. 66 pp.

All of these projects have investigated nutrient deficiencies in cropping systems and established "best-bet" solutions to alleviate constraints. In the majority of projects there has been a strong focus on improving the organic carbon status of the soils to improve crop nutrition. All of the projects have successfully identified constraints to individual cropping systems but barriers still exist that are preventing uptake and utilisation of the research findings. It is clear from past projects that good project management and close collaboration with industry and growers is a pathway to success. For example, FST/9114 successfully changed nursery nutrition strategies and FST/9685 changed management of bark by Kolombangara Forest Products Ltd, Solomon Is, through strong interaction between project and senior company staff; FR2009-11 & FR2009-09 were successful because of close association with the industry; HORT/2007/118 was not successful because of changes of staff in the project team, which resulted in poor management; and SMCN/2009/038 was successful because of close association of project staff with a farmer group in Taveuni.

It is also clear from the past work that any future projects will need to:

1. identify barriers that have prevented the uptake and utilisation of the previous research findings to ensure a clear pathway to impact;
2. quantify nutrient budgets within key soil types and use this as a basis for generalisation across the landscape (e.g. through improved recommendations on crop nutrition that are delivered via the soil portal);
3. focus on iconic taro and it's production system to improve impact and highlight the importance of soil knowledge in nutrient budgeting and farm management;
4. use rapid assessment techniques to measure soil chemical properties and plant nutrients;
5. work closely with growers, industry and government; and
6. have a strong and stable project team with excellent leadership and high quality management.

The three recent and current ACIAR projects (Hort/2012/011, SMCN/2014/089 and SMCN/2009/003) have demonstrated the importance of taro production in the Pacific Islands and future work should substantially widen the impact of these projects. This could include:

1. utilizing the results from these project trials and related the data on soil types within the soil portal to allow generalization of research findings to other similar areas;
2. collecting data relating to nutrients and hydraulic properties to improve the predictive capability across a range of soil types of the taro production model (Hort/2012/011).
3. focusing on taro production in both mono- and mixed-cropping systems building on the valuable knowledge from Hort/2012/011, SMCN/2014/089, SMCN/2009/003 and ASEM/2008/036;
4. undertaking crop management based on the findings of Hort/2012/011, SMCN/2014/089 and SMCN/2009/003; and
5. assessing soil biological function.

7 Proposed avenues for future research

Comprehensive nutrient budgeting and the benchmarking of 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 longer-term outcome of the project is to solve this problem and ensure that soil knowledge is enhanced to provide a reliable foundation for sustainable intensification of agricultural systems

To this end, the following soil research questions were identified at the Pacific Regional Soil Partnership Meeting (Nadi, December 2015) and the Volcanic and Atoll Soil Workshop (Nadi, August 2016).

Research questions

1. What are the barriers to adopting improved nutrient management systems?
2. What are the budgets for key nutrients (N, P, K, S, Cu, Fe Mn B, Zn, and Ca) 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?

8 Impact Pathways – from research outputs to development impact

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) one key issue facing growers is the lack of knowledge about the nutrient status of the soil and the crop requirements (Sharma 2016). Addressing this problem requires an understanding of nutrient balances in the overall farming system and particularly at the scale of the island and country. The quantification of national nutrient balances for key crops will highlight issues about soil nutrient management where governments and the agricultural sector need to intervene. It has been identified that food imports are increasing across the PICTs and perhaps there are enough nutrients imported with this food to offset soil nutrient decline.

To improve soil knowledge, any future work must build on the existing and proposed body of research to develop a soil portal that will provide growers and extension officers with spatial information on soil conditions and the most appropriate options for managing soil and crop nutrition. This is the digital soil knowledge repository. Evidence from Australia and New Zealand shows that digital repositories have been critical factors in improving farm management and they have helped to develop a new farm support sector. While the PICTs are in a different stage of agricultural development, the portal will deliver guidance on soil management that is tailored to local needs. Currently, soil information is held in hardcopy reports that are effectively inaccessible to growers, extension officers and researchers. A soil portal will enable individuals to access data and nutrition information via maps (similar style to Google Maps). This can be accessed 'on the go' if there is internet-access or downloaded to a phone/tablet or printed to provide information to individuals seeking advice. The system also allows geo-located data and geo-located advice to be uploaded. Essential soil knowledge will be expanded by opening access to the vast amounts of legacy information collected in the PICTs.

A key limitation in the development of soil knowledge and wisdom is the availability of tools to measure soil nutrient status and techniques to quantify nutrient flows at the farm, region and island scale. The utilisation and building of human capacity to use tools such as mid-infrared and portable XRF to rapidly quantify soil nutrient status would be a significant step forward. Other in-field tests (for example soil respiration) could be used as well by soil extension officers in conjunction with growers to examine soil health and function. The calculation of nutrient flows and nutrient management within the taro farming system should be done via an "education community" in which the participants learn through measurement and quantification.

Any future work should be centred on the taro production system because of its cultural significance and importance for food security across the PICTs. In Tonga, Fiji and Samoa it is also traded domestically and internationally providing valuable farm income. Improving soil knowledge and hence soil nutrient management is key to improving yields. The cultural significance of taro makes it an ideal means for promoting the importance of soil nutrient management and crop production.

9 Conclusions and recommendations

It is apparent that soil nutrient management and knowledge in the agricultural systems of the Pacific needs to improve. There is clear evidence that fertile soils are being mined of nutrients and various barriers are preventing farmers from utilising fertilisers. These barriers need to be understood and overcome to ensure the success of strategies to improve soil fertility. Comprehensive nutrient budgeting is essential for diagnosing soil nutrient issues and it needs to become a normal part of agricultural practice on volcanic islands and coral atolls. Once the stores and fluxes of all relevant elements have been identified, effective organic and synthetic fertiliser management plans can be developed.

An initial priority is to stabilize systems where excessive fertiliser has been applied to maximise yields but the result has been significant export particularly into the groundwater systems. This should include situations where the application of organic residue may still result in the export of nutrients to groundwater. Further work also needs to be undertaken to identify the appropriate management practices for both organic and synthetic fertilisers in the region.

A second priority is to improve soil information delivery and ensure better linkage with agronomic information. Integrated soil-crop management systems are needed to provide growers and extension officers with the tools and knowledge needed to improve yields.

Finally, new measurement techniques and rapid assessment tools make it possible for growers and extension officers to measure nutrient and water fluxes directly in the field and rapidly analyse soil nutrient status to improve management decisions. These techniques and tools need to be tested and deployed as soon as possible.

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12 Publications

At present one publication has been developed from this work and the material presented in this report.

Macdonald et al (unpub). Soil nutrient management in the Pacific Island Countries and Territories.

Journal of Regional Environmental Change or Soil Research