Development of sustainable nutrient management strategies for taro growers on Taveuni Island, Fiji.

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Abstract

Taro (*Colocasia esculenta*) is a major component of the socio-cultural, dietary and economic livelihood of Pacific Island countries, including Fiji. However, Fiji's total taro exports have substantially declined over the last decade, mainly due to a reduction in production from Taveuni Island. A trend of decreasing taro yields has been further exasperated by recent extreme climate events, which have reduced the availability and affordability of planting material. The combination of lower yields and increased costs have reduced farmers' returns on existing farmland, which has contributed to further deforestation of forest reserves. The overall aim of this study was to develop improved nutrient management practices on existing farmland, to help growers to achieve sustainable taro yields and financial returns.

This study included a survey of 73 taro farmers, which included a quantitative analysis of taro yields and soil fertility. Fresh taro corm yields were very low, 6.9 t/ha. About 75% of the farms surveyed had low soil Olsen phosphorus (P) levels of < 10 mg/kg and 65% had low soil exchangeable potassium (K) levels of < 0.4 me/100g. Fertiliser nutrient inputs were also low, with semi-commercial farmers using an average of 31 kg nitrogen (N), 17 kg P and 27 kg K/ha, and commercial growers using an average of 41 kg N, 26 kg P and 40 kg K/ha per crop. The survey also identified that fertiliser placement and application timing practices may also reduce nutrient use efficiency by the crop.

Two successive field experiments were repeated over three sites, on Taveuni Island, to evaluate a range of nutrient management strategies to improve soil fertility and taro productivity. When no N and P fertiliser was applied, average fresh taro corm yields were very low (6.2 t/ha), irrespective of even K and sulphur (S) fertiliser inputs. The addition of up to 200 kg N/ha and 120 kg P/ha, resulted in substantial yield increase to 14.9 t/ha. Taro yields were also responsive to K fertiliser use, with significant increases in yield up to 200 kg K/ha, the highest rate of K assessed.

There was a strong linear relationship between N fertiliser use and taro sucker population up to 300 kg N/ha. In the second experiment, sucker numbers increased with increasing N fertiliser rate up to 280 kg N/ha. Further increasing N rates up to 360 kg N/ha did not further increase sucker production. When no fertiliser was applied, the average taro sucker

population across the three sites was about 20,500 suckers/ha, which increased to about 122,500/ha at 280 kg N/ha. The response of sucker numbers to N was not influenced by P fertiliser use, but there was a small effect with increasing K fertiliser rate, from 100 to 200 kg K/ha. Following natural disasters, when sucker numbers are limited, the use of N fertiliser may be an effective short-term strategy to help re-establish the taro industry and minimise inflated sucker prices. The use of the legume Mucuna, as a green manure crop intercropped with taro, reduced N fertiliser requirements. Mucuna provided a benefit, for both corm yield and sucker numbers, equivalent to N fertiliser applied at a rate of approximately 80-100 kg N/ha. Some of the benefit may also be due to improved weed suppression and a mulching effect from Mucuna.

Mixing P fertiliser in the planting hole increased corm yields by 38%, compared to the when P fertiliser was placed at the bottom of the hole. Despite the high rates of P fertiliser used in the first experiment there were no significant P carry-over effects on taro yields in the second experiment. This was due to the higher soil P status from P fertiliser application being confined in close proximity to the planting holes.

The Soil Plant Analysis Development (SPAD) chlorophyll meter was evaluated as being effective at predicting N status of taro crops and yield potential when other major nutrients were non-limiting. When SPAD readings were greater than 65, at 8 and 12 weeks after planting (WAP), then the taro yields were mostly high (i.e. > 12 t/ha). SPAD readings less than 40, at 8 and 12 WAP, would indicate that plant N status is likely to limit taro yield and that a review of N fertiliser use is required.

The recommended nutrient management strategy for taro farmers with farms with degraded soil fertility, involves the use of inter-cropping taro with a Mucuna green manure crop in combination with fertiliser at the following nutrient rates; 120 kg N, 120 kg, 200 kg K/ha and 80 kg S/ha. At current taro corm and sucker prices, this recommended strategy is expected to provide a net income of NZ$35,835, which is 247% higher than for the average grower practice. The recommended practice produces 74% more taro suckers than the current grower practice. Increasing sucker production is an important strategy to enable taro growers to increase production quickly following a natural disaster, helping farmers be more resilient to the effects of Climate Change.

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Chapter 1 Introduction

1.1 Reasons for the study

Root crops are the mainstay of food consumption in many countries. Taro (*Colocasia esculenta*) is an important staple food crop grown throughout many Pacific Island countries, parts of Africa, Asia and the Caribbean (Akwee *et al*., 2015). Its corms, cormels, leaves, stalks and inflorescence are all consumed. It is the fourteenth most consumed vegetable worldwide (Lebot and Aradhya, 1991). Taro is a vegetatively grown root crop species belonging to the monocotyledonous family *Aracae* (Figure 1.1). It originated from south central Asia, probably in India or the Malay Peninsula and has been dispersed since then by various means (Purseglove, 1972).

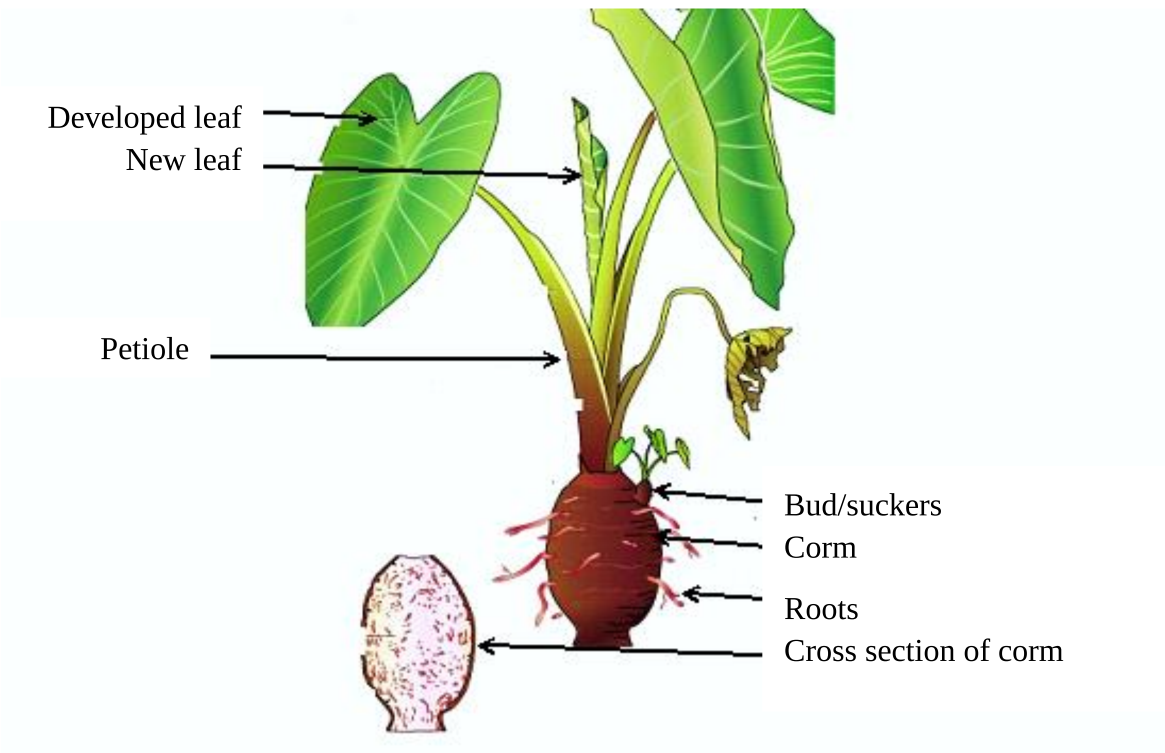


Figure 1.1 Showing components of a Dasheen type taro

Taro is a major component of the socio-cultural, dietary and economic livelihood of Pacific Island countries (Onwueme, 1999, He *et al.*, 2008). It is a highly nutritious food that is rich in carbohydrates, protein, vitamins and minerals (Vishnu *et al*., 2006). The socio-cultural importance of the crop has created the export market for the commodity to New Zealand, Australia and United States of America, where the consumers are often migrants from smaller Pacific Island countries (Onwueme, 1999).

Fiji, Solomon Islands, Samoa, Kiribati and Tonga produced 49,271, 45,925, 25,115, 1,925 and 3,264 tonnes respectively in 2014 (FAOSTAT, 2020). Pacific Island countries export up to about 12,000 tonnes of taro annually of which 95% originates from Fiji (FAOSTAT, 2020). It has been estimated that Pacific countries have the potential to double their exports if the product can be made more competitive in terms of quality and price (SPC, 2011). Fiji is ranked as the 18th largest taro producer in the world (FAOSTAT, 2018), and is the 4th largest exporter of fresh taro globally after China (ITC, 2020).

For centuries taro has been a staple diet for Fijians, however, its cultivation as a highly significant export crop only began in 1993, after the taro leaf blight caused by the fungus *Phytophthora colocasiae* devastated the taro industry in the neighbouring country of Samoa (McGregor, 2011). Fiji was able to replace the production drop from Samoa and was soon supplying the same variety of taro internationally. There are mainly two groups of taro: the Eddoe type, which has a relatively small central corm surrounded by large well developed cormels (*Colocasia esculenta* var. *antiquorum*) and the Dasheen type, which has a large central corm and numerous small cormels arising from its surface (*Colocasia esculenta* var. *esculenta*). The main varieties of taro exported from Pacific Island countries are the Dasheen type and are characterised by the white and pink types of taro. The pink taro, commonly known as Taro Niue in Samoa and Tausala-ni-Samoa in Fiji, is preferred in Samoa, having a unique taste, firm texture and longer storage life. (Mcgregor *et al*., 2011).

Taro is third most important economic crop after sugar cane and coconuts in Fiji. Fiji's total taro exports reached its peak in 2007 of 12,000 tonnes and started to decline over subsequent years (Figure 1.2). In 2010 the country was struck by Cyclone Thomas leading to significant losses sustained by the industry. The government provided fertiliser assistance to help recovery of the industry and this led to the increase in production and exports in 2011, however, once this assistance ended, Fiji's total taro exports subsequently declined to 5,166 tonnes in 2018 (Ministry of Agriculture, 2019).

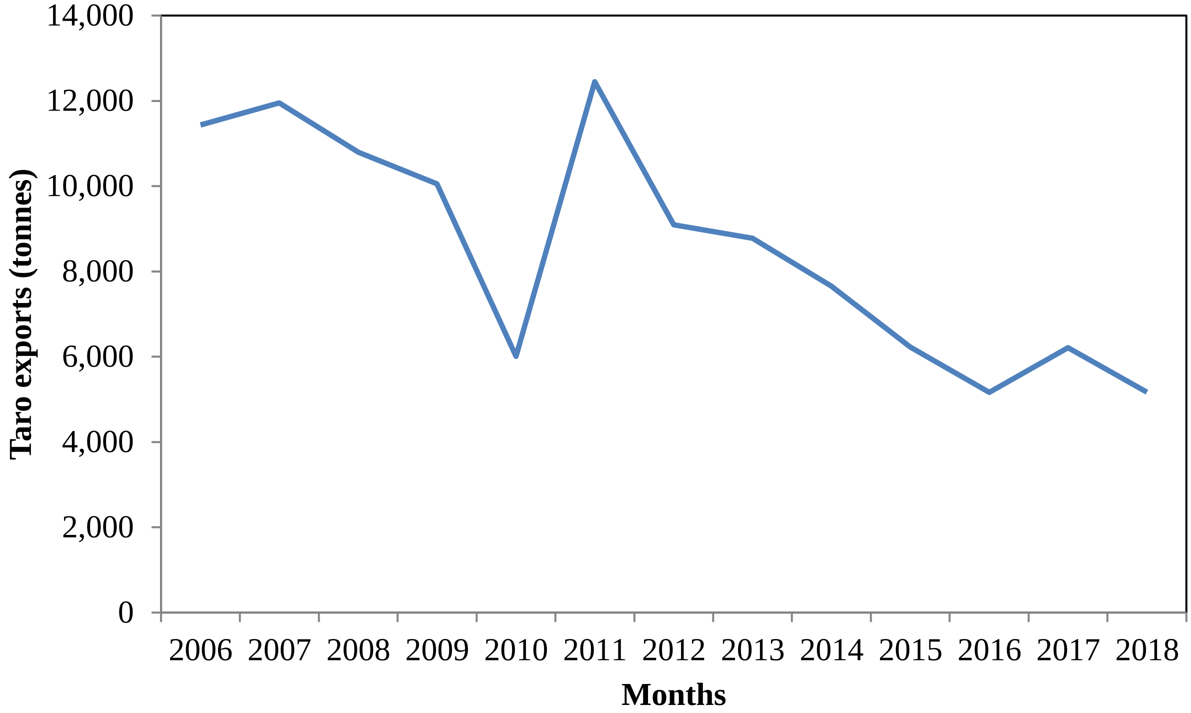


Figure 1.2 Fiji's Taro Exports (Source: Fiji Bureau of Statistics, 2018)

Taveuni Island produced 70% of Fiji's total exportable taro until 2011. Taveuni is the third largest island in the group with 470 km^2 of land area (Fiji Government Online Portal, 2009). The climate is typically oceanic with the southeast trade winds prevailing. The hot, wet months are from November to April and the annual rainfall ranges from 2,400-4,500 mm (All Fiji, 2011). Figure 1.3 shows export taro production in Taveuni from 2004 to 2019, which has fluctuated from 8,167 tonnes to 1,414 tonnes over this period. Taveuni taro production for the export market reached its peak in 2007 of 8,167 tonnes, remained relatively constant until 2014 and started to decline to 1,414 tonnes in 2016 (Ministry of Agriculture, 2019). In 2018, Taveuni only produced 30% of Fiji's export taro. The export industry requires that the weight of taro corms be between 1-3 kg, but currently about 40% of the product from Taveuni is below this minimum standard. With the increase in demand for exports, the number of taro growers in Fiji increased from 900 in 1994 to 3,600 in 2009 (Ministry of Agriculture, 2015). Farmers are increasingly, either continuously mono-cropping the same piece of area, or expanding agricultural activity on to marginal land.

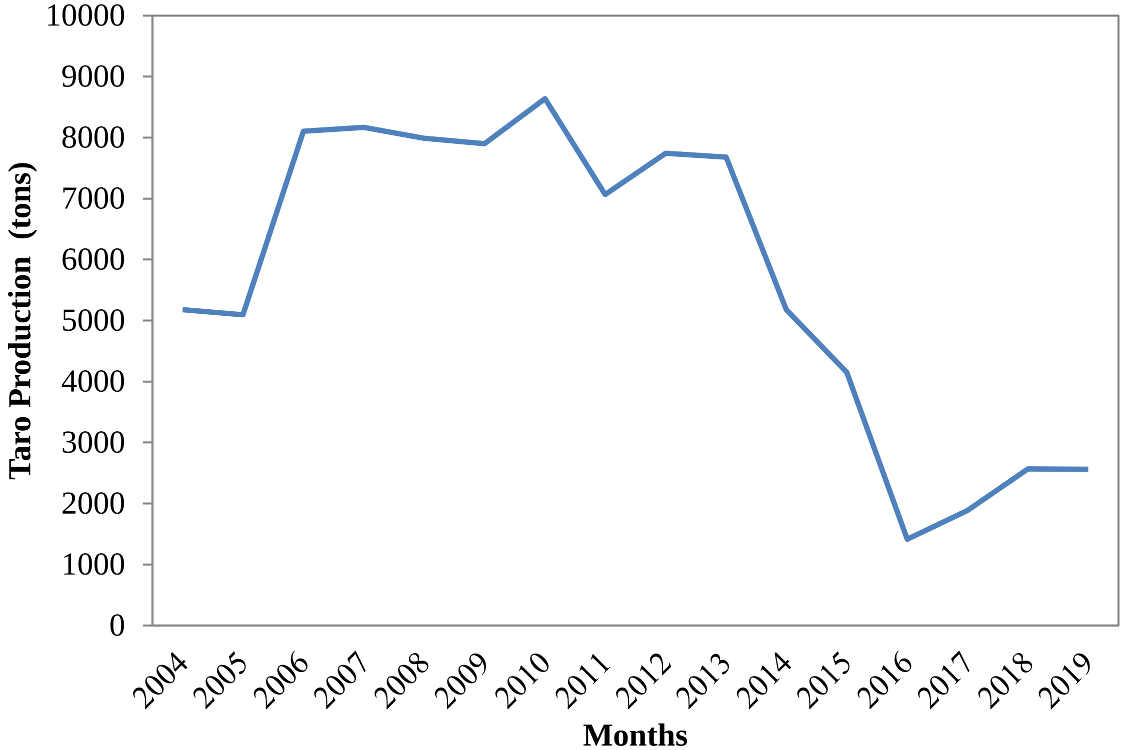


Figure 1.3 Export taro production on Taveuni Island (Source: Ministry of Agriculture, 2015)

There are three forest reserves in Taveuni (Figure 1.4); Taveuni Forest Reserve with 11,160 hectares of land, Ravilevu Nature Reserve with 4,108 hectares of land and Bouma National Heritage Park with 1,417 hectares of land (Fiji Nature Conservation Trust, 2015). These reserves support a wide diversity of native tree species and are conserving sensitive resources, such as steep slopes, fragile young volcanic soils and habitat for rare endemic and native flora and fauna species. The largely untouched rainforest ecosystem on the island of Taveuni contains several known species of palm, ferns, orchids and other plants that cannot be found anywhere else in the world, including the rare Tagimoucia flower (*Medinilla waterhousei*), a species of flowering plant in the family Melastomataceae endemic to highland rainforest of Taveuni. The forest reserves protect more than 100 streams and four rivers. However, current trends of widespread soil degradation on the island and the increasing demand for fertile agricultural land mainly for taro (*Colocasia esculenta*) and yaqona (*Piper methysticum*) production is threatening this forest reserve (SPC, 2015). An assessment of these forest reserves by the Secretariat of Pacific Community in 2015 showed that farmers are encroaching into forest reserves to get short term yield gains without realising the negative consequences of their activity on the environment (SPC, 2015). They warned that encroachment of farming activities into forest reserves will continue unless sustainable farming practices are developed to maintain higher yields in their existing farms.

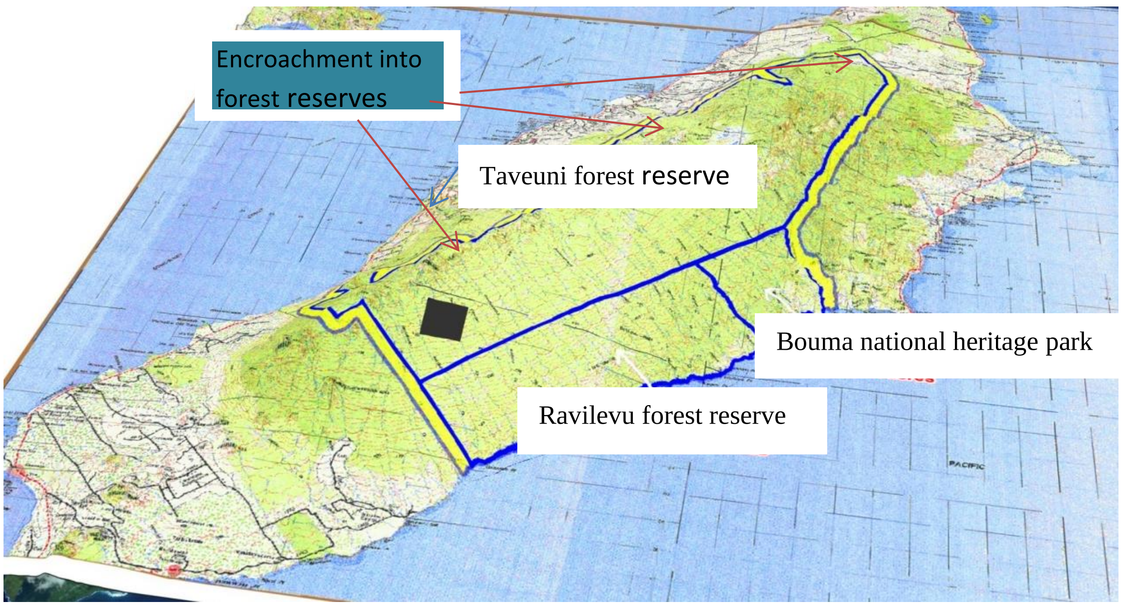


Figure 1.4. Taveuni forest reserves

In the Asia Pacific region taro leaf blight (*Phytophthora colocasiae)*, taro beetle (*Papuana huebneri*), soil fertility, scarcity of planting material, post-harvest handling and limited research all contribute to low crop productivity (Global Forum for Underutilised Species, 2009). A study undertaken by Dr Richard Markham of the Australian Centre for International Agricultural Research confirmed that there is a declining trend in soil fertility in the taro growing areas of Fiji (Ministry of Agriculture, 2009). Nutrient loss through exports of taro corms and soil erosion is a major problem affecting the sustainability of the system.

Taro yields differ greatly according to cultivar, climatic conditions, crop duration, management practices and soil fertility. Management practices such as size of planting material, variety, weed control, number of suckers, type of planting material and population density influences taro yield (Tsedalu *et al.*, 2014). Research conducted in different parts of the world has proven that under intensive commercial cultivation taro yields of > 20 t/ha can be achieved (Goenaga and Chardon, 1985; Silva *et al*., 1992; Daniells *et al.,* 2009). In the Pacific typical high yields range from15-30 t/ha (Daniells *et al*., 2009; Sivan, 1981). In Fiji, yields as high as 25.6 t/ha have been recorded in research fields (Sivan, 1981), but yields of 7 t/ha are more typical (Ministry of Agriculture, 2015).

This research will focus on developing sustainable nutrient management strategies for taro growers on Taveuni Island. This envisages the use of fertilisers in combination with a legume-based green manure crop with the objective of improving soil fertility and sustaining optimum yields.

1.2 Hypothesis

Degraded soil fertility is a prominent limiting factor influencing low taro yields on Taveuni Island, Fiji. Improving soil fertility, through developing and evaluating improved nutrient management practices that are specific to soils and farms on Taveuni Island, will improve taro yields and growers' financial returns.

1.3 Aims and Objectives of the Research

The aim of this research is to develop a sustainable nutrient management practices to support taro growers on Taveuni Island, Fiji.
The specific objectives are:

1. To quantify current taro corm yields, cropping practices and soil fertility, through the use of a grower and soil fertility survey, to help identify and better understand which factors are affecting taro corm yields (Chapter 4).
2. To quantify the nitrogen (N), phosphorus (P) and potassium (K) fertiliser inputs required to achieve optimum taro corm yields on farms with degraded soil fertility (Chapters 5 and 6).
3. To evaluate the effect of different P fertiliser placement methods at planting on taro corm yields and spatial variability in soil P status (Chapters 5 and 6).
4. To evaluate the effect of different N fertiliser application timings (Chapters 5 and 6).
5. To quantify the effect of Mucuna green manure crop on reducing N fertiliser requirements and for weed control (Chapters 5 and 6).

6. To evaluate the use of liming on taro corm yields and the incidence of taro rot disease (Chapter 6).
7. To predict the taro plant status and corm yields by using a non-destructive method of chlorophyll measurement. (Chapter 7).

Chapter 2 Literature review

This chapter reviews literature on taro yield and related parameters. It summarises studies on taro planting density, nutrient uptake and removal, nutrient requirements, taro related research in Fiji, use of cover crops to improve yields and soil P building strategies.

2.1 Taro planting density

In taro the total corm yield increases with an increase in population but the individual corms became smaller as planting become denser (Villanueva *et al.*, 1991). Export market requires taro corms to be 1-3kg/ha so planting at optimum planting densities is vital. Sato and Silva (1990) did a study on upland taro spacing and fertiliser timing in Hawaii. Five plant spacing (30cm x 120 cm, 60 cm x120 cm, 30 cm x 90 cm, 30cm x 30 cm x 120 cm & 15 cm x 120 cm) and four fertiliser timing treatment (T1 basal application, T2 - 3 split application, T3 - 4 split application & T4 - 5 split application) were evaluated. All the four treatments received the same amounts of fertiliser (778 kg urea/ha and 704 kg potassium chloride/ha) but were applied at different times. The pre-plant soil pH was 6.12, P was 281 mg/kg and K was 0.18 me/100 g. The result showed that there were no differences between fertiliser timing treatments. The spacing of 60 cm x 120 cm, 30cm x 90cm and 30 cm x 120 cm produced a yields of 52.3 t/ha (1.8 kg/corm/plant), 69.6 t/ha (1.3 kg corm/plant) and 70.4 t/ha (1.16 kg corm/plant).

In Fiji, Sivan (1981) concluded that mean yield of almost 17 t/ha and average corm weight of 0.6 kg can be obtained at the spacing of 60 x 60 cm. This spacing produces optimum yields per unit area; however, corm weights are below export requirements (< 1 kg). A spacing of 90 cm x 90 cm yields 10.8 t/ha and produces corms above 1 kg. Most farmers use planting densities of 10,000 plant/ha.

2.2 Taro Nutrient uptake

There is huge variation in the researched nutrient uptake by taro corms, ranging from; 14-65 kg/ha, 4-12 kg/ha and 25-86 kg/ha for N, P and K, respectively (Anand, 2015; Hartemink and Johnston, 1998; Blamey, 1996). Nutrient uptake can vary between crop varieties, yield, nutrient availability, biomass produced and growth conditions. Anand (2016) stated there were significant differences in nutrient uptake by taro corms of two cultivars (Samoa 1 and

Samoa 2) as shown in Table 2.1. The number and size of tubers vary with cultivar. Planting date and fertiliser regime affect crop performance, regardless of whether the crop is a landrace or an improved cultivar. Hartemink and Johnston (1998) stated that fertiliser application had an effect on nutrient uptake by taro corms as shown in Table 2.1. Yield of root crops has been shown to be affected by water availability and temperature at different sites and planting dates (Hagman *et al.*, 2009). Time of planting, cultivar nutrient use efficiency and fertilisation of taro are, therefore, likely to be critical factors affecting crop performance in response to agronomic practices.

Table 2.1 Nutrient uptake by taro corms as studied by different authors.

Researcher	Corm fresh weight (t/ha)	Corm dry weight (t/ha)	N uptake (kg/ha)	P uptake (kg/ha)	K uptake (kg/ha)	Treatment type
Anand, 2016	13.6	5.8	65.1	9.3	41.9	Site 1 (Upolu)
Anand, 2016	10.2	4.7	51.2	7.1	29.9	Site 2 (Savaii)
Anand, 2016	8.1	4.0	40.6	4.7	22.6	Cultivar Samoa 1
Anand, 2016	10.0	5.3	61.7	9.40	37.3	Cultivar Samoa 2
Hartemink and Johnston, 1998	23.3	7.0	31.0	12.0	86.0	Fertilized taro (100 kg/ha N, 50 kg/ha P & 100 kg/ha K)
Hartemink and Johnston, 1998	8.0	2.5	13.0	5.0	42.0	Unfertilized taro (cultivar Nomkoi)
Blamey, 1996	8.0	2.4	14.0	4.0	25.0	

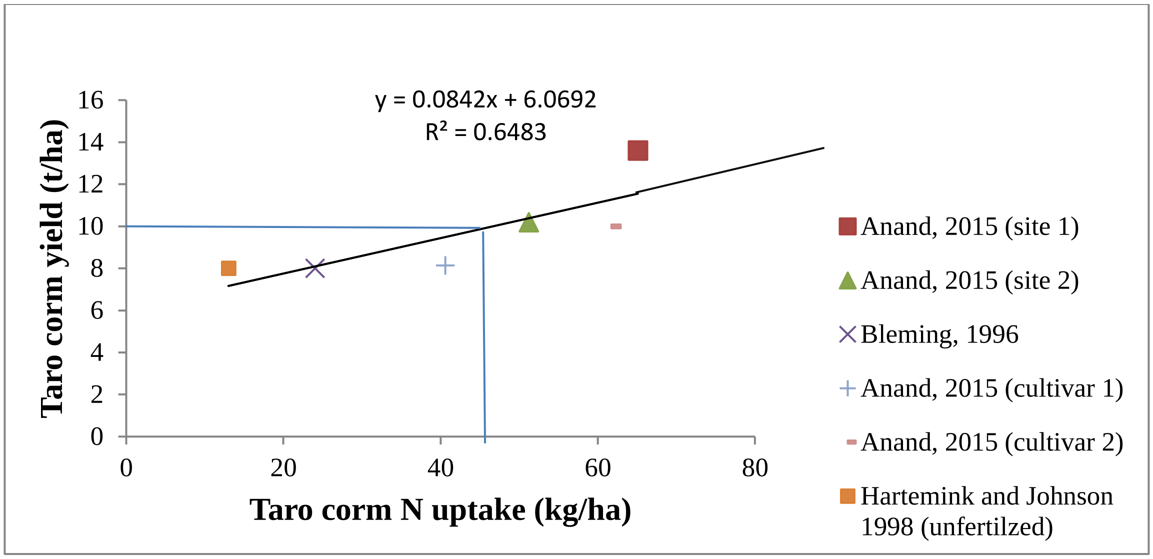


Figure 2.1 Influence of N uptake on taro yields

The relationship between N uptake and taro corm yield is shown in Figure 2.1. Nitrogen deficient taro plants have stunted roots, main shoots, and suckers (Miyasaka *et al*., 2002). Yellowing of the leaf blade starts in older leaves. As the deficiency progresses, all of the leaf blades turn yellow. Premature death of older leaves often results in fewer numbers of active leaf blades, which reduces growth and lowers crop yields. With the desirable yield of 10-15 t/ha, taro corms will be removing 46.7 - 106.1 kg N/ha from the soil at each harvest (7 month crop cycle).

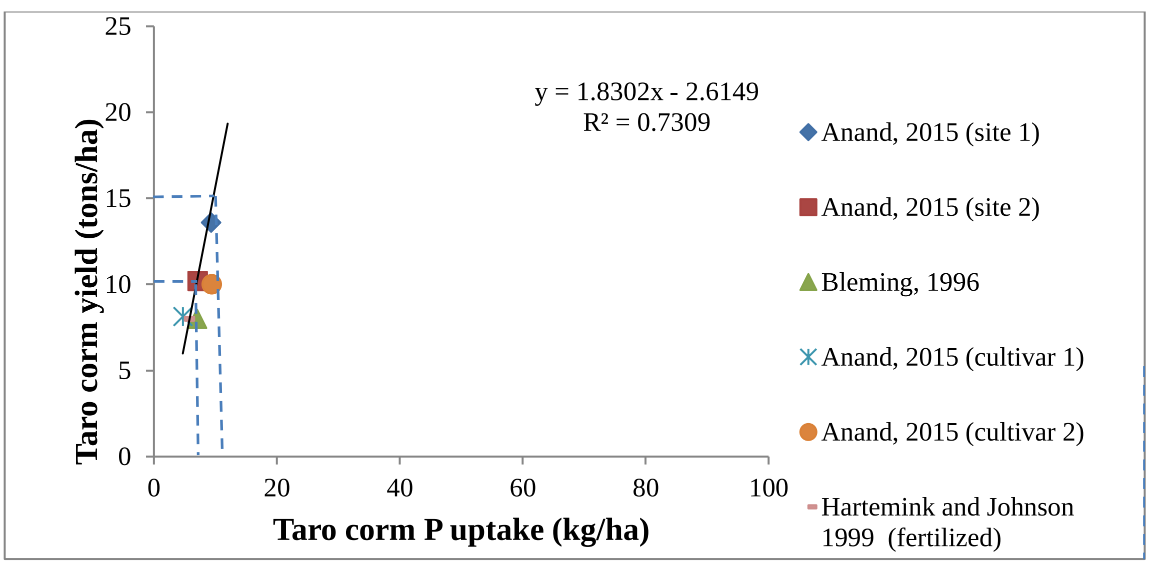


Figure 2.2. Influence of P uptake on taro yields

The relationship between P uptake and taro corm yield is shown in Figure 2.2. Phosphorus deficient taro plants have stunted root and shoot growth. Older leaf blades may appear darker green due to greater retardation of leaf expansion relative to chlorophyll (green pigment) reduction. As the deficiency progresses, areas of the leaf margins begin to yellow and turn brown (Miyasaka *et al*., 2002). Phosphorus deficiency is a critical nutrient-deficiency problem in many soils and may cause up to 29-45% yield losses depending on crop species and state of deficiency (Ahlawat *et al*., 2007). With the desirable yield of 10-15 t/ha, taro corms will be removing 6.9 – 9.6 kg/ha P from the soil at each harvest.

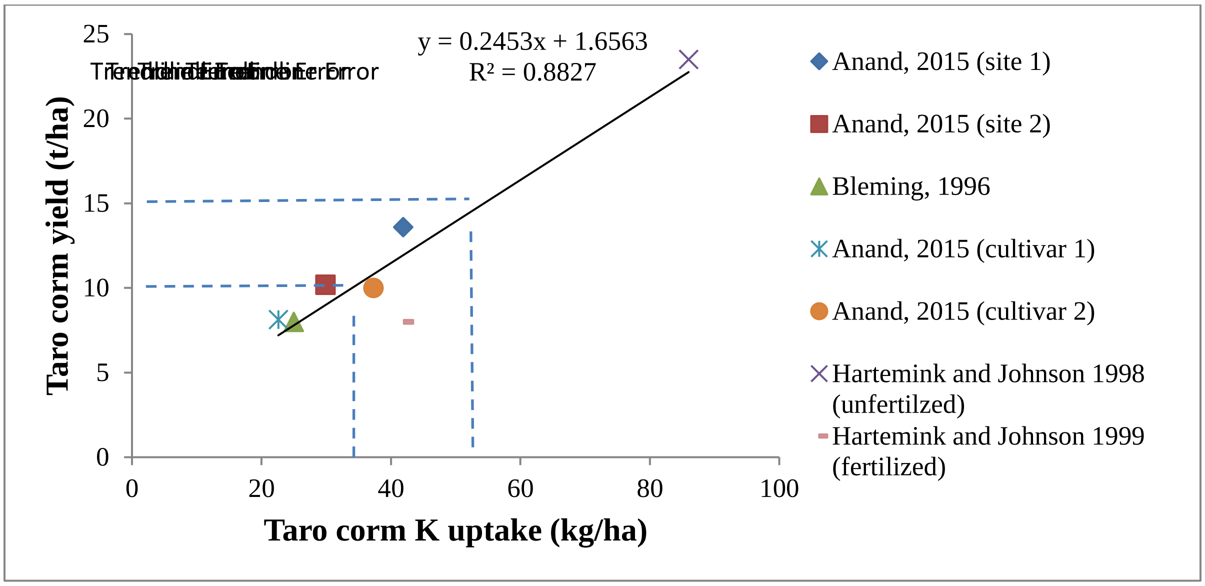


Figure 2.3. Influence of K uptake on taro yields

The relationship between K uptake and taro corm yield is shown in Figure 2.3. Taro has high demands for potassium, as large amounts of K are exported in the harvested corms. Potassium deficient taro are characterized by slower growth rate, increased tendency to wilt, reduced size of leaf blades, and interveinal or marginal "scorching"—a burnt appearance between the veins or around the leaf margins. As the deficiency progresses, the spots may coalesce, with the whole leaf turning yellow or brown. K deficiency can be addressed by improved diagnosis of K deficiency, and measures to conserve and replenish soil K reserves (Miyasaka *et al*., 2002). With the desirable yield of 10-15 t/ha, taro corms will be removing 34.0-54.0 kg/ha K from the soil at each harvest.

Estimates of overall efficiency of these applied fertilisers have been about 50% or lower for N, less than 10% for P and close to 40% for K (Baligar and Bennett, 1986). Previous studies on phosphate adsorption on Fiji soils have shown that significant quantities of added P are strongly adsorbed by soils, especially by the Al and Fe oxyhydroxide materials, and only limited quantities (10-30%) of fertiliser P are utilized by plants (Gounder *et al*., 2014).

Knowledge of physiological processes of taro growth, development and partitioning into yield components is necessary for optimising yield. The taro yield related components that contribute to growth and corm yield are leaf number, leaf length, leaf area, leaf area index, plant height and number of suckers. Yield components do not influence crop yield independently but are interrelated (Fageria *et al.*, 2007). Table 2.2 shows nutrient uptake and dry matter portioning by taro roots, leaves (as well as petioles) and corms at mid growing season (18 WAP) and at maturity (33 WAP).

Fiji grown taro is harvested at 7 months after planting. The plant is pulled out by hand and corms are separated from petioles with a knife. The corms are then manually cleaned from soil and roots in the field. Corms are packed in bags and exported off the field. Taro leaves, roots and petioles are left in the field as mulch. Within week's taro leaves and petioles decompose and release tied up nutrients back into the soil.

Table 1.2. Nutrient uptake and dry matter portioning by various plant parts

Parameters	Plant component	18 weeks after planting (WAP)	33 weeks after planting (WAP)
Fresh weight (t/ha)	Roots	10.42	4.53
	Corms	6.37	23.3
	Leaves and petioles	30.43	22.75
	Total	47.22	50.58
Dry weight (t/ha)	Roots	0.52	0.50
	Corms	1.21	6.99
	Leaves and petioles	2.13	3.64
	Total (t/ha)	3.86	11.13
Dry mater (%)	Roots	5	11
	Corms	19	30
	Leaves and petioles	7	16
	Total (t/ha)	31	57
N uptake (kg/ha)	Roots	8	5
	Corms	14	31
	Leaves and petioles	63	55
	Total (t/ha)	85	91
P uptake (kg/ha)	Roots	1	1
	Corms	2	12
	Leaves and petioles	9	18
	Total (t/ha)	12	31
K uptake (kg/ha)	Roots	25	23
	Corms	22	86
	Leaves and petioles	119	106
	Total (t/ha)	166	215

(Source: Hartemink and Johnston, 1998)

Crop nutrient uptake rates change throughout the growing season as the crop moves from emergence to vegetative growth, through corm formation stages, and on to maturity. To attain optimum yield, sufficient plant-available nutrients must be present where the crop can access them to meet crop demand at all stages through the growing season. However, if the nutrient is present in the soil for an extended time prior to crop uptake, it may move out of the rooting zone or be converted to unavailable forms. The right timing of nutrient application will support crop yield and minimize nutrient losses.

2.3 Growth stages

Root formation and rapid root growth take place immediately after planting, followed by rapid growth of the shoot until 6-8 weeks after planting (WAP) as shown in Figure 2.4. This phase is known as establishment (Figure 2.4). This is followed by a grand growth phases (vegetative growth) in which taro plants accumulate dry matter very rapidly reaching a peak at 22 to 24 WAP. Most fertiliser should be applied during the vegetative phase and should be avoided after 22-24 WAP. Shoot growth and total shoot dry weight show a rapid decline after about 22-24 WAP (Maturity phase). At this time, there is a reduction in the number of active leaves, a decrease in the mean petiole length, a decrease in the total leaf area per plant, and a decrease in the mean plant height on the field. All through the season, there is a rapid turnover of leaves; new ones are continually unfurling from the centre of the whorl of leaves, as the oldest ones die off. Corm formation commences at about 9-12 WAP; corm formation follows soon afterwards in cultivars that produce appreciable corms. By the 22-24 WAP when shoot growth declines, the corm become the main sink and grow very rapidly (FAO, 2006).

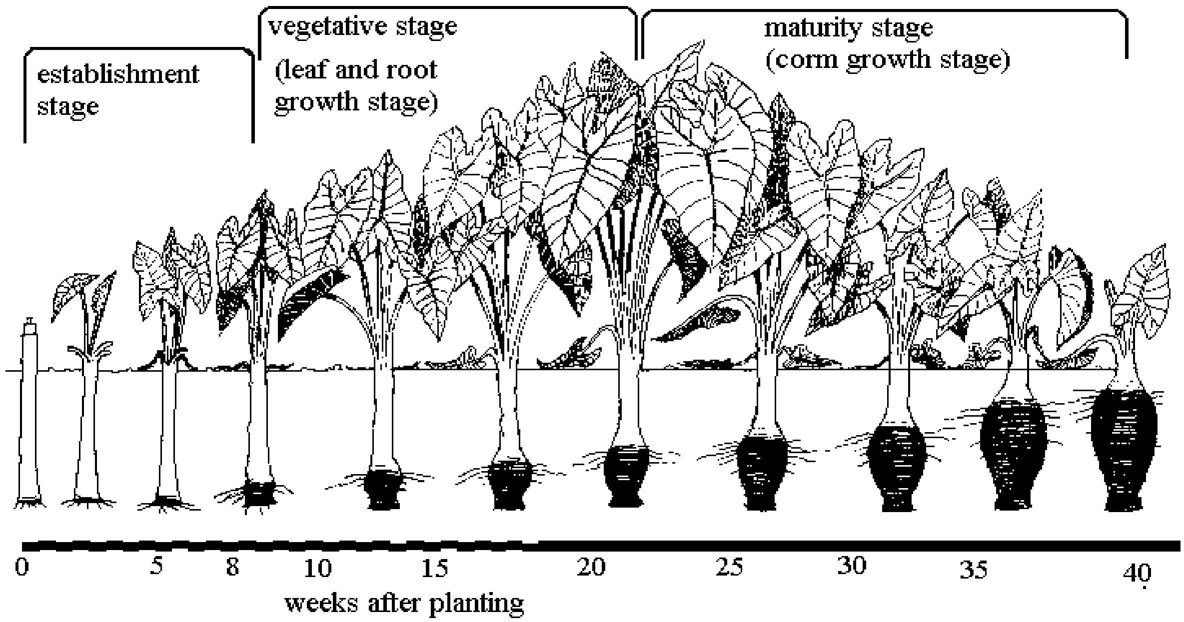


Figure 2.4 Taro growth stages **(Hartemink and Johnson, 1998)**

2.4 Deficiency and sufficiency nutrient ranges for taro

Adequate plant growth can be achieved within the sufficiency range for a nutrient whereas reduced yield will be evident in the deficiency range. According to Uchida (2000) the sufficiency and deficiency nutrient ranges for taro are shown in Table 2.3.

Table 2.3. Deficiency and sufficiency nutrient ranges for taro

Mineral element	**Deficiency range in leaves (%)**	**Sufficiency range in leaves (%)**
N	< 4.0	4.0-4.5
P	< 0.3	0.3-0.5
K	< 3.2	3.2-5.5
Ca	< 0.7	0.7-1.5
Mg	< 0.2	0.2-0.5
S	< 0.2	0.2-0.3

Nutrient removal differs between crops, time of sampling, crop part sampled, soil type, fertiliser applications, crop cultivars and dry matter content at sampling. Plant tissue analysis measures the elements in an "index tissue," a particular plant part determined by experimentation to be the most reliable indicator of the plant's nutrient status. For taro the index tissue is the "leaf number 2". The newly emerging leaf blade is counted as "leaf 0" and the first fully expanded leaf is counted as "leaf 1" (Miyasaka *et al*., 2002).

2.5 Response to fertiliser

Hartemink *et al*. (2000) did a study on N use efficiency on taro crop in Papua New Guinea. He used five levels of fertiliser N (0, 100, 200, 300 and 400 kg N/ha) in split applications (35, 62 and 120 DAP). In addition, 100 kg P/ha (triple superphosphate) and 250 kg K/ha (Muriate of Potash) was applied at 30 DAP. The marketable corm yields with 0, 100, 200, 300 and 400 kg N/ha were 5.8, 5.4, 6.4, 6.9 and 7.8 t/ha respectively. The non-marketable corm yields were 0.6, 1.1, 1.0, 1.5 and 1.4 t/ha respectively. When no fertiliser was applied, the total N uptake of taro was 32.0 kg/ ha of which 9.7 kg was taken up in the marketable corms. At 400 kg N/ha the total N uptake was 67.5 kg/ ha, of which 23% was taken up by the marketable corms. The efficiency by which the applied N was used (NUE) was low and fertiliser recovery was only 10%. The low N fertiliser recovery could be due to other nutrients limiting growth, the loss of N through leaching, the genetic potential of the cultivars used, or the unfavourable weather conditions. However, Manrique (1984) concluded that taro responds to N fertilization, but the response is limited to moderate N levels as levels beyond 120 kg N/ha often result in excessive top growth and reduced corm yield. Application of 100-120 kg. N/ha is sufficient to maintain 95% of maximum yield and only about 40-50% of N applied is recovered by the crop (Manrique, 1984).

Daniells *et al*., 2009 did fertiliser response studies in Australia and stated that 300 kg/ha N, 120 kg/ha P and 720 kg/ha K produced optimum yields of 33.71 t/ha. In their experiment treatment with 100 kg N/ha, 40 kg P/ha P and 240 kg K/ha; and 200 kg N/ha, 80 kg P/ha and 480 kg K/ha produced 31.07 t/ha and 32.59 t/ha taro yield, respectively.

2.6 Taro yield related research in Taveuni

Nisha (2015) surveyed 50 taro growers in Taveuni, Fiji using structured questionnaires. The farmers were targeted from 4 farming communities who were available at the 4 sites during the survey. She found that marketable taro yields ranged from 1.7 tons/ha to 4.4 tons/ha in the study area. In addition she collected and analysed soil samples (20cm depth) from 4 experimental sites. The soils were acidic with pH ranging from 4.6 to 5.5. The desirable pH for taro range from 5.6 to 6.6 (Duke, 1978). Most farms had low P levels (<15.83 ± 1.40 mg/kg Bray 1 P which is equivalent to <7.7 mg/kg Olsen P based on equation y = 0.1503x+5.3185 (Madeira, 2007)), low K levels (3 experimental sites had (<39.54 ± 4.61 mg K/kg or <0.1 ± 0.01 me/100 g) and low $NO3^{-}$-N (5-15mg/kg). For taro the optimum Olsen P range is > 20 mg/kg and optimum K is > 0.4 me/100 g (Thiagalingam, 2000).

Nisha (2015) stated that <20% of farmers used N, P, K fertilisers ranging from 102-518 kg N/ha, 62-210 kg P/ha and 72-232 kg K/ha respectively. The remaining farmers either used organic inputs such as compost (16% farmers use 1125 kg/ha), mulch fish meal (14% farmers use 500-792 kg/ha) and lime (18% farmers use 500-937 kg/ha) or did not use any fertilisers at all.

The survey revealed that 94% of the farmers interviewed have never had the soil on their farm tested. Fertilisers were applied either based on traditional knowledge or on their availability. Nisha (2015) concluded that that there is substantial gap between the nutrient demand of the farms and the nutrient supplied. There was an imbalanced and insufficient use of chemical and organic sources of nutrients and this was evident in the poor quality of taro corms produced in the island. She recommended that more research needs to be conducted on soil fertility management practices including organic and inorganic inputs. However, there was no random selection of farmers and this could have created some bias on the result. The taro yields presented in her research are quite low (1.7-4.4 t/ha) and this could be attributed to selection of large numbers of subsistence farmers during the survey. In addition questions were asked on how much elements such N, P and K were applied. Most farmers in Taveuni use blended fertilisers and their ability to recall quantities of individual nutrients being used may not be accurate.

Sharma (2015) analysed 20-year data on total taro yields and reject rates in Taveuni, Fiji. He identified a decline in mean taro yield from 3.5 kg/plant (35 t/ha) in 1994 to 0.9 kg/plant (9 t/ha) in 2013. In 1994, 20% of taro corms were classed as rejects due to oversized corms (> 3 kg corm), which are not accepted by the market. However, in 2013 reject rates had increased to 40% but this was due to under size corms (< 1 kg). The decline in taro yields can be attributed to the interactive response of deterioration of soil chemical, biological and physical properties, resulting from continuous mono-cropping and shorter fallow duration. Mean values of selected soil properties across Taveuni for soil pH was 5.67, Total Organic Carbon was 4.34, total N was 0.46%, Olsen P was 6.87 mg P/kg and Exchangeable K was 0.4 me/100 g (Sharma, 2015). There was a high proportion of farms with below optimum soil tests (0-20 cm) including soil pH (<5.6-6.6), 47.6% for total N (< 0.3-0.6%), 100% for soil Olsen P (< 20 mg P/kg), 78% for exchangeable K (< 0.4-0.8 me/100 g) and 53.3% for soil organic carbon (< 4-10%).

Together Nisha (2013) and Sharma (2015) identified P as the most limiting factor affecting taro yields in Taveuni, Fiji. Nisha (2013) also stated that soil pH for some farms are in the 4.6 to 5.5 range and this could also be a yield limiting factor. Both the researchers stated that mean K levels were ≤ 0.4 me/100 g indicating that exchangeable K could decline rapidly due to leaching and crop removals. Nutrient removal trials including N, P, K and raising soil pH above 5.6 should be a priority for sustaining taro yields in Taveuni, Fiji.

2.7 Cover cropping

Cover cropping is one method to sustain soil fertility. Soil cover is one of the most vital factors affecting the intensity and frequency of overland flow and soil erosion (Nunes et al., 2011). Cover crops have long been recognized to play an important role in sustainable agriculture due to their functions in preventing soil erosion, improving soil productivity, contributing nutrients to succeeding crops, and suppressing weeds (Adiele and Volk, 2011; Ramos et al., 2010). Soils under cover crops typically have higher levels of soil organic matter and increased nutrient cycling capacity (Ramos et al., 2010). Thus, the introduction of cover crops to replace the natural regrowth of fallow will result in efficient management of the cropping system. A leguminous cover crop can contribute to soil nitrogen, soil organic matter and improve crop yield.

Several authors have recommended Mucuna (*Mucuna pruriens*) as an improved cover crop for maintaining soil fertility (Ceballos *et al.*, 2012). Mucuna, commonly known as velvet bean or magic bean, is a vigorous annual climbing legume, which originated from southern China and eastern India (Carsky *et al.*, 1998). The plant belongs to the Fabaceae family which has about 100 species of annual and perennial legumes (Buckles, 1995). Mucuna has traditionally being used as a fallow crop to restore soil fertility, a cover crop to suppress weeds, and as a forage plant. Mucuna was first reported in Bali, Java, and Sumatra in the 17th century to recuperate worn-out fields (Burkill, 1966).

Buckles *et al.* (1998) described Mucuna as one of the best fallow crops based on the following characteristics:

- Very vigorous growth
- Non-palatability to cattle
- Shade tolerance
- High biomass production
- Low labour and chemical requirements for its establishment
- Easy establishment and low seed rate
- High drought tolerance
- Presence of allelopathic chemicals to enhance competitive ability against weed growth
- Tolerance to pest and diseases
- Good control against soil erosion

Lal (2013) did field trials in Taveuni, Fiji to study the influence of Mucuna fallow on selected soil properties and taro yields. He concluded that taro grown under Mucuna fallow significantly outyielded those grown under a grass fallow system by 33.5% (11.8 vs. 8.8 t/ha). Crop yields and N uptake following cover crops were reported to be usually greater with legume cover crops than with non-legumes or with no cover crop treatment mainly due to higher N supply by legumes. Mucuna fallow added 145 kg N/ha, 23 kg P/ha and 162 kg K/ha after 6 months of fallow duration. In addition, mulches from Mucuna residues increase soil moisture content and supresses weeds (*Carsky et al*., 1998).

Anand (2016) investigated the efficacy of six-month fallow effects of three contrasting cover crops (traditional weed cover crop), Mucuna (*Mucuna pruriens*) and Erythrina (*Erythrina lithosperma*) over four agro-ecological taro growing zones in Samoa. Results from his study indicated that all the fallow treatments significantly improved the soil active carbon stocks upon decomposition which, however, were largely dependent on the biomass production. Mucuna fallow contributed to the largest additions of biomass across all the agro-ecological sites and as such proved to be the superior cover crop with regards to improving soil active carbon, soil biological activity as well as the potentially mineralisable N pools. Mucuna fallows also resulted in significantly greater inputs of mineral N to the soil system and showed significant net mineralisation potentials over two of the sites. It also significantly contributed to the suppression of plant parasitic nematodes while enhancing the activity of free-living genera. Nutrient uptake and the corresponding yields of taro were comparatively higher under the Mucuna fallow, both with and without supplementation with complete mineral fertilisers. Taro yields under grass fallow, Mucuna fallow, Erythrina fallow and Mucuna fallow with 200kg/ha NPK fertilisers were 5.6-8.6, 7.6-11.7, 6.5-9.7 and 10.1-13.6 t/ha. The dry matter accumulation and nutrient uptake of the two taro cultivars revealed that the cultivars exhibited significant differences for the various nutrients with regards to their efficiency of utilisation towards production of a unit of edible dry matter. He stated that the effects of green manure cover cropping should also be applied to other crop and site specific situations, the comparative study between the methods of cover crop residue management systems, namely mulching and ploughed incorporations also needs to be determined, comparative economic analysis of fallow cropping systems is highly recommended and future researches need to investigate the comparative effects of other proven short term and practical best-bet leguminous systems for fallow purposes for Samoa soils.

2.8 Soil-based P management strategies

2.8.1 Traditional approach: Yield response to fertiliser dose

The analysis of yield response to P fertiliser is based on field experiments and statistical methods. A yield response curve for nutrients can be obtained by linear, quadratic or multiple regression equations. Then, the maximum and economically optimum fertiliser rates can be estimated from the regression equation of yield response to fertilization. The method describes the crop fertiliser response for different soil fertility conditions. This approach has helped to secure high crop yields and to optimize fertiliser use at a large scale by considering macroeconomic management and distribution of fertilisers. When nutrients are deficient, crop yields increase with increases in fertiliser application (Li *et al*., 2011). However, the yield increment per kg fertiliser and the economic benefits of fertilization decrease with improving soil fertility and the economic benefits decline to zero when the value of increase yield equals the costs of the fertiliser application. Although this is not unusual on soils that have high P sorption capacity, it could also arise from over application of P fertiliser as a result of not updating the fertiliser requirements of crops on soils where soil fertility was rising. It is therefore necessary to continually update yield response functions to determine the appropriate.

2.8.2 P management: Building-up and maintenance

The approach aims at maintaining the soil Olsen P at the optimal level for plant growth by fertiliser application management (Li *et al*., 2011). The optimal level is more than the critical concentration of soil Olsen P needed to sustain high crop yield and less than P leaching level. The critical level for crop yield depends on the characteristics of the different plant species and cropping systems and can be found through long-term fertiliser experiments or multi-year field experiments. This approach helps keep soil P at an optimal level, meets the needs of crops, increases profitability and achieves maximum economic efficiency, and reduces environmental risk of P leaching. The objective is to move from the environmental risk level (very high P-status) or P deficient level (very low P-status) to the level of ensuring stable crop yield (medium P-status). When soil Olsen P is too high, either no P fertiliser or the amount of 50 – 70% take up by the crops should be applied to reduce excessive soil P reserves (Li *et al*., 2011). When soil Olsen P is at an optimal level, the amount of P fertiliser equals to crop removal to maintain soil P level (Figure 2.5).

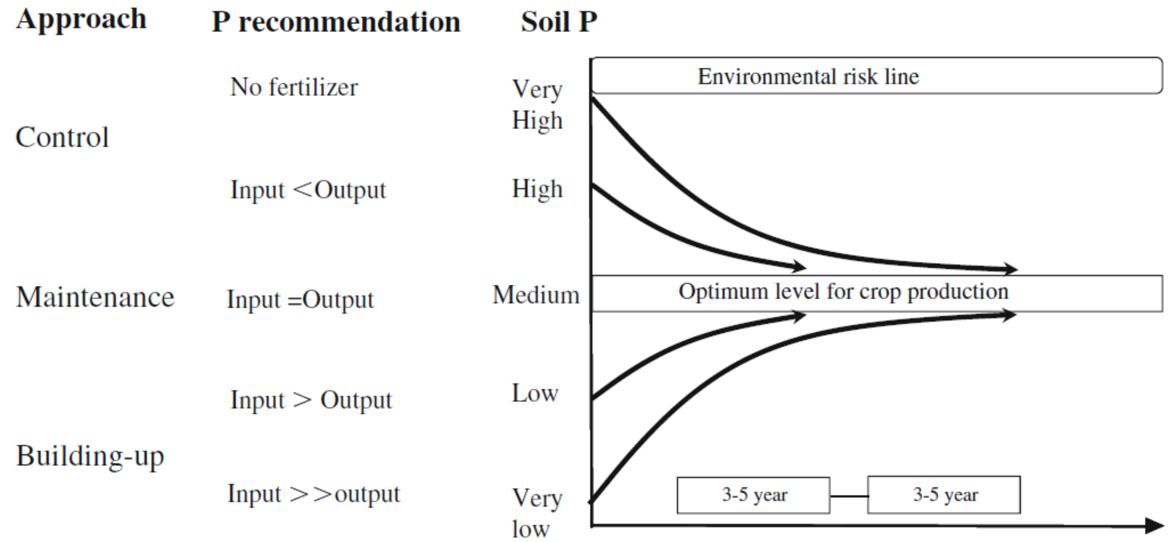


Figure 2.5 Theoretical model of P build-up and maintenance approach (adapted from Li et al., 2011)

2.9 Strategies for building Soil Olsen P in taro growing fields of Taveuni, Fiji

There is a need to correct P deficiencies in taro growing soils of Taveuni, Fiji. Taro growers in Taveuni can build soil Olsen P levels in their farms using P build up programs. Phosphate build-up is the additional fertiliser needed above crop removal to increase low- and medium-testing soil P to the target fertility levels for crop production (Stevens, 2007). To achieve a desirable taro yield of 10-15 t/ha, soil Olsen P levels need to be increased to > 20 mg P/kg. Once the desirable yield and optimum Olsen P is achieved maintenance P inputs are required to compensate for the losses of P from the farm. Maintenance fertilisers on high, medium and low P retention soils are 75, 45 and 45 kg P/ha, respectively. The losses include taro corm removal from the farm, P run off and movement of P to non-productive areas (Robert and Morton, 2009). Soil P build-up can be slow or fast depending on the economic situation of the farmer. Total fertiliser applied in slow and fast build-up programs is about the same amount, but the cost may be spread out over more years in slow build-up periods. The soil P build up decision has a large effect on the amount of fertiliser that a farmer will purchase and apply in a given year. The P rate required to overcome P deficiency increases with increasing P retention capacity of the soil. A one-time application, when integrated with appropriate management to overcome other nutrient and crop growth constraints, would ensure a rapid increase in crop yields and rapid soil rehabilitation (Stevens, 2007). Seasonal applications of P for gradual correction of P deficiencies on soil with low to moderate P retention capacity can also build-up soil capital P and eventually lead to greater yields. However, gradual build up soil P capital, will provide less immediate and cumulative crop yields than a relatively large corrective P application with subsequent maintenance application of P on moderate and high P retention soils. Gradual build-up programs help farmers manage their financial resources by spreading fertiliser costs over several years. Research needs to be conducted in Taveuni soils to determine the most profitable and affordable build-up strategy to manage optimum P levels in taro production system. Growers need information concerning the magnitude of yield loss that may occur early in a gradual P build-up program as compared to a rapid build-up program.

2.10 Taveuni soils

Twenty-three soil series have been surveyed and described on the island of Taveuni. Many of the soils are derived from volcanic ash (Leslie, 1997). The soils are classified as Andisols (previously called Andepts), having low bulk density (< 0.9 g/cm^3) with the exchange complex dominated by amorphous materials where phosphate retention is more than 85% and acid oxalate extractable aluminium is 2% or more. Many of the soils belong to the Hapludand or Hyperudand great groups. The soils belong to the Andisol order because of andic soil properties (Morrison *et al.*, 1986).

Chapter 3 Methodology

3.1 Introduction

This chapter discusses the methodology used to achieve the research objectives. A survey of taro growers and the soil fertility of their farms was conducted to achieve objectives 1 and 2 of the study. Field experiments 1 and 2 were used to address objectives 3, 4, 5 and 6. The results of the research overall contributes to objective 7. The experimental methodology focuses on the research location, research site characteristics, experimental design and layout, establishing and management of experiment plots, data collection and analysis needed for this study.

3.2 Research Location

The survey and field experiments used in this study were conducted on Taveuni Island (Figure 3.1). The island of Taveuni is an elongated shield volcano and its peak, Mount Uluigalau, is at a height of 1,241 metres above sea level. The climate is of typically oceanic with the southeast trade winds prevailing. The hot, wet months are from November to April. Figure 3.2 shows the annual rainfall and temperature of the island, which ranges from 2,400-4,500 mm and 21-34 ^{o}C respectively (Fiji Meteorological Service, 2018). The cyclone season falls between January to April annually.

Figure 3.1 Study location

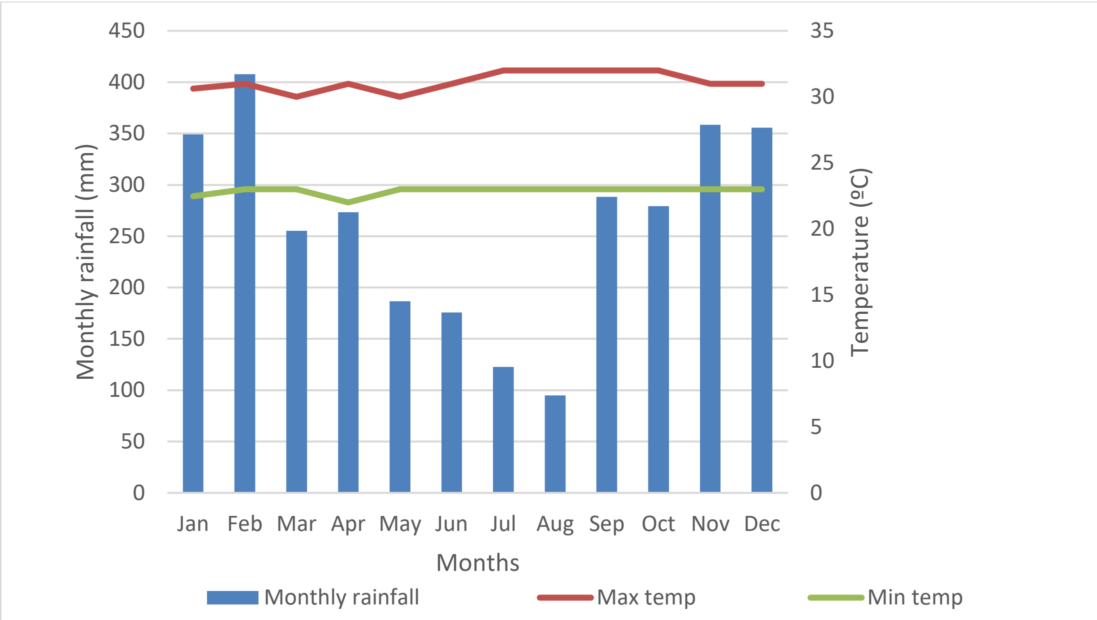


Figure 3.2 Average monthly rainfall and temperatures for Taveuni (5-year period; 2004-2008)

3.3 Taro grower survey

A taro grower survey was conducted in Taveuni from the 1st to 15th August 2016 to document grower farming practices and production details. Taveuni has a total of 3,632 farmers of which 2999 are subsistence growers, 432 are semi-commercial growers and 201 are commercial growers (MPI, 2013).

3.3.1 Grower selection

A list frame and stratified random sampling technique was used for this survey. The names of the growers, based on production level were obtained from Ministry of Agriculture, Taveuni office. The growers were divided into subsistence (< 0.4 ha farm) semi-commercial (0.8-2.0 ha farm) and commercial (> 2 ha farm) groups with the assistance of Ministry of Agriculture extension staff. For this survey only, semi-commercial and commercial farmers were surveyed since they are the farmers who consistently grow taro for the export market. The names of the growers in each category were listed alphabetically in a list frame and ten percent of semi-commercial and commercial growers were randomly selected. Based on this a minimum of forty-three semi-commercial and twenty commercial growers were surveyed representing approximately 10% of the total taro growers in each of these two categories.

3.3.2 Research Instrument for grower survey

Face-to-face farmer interviews were conducted by the researcher with the aid of a semi-structured research questionnaire. Face-to-face interviews have the advantage of high response rates and can be used to ask complex questions, clarify questions and control their sequence. The interviews were conducted in each grower's own language (Fijian, Hindi or English). Questionnaires were pre-tested on a group of farmers prior to the actual survey and amended for relevancy of questions before the actual survey was conducted.

3.3.3 Data analysis

The data was analysed using a Microsoft Excel spread sheet to determine percentages, means and frequency of variables.

3.4 Soils survey

Soil samples (0-20 cm) were collected from all the farms that were initially surveyed. A composite soil sample of 24 individual soil cores was collected along two 50-m transect lines forming a cross (X) pattern. Samples were brought to the Massy University Soils Laboratory, dried, sieved to less than 2 mm and analysed for soil chemical properties. Chemical properties analysed include pH (1:2.5 soil: water ratio), total N by the Kjeldahl method, Olsen P, exchangeable K, exchangeable Ca, exchangeable Mg, exchangeable Na and P retention (Blakemore *et al.*, 1987). To provide an assessment of soil fertility status, values of the various soil chemical properties were compared with critical/optimum or guideline values and with taro crop nutrient uptake levels. Key soil chemical properties were correlated with taro yield data from Taveuni, to establish a relationship between soil fertility status and taro yields. The results from this analysis were used to identify which nutrient limitations were likely to be affecting yields, which was also used to inform fertiliser treatments for the field experiments.

3.4.1 pH analysis

pH of the soil samples were measured by adding 25 ml of distilled water to 10 grams of air-dried soil (particle size of < 2 mm) into 100 ml beaker. The samples were stirred vigorously and left to stand overnight. The following day, pH was measured with a pH meter. Initially pH meter was calibrated with pH 7 and 4 buffer solutions. The electrodes of the pH meter were washed with deionised water thoroughly before each measurement. The electrode was placed in the soil-water solution and without stirring, pH readings were taken and recorded. At intervals, duplicate samples were tested to ensure errors were avoided.

3.4.2 Total N

Total N of the soil was measured by digesting 1g of the soil in a mixture of concentrated sulphuric acid and catalysts at very high temperatures (Kjeldahl Digestion as described by Blakemore *et al.,* 1987). During the digestion procedure, the inorganic N was converted into ammonium ions. The concentrated of this ion in the diluted, digest mixture was determined colourimetrically.

A gram of each soil sample was added to marked 100 ml Pyrex tubes. Four ml of digest mixture regents was added to the tube and the tube was heated in an aluminium block at 350°C for 4 hours. The tubes were then cooled, diluted to 50 ml with distilled water and mixed thoroughly on a vortex mixture. Reagent blanks and standard soil samples were digested with each set of samples to ensure accuracy was maintained. Total nitrogen content of the samples was measured on an auto analyser. The results obtained were in ppm or *u*g/ml and multiplying by 50 (volume of solution) gave results in μg/g.

Digest mixture Reagents

Digest mixture reagent was prepared by adding 250 g potassium sulphate and 2.5 g selenium powder to 2.5 litre sulphuric acid in a 5 litre Pyrex beaker and was heated over a gas ring heater until it became clear (Blakemore *et al.,* 1987).

3.4.3 Olsen P

This method was based on procedures described by Olsen *et al*., (1954). Initially weighed 1 gram of individual soil samples into marked centrifugal tubes. 20 ml of extracting reagent was added to the soil and was shaken for 30 minutes on an end-to-end shaker. The solution was then removed from the shaker and centrifuged in centrifugal machine at 900 rpm for 3 minutes. The centrifugal tube was then removed and the solution was filtered through Watman No. 6 filter paper under suction. 4 ml of filtrate was pipetted into a 50 ml volumetric flask and 32 ml of distilled water was added. Then 10 ml of Murphy and Riley solution was added. The flask was topped with distilled water up until 50 ml mark and closed with stopper.

The solution was thoroughly shaken and left for 30 minutes to develop colour. Sample was then analysed on a Uv/Visible spectrometer at 712 nm using 4 cm cell (Blakemore *et al.*, 1987).

Extracting reagent

Extracting reagent (0.5M $NaHCO_3$) was prepared by dissolving 42 g sodium hydrogen carbonate in 980ml distilled water. A vortex mixture was used to mix the solution. The pH of the mixture was adjusted to 8.5 by adding approximately 50% sodium hydroxide solution drop by drop. The solution was made to 1 litre content (Blakemore *et al.*, 1987).

Reagents for Murphy and Riley solution

The following reagents were prepared to finally prepare Murphy and Riley solution:

a) Ammonium Molybdate solution-by adding 32g Ammonium Molybdate into 1 litre distilled water.

b) Ascorbic acid solution- by adding 42.2g Ascorbic acid into 1 litre distilled water.

c) Antimony Potassium Tartrate solution- by adding 1.07g of Antimony Potassium Tartrate into 1 litre distilled water.

d) 4N Sulphuric Acid solution- by adding 112 ml Sulphuric Acid to 1 litre distilled water.

Murphy and Riley solution

Murphy and Riley solution was prepared by adding 500 ml 4N Sulphuric Acid solution, 150 ml Ammonium Molybdate solution, 100 ml Ascorbic Acid solution, 50 ml Antimony Potassium Tartrate and 200 ml distilled water.

Calculation of Olsen P content

Olsen P content was calculated with the pretested equation developed from standard curve:

μgP/g soil = (10 (y intercept)/0.420 (x intercept)) x (1/4ml of extract) x (20 (volume of $NaHCO_3$) / 1 (weight of soil)) (Blakemore *et al.*, 1987).

3.4.4 P retention

Weighed 5 grams of air-dried soil (< 2 mm particle size) into a stoppered 50 ml centrifugal tube and added 25ml of P retention solution to the soil sample. The solution was shaken for 16 hours on an end-to-end shaker. Then the solution was removed from the shaker and centrifuged in centrifugal machine at 2,000 rpm for 15 minutes. The centrifugal tubes were then removed and the solution were filtered through Watman No. 6 filter paper under suction. Carefully pipetted out 2 ml of supernatants into 50 ml volumetric flask and added 12.5 ml nitric vanadomolybdate acid reagents to the solution. Deionised water was added to make up to 50 ml mark. The diluted sample was shaken vigorously and after 30 minutes, absorbance was read on a Uv/Visible spectrometer at 420 nm in 1 cm cell.

Preparation of reagents

Phosphate retention solution (1mg P/ml)

Dissolved 8.8 g potassium dihydrogen phosphate and 32.8 g anhydrous sodium acetate in water, added 23 ml glacial acetic acid, and diluted to 2 litres in a volumetric flask. The pH of the solution was 4.6 (Blakemore *et al.*, 1987).

Nitric Vanadomolybdate acid reagent

Dissolved 0.8 g ammonium vanadate in 50 ml boiling water in a 1,000 ml beaker. The solution was cooled and 6 ml concentrated nitric acid was added. The mixture was diluted to 1,000 ml with distilled water.

In another beaker Molybdate solution was prepared by dissolving 16 g ammonium molybdate in 50 °C hot water. The solution was cooled and diluted to 1,000 ml.

Then diluted nitric acid was prepared by diluting 100 ml concentrated nitric acid with 1000ml distilled water. To this diluted nitric acid solution, vanadate solution was added first and then molybdate solution. The solution was then mixed thoroughly.

Preparation of working stock solutions

Phosphate retention solution 0, 10, 20, 30, and 50 ml aliquots were pipetted into 50 ml flasks and made to volume with distilled water. The samples were then shaken thoroughly. Then 2ml of solution were pipetted into 50 ml volumetric flask and 12.5 ml nitric vanadomolybdate acid reagents were added to each solution. Deionised water was added to make up to 50 ml mark. The diluted sample was shaken vigorously and left 30 minutes for the colour to develop. Absorbance was read on Uv/Visible spectrometer at 420 nm in 1 mm cell.

These solutions contained 0, 0.2, 0.4, 0.6, 0.8, 1.0 mg P/ml and corresponds to 100. 80, 60, 40, 20 and 0 percent retention respectively.

Calculation of the results

A standard curve was prepared for % P retention against absorbance. The absorbance results from soil samples were compared with the standard curve and P retention values were calculated.

3.4.5 CEC and Exchangeable cations

Cation exchange properties were determined with 1M ammonium acetate solution with pH of 7 (Blakemore *et al.*, 1987). A gram of air-dried soil was mixed with 3 g acid washed silica sand and placed into a semi-micro leaching tube, which had a filter paper plugged in the bottom. Blank samples were made with acid washed sand, while standard samples were made with standard soils with known CEC. The samples were prepared in batches of 24 samples. Sample 1 and 24 were blank samples, while samples 2 and 23 were standard soil samples with predetermined CEC values. The samples 3 - 22 were soil samples, which needed to be tested. The samples were extracted with 1M ammonium acetate solution with pH of 7 into 50 ml plastic containers, which was placed under the leaching tube. About 45 ml of ammonium acetate leachate were collected in each containers and were topped up with distilled water up to 50 ml volume.

The pH value of each leachate was measured and recorded. Then 2 ml of concentrated 26,000 ppm Strontium chloride-Caesium chloride (Sr and Cs) solution was pipetted into each leachate solution. The solution was stirred thoroughly and measured on a MP-AES machine for exchangeable K, Ca, Mg and Na (i.e. basic cations). The soil CEC was determined by combining the charge for the exchangeable basic cations with estimates for exchange acidity displaced from the soil.

3.5 Field Experiment 1

A field trial experimental design was established to evaluate the influence of different nitrogen and phosphorus fertiliser rates and the use of a Mucuna cover crop on taro growth and yield. The experimental design was repeated at three sites located at different locations on Taveuni Island. The sites had different soil types with contrasting P retention levels. The three sites, shown in Figure 3.1 are Delaivuna (73.7% P retention soil), Lagiloa (57.8% P retention soil) and Qeleni (12.1% P retention soil).

3.5.1 Experiment site location and soil characteristics

Site characterisation and soil types, as described by Morrison *et al.* (1986) were summarised for the three sites shown in Figure 3.1 (see Table 3.1). The soils belong to the Andisol (Soil Taxonomy) or Andosol (FAO/UNESCO) soil order (Leslie, 2012). The experimental field sites were identified with the assistance of Ministry of Agriculture staff, based on farmer's interest and availability of land. All three sites were deforested in the early 1970's and coconut plantations were established at a spacing of 10 m x 10 m. Copra derived from this field was sold at the local market. However, since 1996 the fields were primarily under intensive taro cultivation.

Table 3.1 Trial site characterisation

Location	Site characteristics	
Delaivuna	Soil series	Waiqere series
	Classification	Acrudoxic Hapludand, medial, isohyperthermic (Soil Taxonomy); Humic Andosol (FAO/UNESCO)
	Soil texture	Dark brown silty clay
	Physiography	Flat terrace in rolling country, 155m above mean sea level
	Topography	Flat site sheltered surrounded by hills
	Drainage	Well drained
	Current vegetation	Annual weeds under coconut plantation. Taro was recently harvested.
	Parent material	Basaltic ash
	P retention	73.7% (High)
	Soil N, P, K and pH	pH 5.7, total N 0.8%, Olsen P 6 mg/kg, total exchangeable K 0.24 mg/kg
	Climate	Weak dry season (June-October), annual rainfall of 4000 mm with average annual temperature of 24^{o}C

Lagiloa	Soil series	Nabeka series
	Classification	Hapludand, clayey, halloysite, isohyperthermic (Soil Taxonomy); Dystric Nitosol (FAO/UNESCO)
	Soil texture	Moist dark brown stony silty clay loam
	Physiography	Flat terrace in rolling country, 300 m above mean sea level
	Topography	Flat site sheltered surrounded by hills
	Drainage	Well drained
	Current vegetation	Annual weeds after taro crop.
	Parent material	Basaltic ash
	P retention	57.8% (Medium)
	Soil N, P, K and pH	pH 5.6, total N 1.19%, Olsen P 3 mg/kg, total exchangeable K 0.23 mg/kg
	Climate	Weak dry season (June-October), annual rainfall of 3000 mm with average annual temperature of 2^{o}C
Qeleni	Soil series	Naselesele series
	Classification	Typic Tropopsamment, carbonatic, isohyperthermic (Soil Taxonomy); Humic Andosol (FAO/UNESCO)
	Soil texture	Moist dark brown stony loamy clay
	Physiography	Flat terrace in rolling country, 50 m above mean sea level
	Topography	Flat to gentle slope
	Drainage	Well drained
	Current vegetation	Annual weeds under coconut plantation. Taro was recently harvested.
	Parent material	Basaltic ash
	P retention	12.1% (Low)
	Soil N, P, K and pH	pH 5.7, total N 0.63%, Olsen P 7 mg/kg, total exchangeable K 0.39 mg/kg
	Climate	Weak dry season (June-October), annual rainfall of 3500 mm with average annual temperature of 27^{o}C

3.5.2 Experiment 1 treatments

The main experimental fertiliser treatments included combinations of four rates of urea (0, 100, 200 and 300 kg N/ha) and five rates of triple superphosphate (0, 60, 120, 180, 240 kg P/ha) (Table 3.2). In addition, two Mucuna cover crops were used with two treatments (Treatment 23 and 24). For most of the fertiliser treatments, except Treatment 21 and 22, the triple superphosphate fertiliser was mixed with the soil in the planting hole and the urea was applied in 3 equal split applications (5, 10 and 15 weeks after planting; WAP). For Treatment 21 the urea fertiliser was applied in 4 equal applications at 0, 5, 10 and 15 WAP. For Treatment 22, the triple superphosphate was applied at the bottom of the planting hole, which is the common farmer practice. Potassium sulphate was applied to all treatment plots at the rate of 200 kg K/ha and 82 kg S/ha in 2 equal split applications at 5 and 15 WAP. The urea and potassium sulphate fertilisers were surface applied by hand to the soil around each taro plant up to a distance of 15-20 cm from the centre of the plant. Another 2 treatments at the lowest and highest rates of N and P were repeated with Mucuna cover crop.

Table 3.2 Treatment combinations for Experiment 1

Treatment No.	Treatment combinations (kg/ha of each nutrient)
1	N0P0
2	N0P60
3	N0P120
4	N0P180
5	N0P240
6	N100P0
7	N100P60
8	N100P120
9	N100P180
10	N100P240
11	N200P0
12	N200P60
13	N200P120
14	N200P180
15	N200P240
16	N300P0
17	N300P60
18	N300P120
19	N300P180
20	N300P240
21	N100P60 (4 split application of N) at 0, 5, 10 and 15 WAP
22	N300P60 (P applied at the bottom of planting hole)
23	Mucuna + N100P60
24	Mucuna + N100P240

All treatment received 200 kg K/ha as potassium sulphate, which also provided 82 kg S/ha

3.5.3 Experimental design

The field experiments were laid out in a randomized complete block design (RCBD) with four replicate blocks. RCBD reduces experimental error through proper blocking, while retaining much of the flexibility and simplicity of the completely randomized design (Fageria, 2007). Blocks of equal size, each of which contained a complete set of all treatments will be used (Silva and Uchida, 2000). Fertiliser trials require larger plots with ample borders than varietal trials (Fageria, 2006). A minimum plot size for fertiliser and liming experiments should be 6 x 5 m for an experimental duration of three to five years, if soil preparation operations are done mechanically (Fageria, 2007). In area where soil preparation is done manually, a smaller plot size can be used. Each experimental site had 1,472 taro plants. Each replicate block was 24 x 16 m with 2 metre walkway between adjacent main plots. Each individual treatment plot was 4 x 4 m in size. Each treatment plot had 16 taro plants but only the inner eight plants were used as data plants. The treatment combinations were randomised and allocated to treatment plots as shown in Figures 3.3, 3.4 and 3.5.

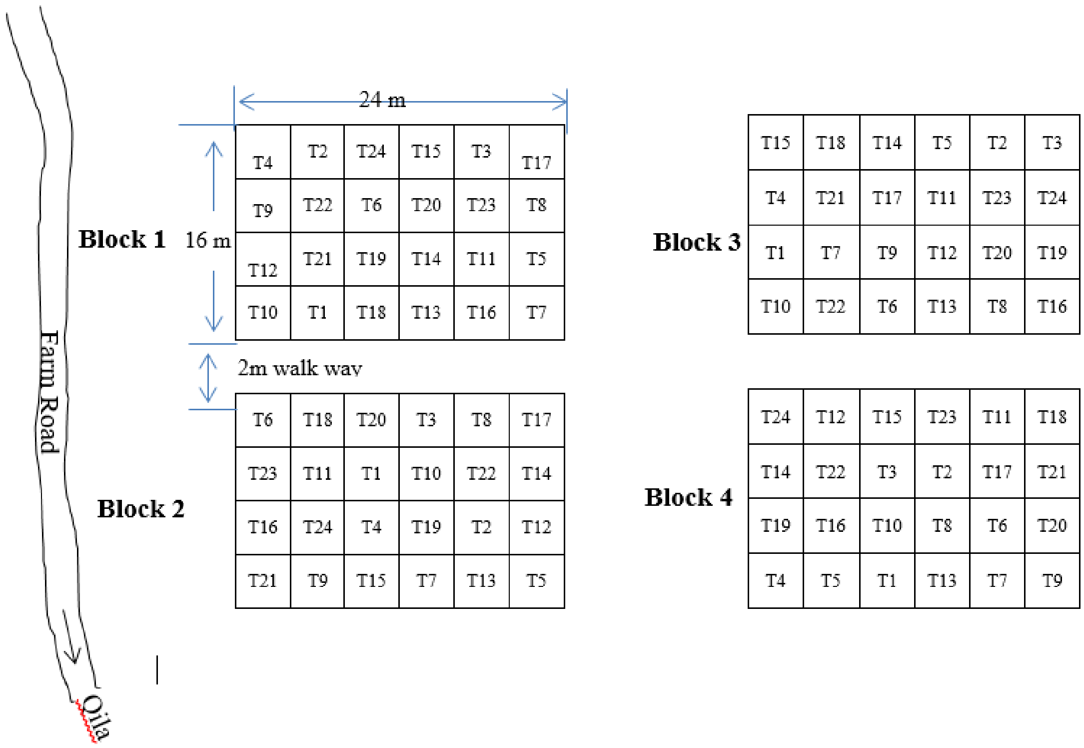


Figure 3.3 Experimental trial plot layout at Lagiloa

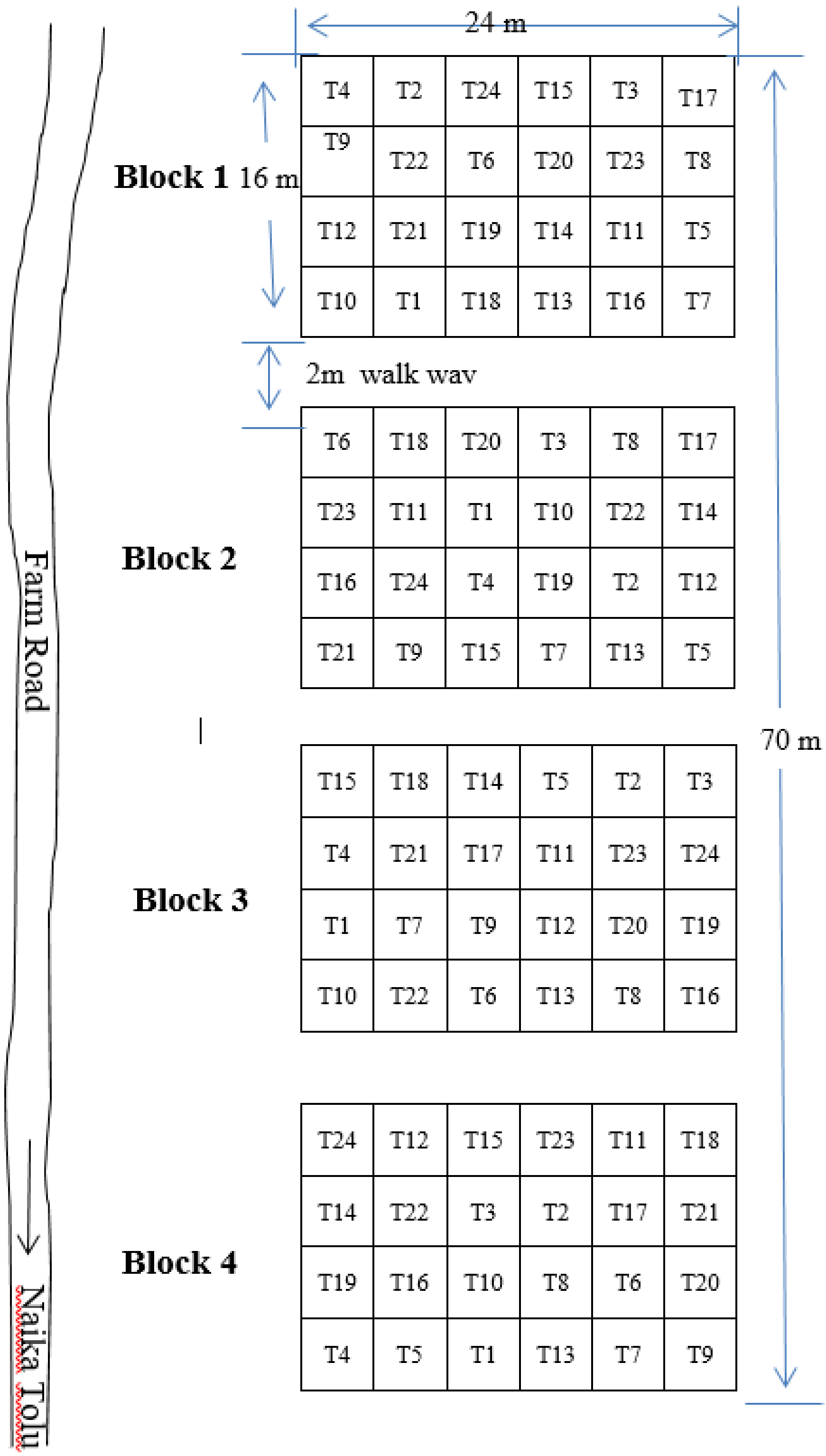


Figure 3.4 Experiment trial plot layout at Qeleni

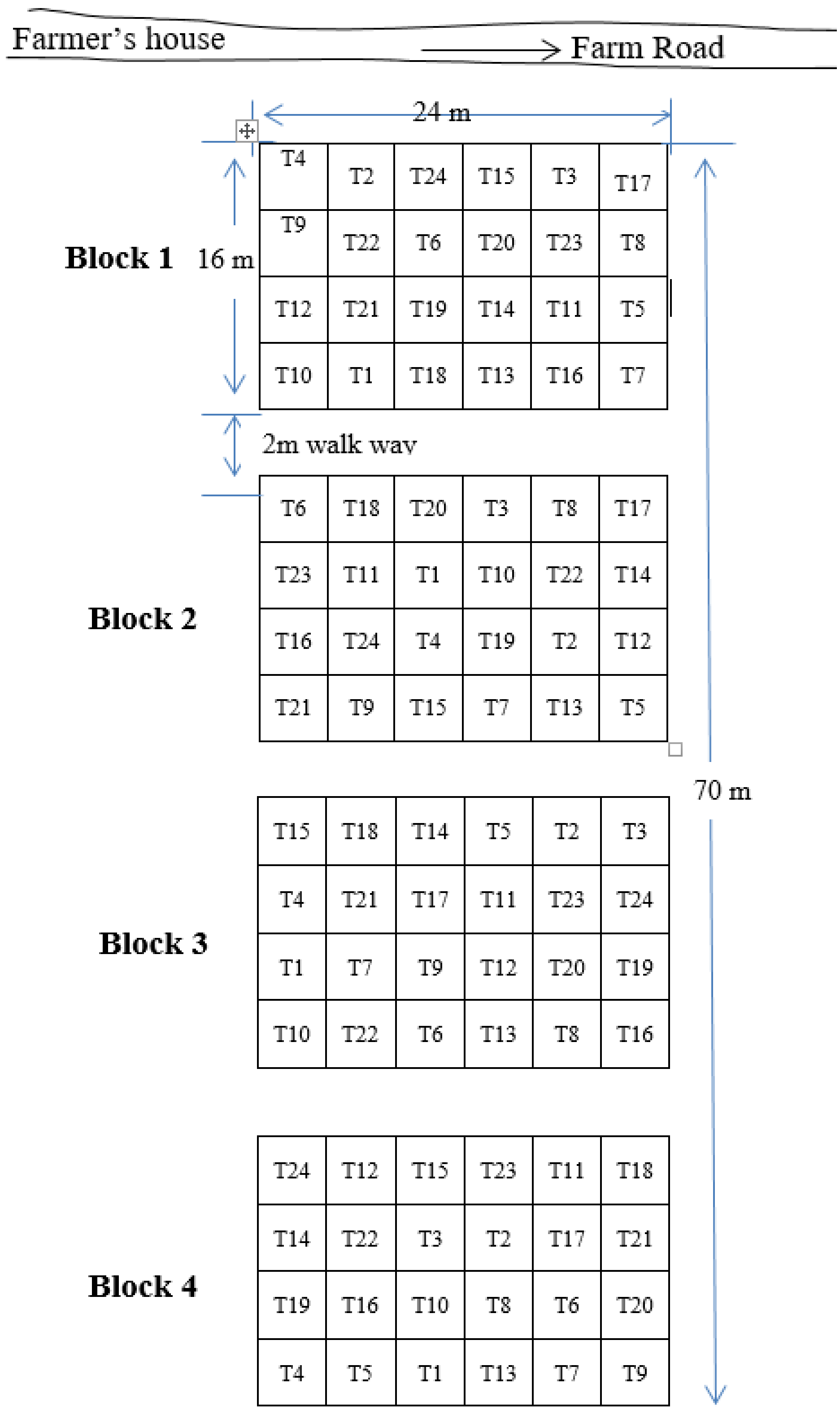


Figure 3.5 Experimental trial plot layout at Delaivuna

3.5.4 Field trial establishment

All 3-trial sites were previously cropped with taro and were under traditional weed fallow. The sites were cleared by spraying 36% glyphosate (150 ml/14 L water). Three weeks after spraying, the Tausala-Ni-Samoa variety of taro (pink taro) was planted in each plot at a spacing of 1 x 1m (farmer practice). The planting holes were dug manually by loosening the soil with a digging fork and taro were planted with a post hole spade (Figure 3.6 and 3.7) at a depth of 0.2 m. Planting material for this experiment was taro suckers obtained from other farmers. The suckers consisted of the upper 1-3 cm tip sections of sucker corms with 30-40 cm of leaf stalk attached. Taro suckers were of different sizes and variations due to size of suckers were reduced by sorting the suckers according to their sizes (small, medium and large suckers) and planting the suckers of same size in a treatment block (Silva and Uchida, 2000). This reduced competition between different sucker sizes as suckers of same size was planted within a block. Mucuna cover crop was planted in selected plots between taro rows at spacing of 50 x 100 cm.

Figure 3.6 Planting of taro suckers in the experimental plot at the Delaivuna trial site

Figure 3.7 Taro planted with mulch covering the surrounding undisturbed soil

3.5.5 Agronomic practices

Weed control was conducted on a monthly basis by spraying glyphosate herbicide. In the Mucuna treatments, Mucuna was chopped and removed when they started creeping onto taro plants. All chopped Mucuna herbage was placed back in the same plots. All management practices were conducted on a block by block basis to control any variation that may have occurred in the management and operation processes. Fertilisers were applied accordingly based on the treatment rates and timings (Section 3.5.2).

Figure 3.8 Weed control and urea application at 5 WAP at the Lagiloa trial site

3.5.6 Data collection for experiment 1

Experimental data were collected from December 2016 to July 2017 the three trial sites for, plant height, leaf length, leaf area taro leaf nutrient concentrations, sucker numbers and taro yield. Data on rainfall and temperature were collected over the experimental period.

3.5.7 Taro leaf analysis

Taro leaf nutrient analyses were conducted for treatments 1, 8, 14 and 20 at 13 WAP. Silva et al. (1998) recommends that leaf tissue analysis samples should be taken at 13 WAP to allow time for the information from the analysis to guide fertiliser applications if necessary. Four central plants from each treatment plot were selected (Figure 3.9) and second youngest open leaf blade (Figure 3.10) were collected (Daniels *et al.*, 2009). The petioles were removed as close as possible to the leaf blade. Leaves were oven dried, milled and analysed. Total N, P and K were analysed.

X	X	X	X
X	X1	X3	X
X	X2	X4	X
X	X	X	X

Figure 3.9 Plants used for dry matter analysis

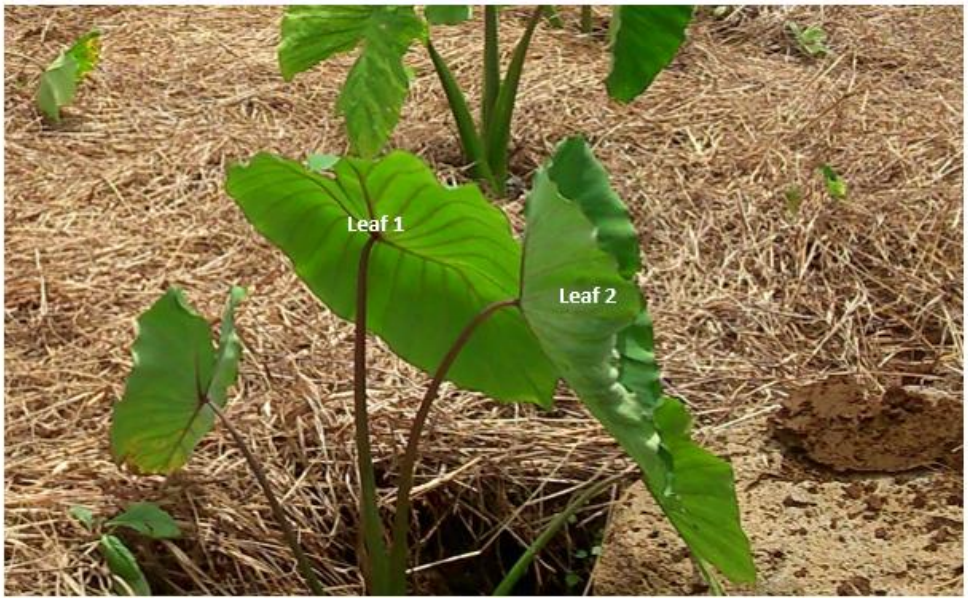


Figure 3.10 Taro leaf numbers

3.5.8 Plant height, leaf length and leaf area

Taro growth parameters, such as leaf length, plant height, and leaf area, were measured at 13 WAP. Plant height was measured as the total distance from the soil surface to the point where petiole connects to the second leaf. Leaf length was measured as the total distance from the tip of the leaf to the point where leaf connects to the leaf petiole. Leaf area was calculated by tracing the leaf area of the second youngest leaf on the graph paper and area was determined by counting the grids.

3.5.9 Taro yield data

The taro plants were harvested 28 weeks after planting (WAP) and quantitative yield data were collected. Corm yield is an important parameter for determining the productive benefit of the treatments. Corm yield refers to the weight of clean fresh corms (without roots and petiole chopped off at a length of 3 cm) harvested from a unit area. Taro plants were harvested manually pulling the entire plant. The eight central plants from each treatment plot were weighed for yield (Figure 3.11). Corms were chopped off from the petiole with 3 cm of petiole left attached to the corm. Soil, roots and outer decaying older petiole were removed from the corm (Figure 3.12). The corms were then weighed to determine the corm fresh weight, which was recorded individually for each plant. After harvesting each plot, the numbers of marketable and non-marketable corm were counted. Marketable corm yield refers to taro corms, which were above 1kg fresh weight and were free from rots and other damage. Non-marketable corms were further categorised into wither rotten corms or under size corms and their weights were recorded.

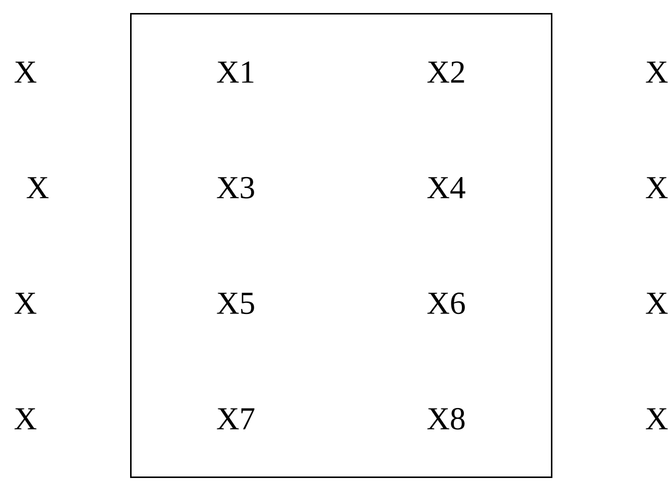


Figure 3.11 Data plants in each plot (X1-X8)

Figure 3.12 Taro corm with attached petiole

3.5.10 Taro sucker data

At maturity taro suckers' numbers were counted from 8 data plants in each treatment plot and recorded respectively (Figure 3.13).

Figure 3.13 Taro suckers around the central 'mother' plant

3.6 Experiment 2

Experiments 2 was conducted on the same sites as experiment 1 to further fine-tune and re-confirm the results of Experiment 1. In experiment 1 it was seen that application of N up to 300kg/ha had a significant effect on taro sucker population, as a result rates of above 300 kg/ha were included in the second experiment to confirm the optimum N rate for taro sucker production. Also in the first experiment only K rates of 200 kg/ha were used and it was important to test lower rates to reconfirm optimum K fertiliser requirements. It was also important to know if optimum rates of P application during the first crop will have any effect on a succeeding crop. Mucuna was also seen to be an effective treatment in experiment 1 and further studies were needed to reconfirm the N rate and Mucuna combination to effectively reduce N fertiliser costs and leaching risks. Effect of lime on taro yield and soil properties were also evaluated in experiment 2.

3.6.1 Experiment 2 treatments

The main experimental fertiliser treatments included combinations of 5 rates of urea (0, 120, 200, 280 or 360 kg N/ha), 4 rates of triple superphosphate (0, 60, 90 or 120 kg P/ha) and 3 rates of potassium sulphate (100, 150 or 200 kg K/ha) (Table 3.3). Four treatment plots also included a Mucuna cover crop, which was planted at a spacing of 50 x 50 cm.

Phosphorus fertiliser placement treatment was also evaluated in this experiment. For all treatments except Treatment 22, P fertilisers were mixed in the planting hole. Treatment 22 involved applying P fertiliser at the bottom of planting hole (i.e. farmers practice).

Lime was also included in treatments in this experiment. Two types of lime; Fijian lime and imported New Zealand (NZ) lime, were compared. The Fijian lime was applied at 2 t/ha and the NZ lime applied at both 1 and 2 t/ha. Each lime treatments was broadcast to the whole area of the treatment plot.

Treatments were allocated based on the previous treatments used in Experiment 1 and some treatments were repeated. This was done to evaluate the carry over effects of P and N addition from Experiment 1. Table 3.3 shows the treatment combinations for experiment 2 based on treatments applied in experiment 1.

3.6.2 Experimental design

Experiment 2 was purposely laid out in the same fields and plots as experiment 1. The treatments were applied to treatment plots based on the initial experimental design and randomisation as described in Figures 3.3, 3.4 & 3.5, to study the treatment carry over effects.

Table 3.3 Treatment combinations for Experiment 2

Treatment	Previous treatments (experiment 1)	Treatment combinations for experiment 2 (kg/ha of nutrients applied)
1	N0P0	N0P0K200
2	N0P60	N360P120K200
3	N0P120	N280P120K200
4	N0P180	N200P120K200
5	N0P240	N120P120K200
6	N100P0	N280P120K200
7	N100P60	N120P60+Mucuna
8	N100P120	N280P120 + NZ lime (1 ton/ha)
9	N100P180	N120P60K200
10	N100P240	N280P120K200
11	N200P0	N280P90K200
12	N200P60	N120P120K200
13	N200P120	N280P120K200 + NZ lime (2t/ha))
14	N200P180	N280P120K200 + Fijian lime (2t/ha)
15	N200P240	N280P90K200
16	N300P0	N280P60K200
17	N300P60	N120P120K200
18	N300P120	N280P120K150
19	N300P180	N280P120K100
20	N300P240	N280P60K200
21	N100P60 (4 split application of N) at 0. 5, 10 and 15 WAP	N280P120K200+Mucuna
22	P applied at the bottom of the planting hole	N280P120K200 (P applied at the bottom of planting hole)
23	Mucuna + N100P60	N120P60K200 +Mucuna
24	Mucuna + N100P240	N120P120K200+Mucuna

All experiment 1 treatments received 200 kg K/ha

3.6.3 Field trial establishment for experiment 2

Experiment 2 was planted in August 2017 using the same experimental plots as Experiment 1 at all 3 sites. Site weed spraying and taro variety, planting density and sucker size allocation to blocks were the same as used in Experiment 1. Mucuna cover crop was planted in selected plots between taro rows at 50 x 100 cm spacing.

3.6.4 Data collection

Data were collected from 3 experimental sites for soil, plant and treatment interactions as outlined below.

3.6.4.1 Soil data

Baseline soil samples were randomly collected from the trial sites at the depth of 0-20 cm prior to planting of the crop to determine the initial soil fertility status. At crop harvest, soil samples were collected again from selected treatments (T1, T3, T5, T6, T8, T11, T13, T14, T18, T19 and T22) to determine the effect of different treatments on the soil nutrient status. Fertiliser treatments were applied to planting holes and near the taro plants, therefore, soil samples were collected at various distances from the taro plants to assess the impact this has on spatial variability in soil fertility. Two sets of composite soil samples (12 cores; 0-20cm depth) were collected from each plot to identify soil fertility levels at different proximities to the planting hole. The first set of samples was collected about 15 cm away from the centre of the planting hole. The second sets of sample were collected 30 cm from the centre of the planting hole. Third samples were taken 50 cm from the centre of the planting hole. Samples were subsampled, air dried and exported to Massey University Biosecurity facility and analysed at their soils laboratory.

Soil samples were air dried and sieved through a 2 mm sieve. Samples were analysed for soil pH, Olsen P, exchangeable K, Ca and Mg as described in section 3.4.1 to 3.4.5.

3.6.4.2 Dry matter and nutrient uptake

The experiment was harvested in February 2018 and at harvest, the dry matter (DM) yield was determined to obtain data regarding nutrient accumulation by the crop during the season. To determine DM yield, the inner 4 plants were selected from plots of selected treatments (T1, T2, T3, T4, T5, T7, T21, T23 and T24). All 4 plants were harvested, and soil and roots were removed from the plant components. Plant components (taro leaves, petioles, suckers and corm) were separated, weighed, then chopped into small pieces and packed separately in clearly marked bags. These plant components were oven dried (72 ºC for 48 hours) and their dried weights were recorded. Dried samples were ground to pass through a 1 mm mesh screen. Representative samples from each plant component was exported to the Massey University soils laboratory, New Zealand and analysed for total N, P and K.

3.6.4.2.1 Nitric acid digest for herbage cation analysis

Oven dried samples of herbage material were weighed to 0.1 g on a 4 decimal place balance and placed in 25ml marked digestion tubes. In each block 2 blank samples were included. In a fume cupboard 4 ml concentrated nitric acid was added to each tube and a small glass funnel was placed on top. The tubes were then digested at 150 ºC overnight. The funnel was removed next morning and the temperature was increased to 200 ºC. The solution was allowed to evaporate until it was dry (approximately 2.5 hours of heating). The tubes were removed from the block while they were still warm and 5 ml of 2 M HCL made up in deionised water (172 ml concentrated HCL/litre water) was added. A vortex mixer was used to mix the solution. Mixing was repeated again after 2 hours to ensure dissolution of sample from the walls of the tubes. Then 1 ml of concentrated 25,000ppm Strontium chloride-Caesium chloride (Sr and Cs) solution was pipetted into each tube. The solution was stirred thoroughly and measured on a Microwave Plasma Atomic Spectrometry (4210 MP-AES, Agilent, USA) machine for total K, Ca, Mg and Na.

3.6.4.2.2 Herbage Total N and P analysis

Oven dried samples of herbage material were weighed to 0.1 g on a 4 decimal place balance. The herbage material was wrapped on a cigarette paper and placed in 50 ml marked digestion tubes. In each block 2 blank samples were included. In each tube 4 ml of digest mixture (Kjeldahl Digestion) was added and heated up in an aluminium block at 350 ºC for 4 hours. Tubes were cooled and diluted with deionised water until 50 ml mark. The solution was thoroughly mixed on vortex mixture. Samples were than analysed on a total N and P auto analyser. Digestion mixture is described in the section 1.4.2.

3.6.4.2.3 Cover crop (Mucuna) data

Dry matter and nutrient analysis were conducted on Mucuna cover crop 16 WAP in various treatment plots. Samples were taken by randomly placing a 1 x 1 m quadrant and collecting the above ground biomass as shown in Figure 3.14. Initial green weights were measured and sub-samples were oven dried at 72 ºC for 48 hours. Dried weights were recorded and samples were then ground and analysed for total N, P and K content.

Figure 3.14 Mucuna cover crop growing in between taro plant

3.6.4.2.4 Weed infestation with and without Mucuna cover crop data

Weeds surveys were conducted on Mucuna treatments plots (T21, 23 and T24) and non Mucuna treatment plots (T1 and T3) at 4 and 8, 12, 16 and 20 WAP. During each survey, a 1 m x 1 m quadrant was placed in 3 randomly selected areas within each plot. Weeds within the quadrants were identified and counted (Figure 3.15). Following each weed assessment, weeds were removed by hand from each plot and time spent on hand weeding (weeding and pulling) was recorded. The removed weeds were transferred to brown envelops, labelled and oven dried (72 º C for 48 hours) and their dried weights were recorded.

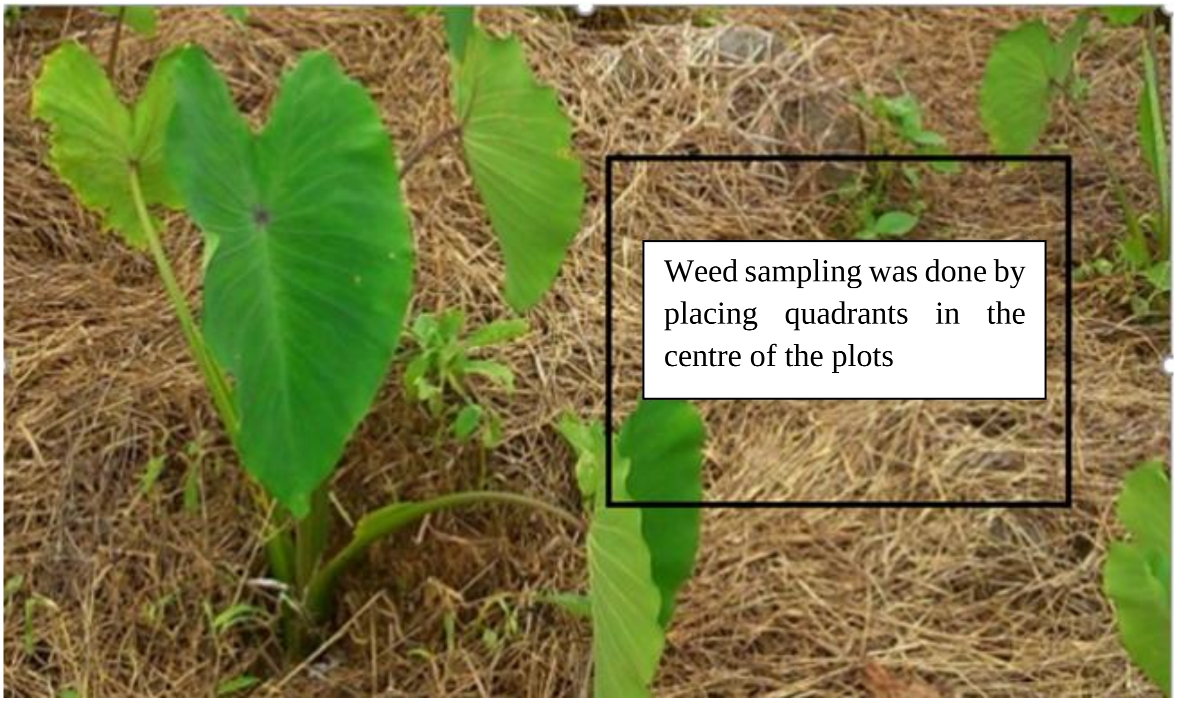


Figure 3.15 Quadrant was placed in the centre of a plot for counting the number of weeds

3.6.4.2.5 Taro yield data

The final harvest of the taro plants at all three trial sites was 28 WAP and quantitative yield data were collected as outlined in section 3.5.9.

3.6.4.2.6 Cost benefit analysis

All costs and benefits associated with taro yield were recorded for the entire trial period. Taro gross margin and cost benefit analysis were conducted to identify the most cost-effective treatment combinations for optimum yields.

3.6.4.2.7 Additional research related data

Data were recorded on diseases (Figure 3.16), insects, and other environmental stresses, which were prevalent during the conduct of this experiment. Rainfall and temperature data were also collected.

Figure 3.16 Taro corm rots

3.6.5 Analysis of data

Data was analysed with GenStat 19th Edition statistical package. Analyses of variance were performed on selected collected parameters. Least significant difference (LSD at $P \leq 0.05$) was used to compare treatment means and their interactions. Simple graphs were plotted to show treatment effects on taro yield and changes in soil properties. Data on taro yield, soil nutrient levels, plant nutrient contents were subjected to regression analysis to identify the sufficiency and deficiency ranges of the nutrients tested (Fageria, 2007). Regression equations were developed to describe the relationship between various soil analyses data, yield data and SPAD and the predicted response curve were plotted.

3.6.6 Dissemination of results

Divulgation of results from this research is important in the process of improving taro yield in Taveuni, Fiji. The best instrument of divulgation of research results is through demonstration in the farmer's fields along with the extension service (Fageria 2007). This research was carried on farmers' field and ensured farmer participation throughout the research. At harvest other growers were invited to witness the results.

Chapter 4 Taro grower and soil fertility surveys on Taveuni Island.

4.1 Introduction

Taro is third most important economic crop after sugar cane and coconut in Fiji. Fiji's total taro exports peaked in 2007 at 11,949 tonnes and declined over subsequent years. In 2010 the country was struck by Cyclone Thomas leading to significant losses sustained by the industry. The Government provided fertiliser assistance to help the industry recover and this led to the increase in production and exports in 2011, however, once this assistance ended, Fiji's total taro exports subsequently declined to 5,166 tonnes in 2018.

Several factors could be contributing towards the declining production and identification of these factors would be an initial step towards increasing taro production in Fiji. Taro grower and soil surveys are useful tools to identify the soil fertility status of the growers' farms. A taro grower survey was conducted in Taveuni from the 1st to 15th August 2016 to document grower farming practices and production details. Taveuni has a total of 3,632 farmers of which 2,999 are subsistence growers, 432 are semi-commercial growers and 201 are commercial growers (MPI, 2013). This chapter examines and discusses the soil fertility status and grower practices in Taveuni.

4.2 Materials & methods

Details of materials and methods for the taro grower and soil survey are provided in Chapter 3.

4.3 Results and Discussion

The taro grower and soil survey documents current taro growing practices and identifies production constraints affecting taro growers on Taveuni Island. Results from this survey provide information to help identify the potential limitations to taro production, which inform the objectives of research presented in subsequent chapters in this thesis.

4.3.1 Land tenure systems

A total of 43 semi-commercial and 20 commercial taro growers on Taveuni Island were surveyed. Land used to grow taro has three types of ownership, which are include freehold land, leased land and communal (community) owned land. The tenure systems used by the surveyed semi-commercial and commercial growers are shown in Figures 4.1 and 4.2, respectively. In the semi-commercial category, 51% of the growers cultivate leased land, 25% cultivate communal land without a leasing agreement and 23%, freehold land. In the commercial category 50% of the growers cultivate freehold land, 47% leased land and only a small percentage (3%) is communal land used without leasing agreements. Communal land is owned and governed by the chief of each clan, known as *turaga ni mataqali*. All clan (mataqali) members have access to this land and major decisions on development of the land are made during village meetings. Taro growers on Taveuni Island can access two types of leasing arrangements, namely long-term lease from Itaukei Land Trust Board (ILTB) and short-term communal leases from respective clans. Short-term communal leases can be acquired through payment with cash or a proportion of the crop. Often poor crop husbandry and soil fertility practices are more typical of short-term communal leases because farmers only use of the land for short durations of 3-5 years.

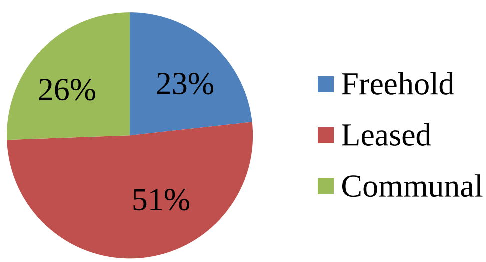


Figure 4.1 Land tenure system used by the semi-commercial taro growers

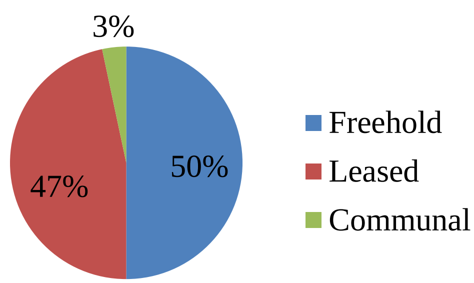


Figure 4.2 Land tenure system used by the commercial taro growers

4.3.2 Soil parent materials and types

Taveuni Island consists of the youngest of a series of volcanoes that formed around the margins of the Koro Sea, following a major change in the tectonic setting of Fiji around 3 - 3.5 million years ago (Rodda & Kroenke 1984). Cronin and Neall (2001) have stated that about 100 eruptive episodes have occurred in Taveuni over during the 1,000-10,000 BC period. Each eruption deposited volcanic ash and cinder, which formed the parent materials for the Taveuni Island soils (Table 4.1). Volcanic soils largely consist of non-crystalline (amorphous) minerals, such as allophone and imogolite. Allophane and imogolite form in weathering environments with pH values in the range of 5 to 7 and a low content of complexing compounds (Ugolini and Dahlgren, 1991). When not highly weathered, volcanic soils are typically very fertile soils. However, the humid tropical climate of Taveuni Island causes rapid weathering of parent material and soil development. Thus almost all pre-Holocene tephras are reduced to kaolin-group clay. Taveuni soils predominately belong to the Andisol (Soil Taxonomy) or Andosol (FAO/UNESCO) soil order (Leslie, 2012). Many of the soils belong to the Hapludand or Hyperudand great groups. According to Leslie (1997), majority of Taveuni soils have low bulk density (less than 0.9 g/cm^3), acid oxalate extractable aluminium of 2% or more and high phosphorous retention capacity (> 60%).

Table 4.1 Soil characteristics surveyed farms

Location	Soil series (Soil texture)	Average P retention (%)	No. of growers surveyed
Tabakau & Vuna	Vuna series (Stony black sandy loam)	20	5
Waimaqera	Vuna variant (dark brown clay loam)	79	13
Qarawalu, & upper Delaivuna	Waiqere variant (dark brown silty clay)	77	29
Lagiloa and Wailagi	Nabeka series (moist dark brown silty clay loam)	43	4
Nacaugai	Nacaugai series (brown clay loam)	82	2
Qeleni & Qeleni Rd	Naselesele series (moist dark brown stony loamy sand)	22	3
Nayalyala	Waioba series (dark reddish brown stony clay loam)	96	7

4.3.3 Soil chemical properties

Of the 63 growers surveyed, 51 had soil test values that are considered to have high P-retention (> 60%), which are predominately the soils with clay loam textures. Four growers had medium P-retention (30 – 60%) soil test values with and 8 growers had low P-retention (0-30%) (Table 1). Overall, soil fertility was low at most farm sites survived, particularly for Olsen P and exchangeable K (Table 4.2). The average pH, Olsen P and exchangeable K values were 5.76, 7.6 mg P/kg, and 0.4 me/100g, respectively. There was a wide range in soil test values, with pH ranging from 4.5-6.6, Olsen P ranging 1-38 mg P/kg, and exchangeable K ranging from 0.01-1.34 me/100 g. Average total N was 0.97%, which also has a wide range of 0.29-1.68%.

Table 4.2 Soil (0-20 cm soil depth) chemical properties of surveyed taro growing farms

P retention (%)	**No. of growers**	**Soil pH**	**Total N (%)**	**Olsen P (mg/kg)**	**Exch. K (me/100g)**
Low (0-30%)	8				
Mean	-	5.6	0.9	6	0.4
Range	-	4.5-6.2	0.59-1.47	3-13	0.19-0.63
Medium (30-60%)	4				
Mean	-	5.6	0.8	7	0.4
Range	-	5.1-5.8	0.36-1.23	1-22	0.14-1.17
High (>60%)	51				
Mean	-	5.8	1.0	7.9	0.4
Range	-	5.2-6.6	0.29-1.68	1-38	0.01-1.34

About three-quarters of both semi-commercial and commercial growers surveyed had very low soil Olsen P levels (< 10 mg P/kg). To achieve good taro yields (i.e. >10 t/ha), the considered optimum Olsen P levels are > 20 mg P/kg (Thiagalingam, 2000). In the semi commercial category, 21% of growers had Olsen P levels of 10-20 mg P/kg and only 2% had levels > 20 mg P/kg. Whereas for the commercial growers, 13% had Olsen P levels of 10-20 mg P/kg Olsen P and 10% had levels > 20 mg P/kg.

Based on Thiagalingam's (2000) recommendation that optimum K level for taro needs to be > 0.4 me/100g, it could be stated that 65% of both commercial and semi-commercial growers have low K levels in their farms. In an earlier survey, Sharma (2015) also observed that a high percentage (78%) of the farms sampled on Taveuni Island had low available K (< 0.4 me/100g).

The desirable pH for taro range from 5.6 - 6.6 (Duke, 1978). In the current survey, growers had soil pH ranging from 5.2 - 6.6. Of this 16% had soil pH below 5.6, 63% had pH in the range of 5.7-6.0 and 21% had pH above 6.0. High rainfall in Taveuni could be associated with low pH in most of the farms. In addition, only 31% of the growers used lime. Nisha (2013) had also stated that soil pH for most farms is in the 4.6 to 5.5 range and this could also be a yield limiting factor.

4.3.4 Taro yields

The mean total and mean marketable taro yield over 3 years (2013-2015) for the surveyed growers are presented in Figures 4.3 and 4.4. Mean total taro yields over the three years was on average 6.9 t/ha for both semi-commercial and commercial growers. However, in each year there was a wide range of yields being documented. The average lowest yield was 4.6 t/ha for semi-commercial and 5.2 t/ha for commercial growers. Whereas the average highest yield was 10 t/ha for the semi-commercial growers and 9.2 t/ha for commercial growers. The mean marketable % over the three years, was 92% and 81% for the semi-commercial growers and commercial growers, respectively.

Taro yields are low as compared to other taro producing areas. Research conducted in different parts of the world has proven that under intensive commercial cultivation taro yields of >20 t/ha can be achieved (Goenaga and Chardon, 1985; Silva *et al*., 1992; Daniells *et al.*, 2009). In the Pacific typical high yields range from 15-30 t/ha (Daniells *et al*., 2009; Sivan, 1981). In Fiji yields as high as 25.6 t/ha have been recorded in research fields (Sivan, 1981), but yields of up to approximately 15 t/ha were more typical on commercial farms (Sharma, 2016).

Taro yields differ greatly according to cultivar, climatic conditions, crop duration, management practices and soil fertility. Management practices such as size of planting material, variety, weed control, number of suckers, type of planting material, fertiliser inputs and population density influence taro yield (Tsedalu *et al.*,2014). Commercial taro production in Taveuni started in 1994 and prior to this, most agricultural activities were at subsistence level. Taveuni soils were derived from volcanic ash and had inherent property of accumulating high amounts of organic matter over time. However, as commercial cultivation began organic matter levels declined and yields eventually declined (Sharma, 2015). As production declined some farmers who had access to newer areas, deforested more land to grow taro, while other farmers with limited land continued to cultivate their existing land. During the current survey it was observed that taro yields of land close to growers' homes, tended to be lower than from newly deforested areas.

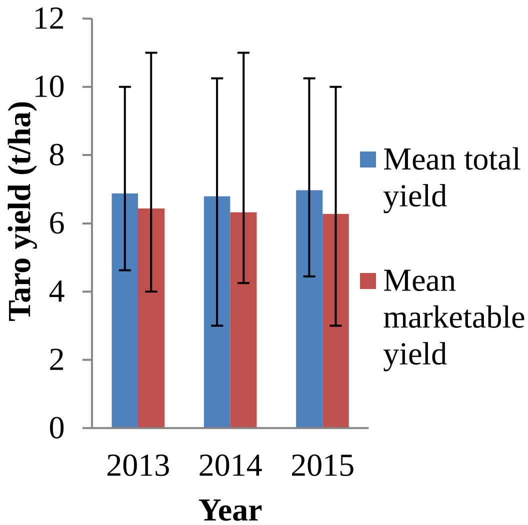


Figure 4.3 Total and marketable taro yields of semi-commercial growers (*bars represent range for taro yields*)

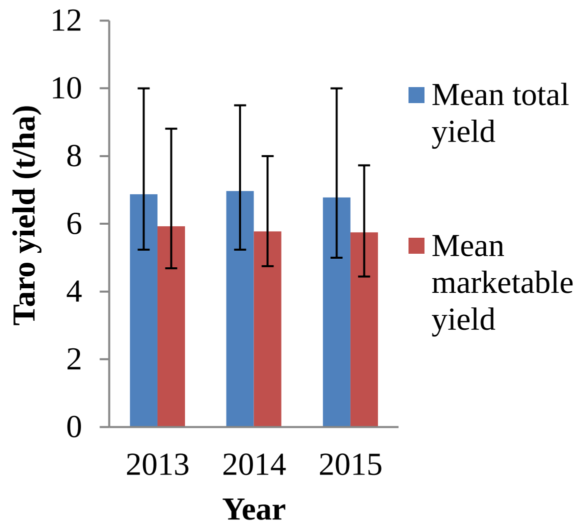


Figure 4.4 Total and marketable taro yields of commercial growers (*bars represent range for taro yields*)

The typical symptoms of phosphorus deficient taro plants include stunted root and shoot growth. Older leaf blades may appear darker green due to greater retardation of leaf expansion relative to chlorophyll (green pigment) reduction. As the deficiency progresses, areas of the leaf margins begin to yellow and turn brown (Miyasaka *et al.*, 2002). The relationship between Olsen P and taro corm yields from the survey are shown in Figure 4.5. There is a general trend of yields increasing up to 10 t/ha with increasing Olsen P levels up to between an Olsen P of 15-20 mg P/kg. Above an Olsen P of 20 mg P/kg it is possible that some other factor has become more limiting. At three sites, it was possible to achieve a yield of 10 t/ha when Olsen levels were between Olsen P of 9 and 20. However, no sites with Olsen P levels of less than 9 mg P/kg achieved yields greater than 9 t/ha. These results support that to attain yields of 10 t/ha, then Olsen P levels should be maintained at least above approximately 15 mg P/kg, but ideally > 20 mg P/kg. In order to gain a benefit from maintaining Olsen P levels above 20 mg P/kg, then other limiting yield factors need to be identified.

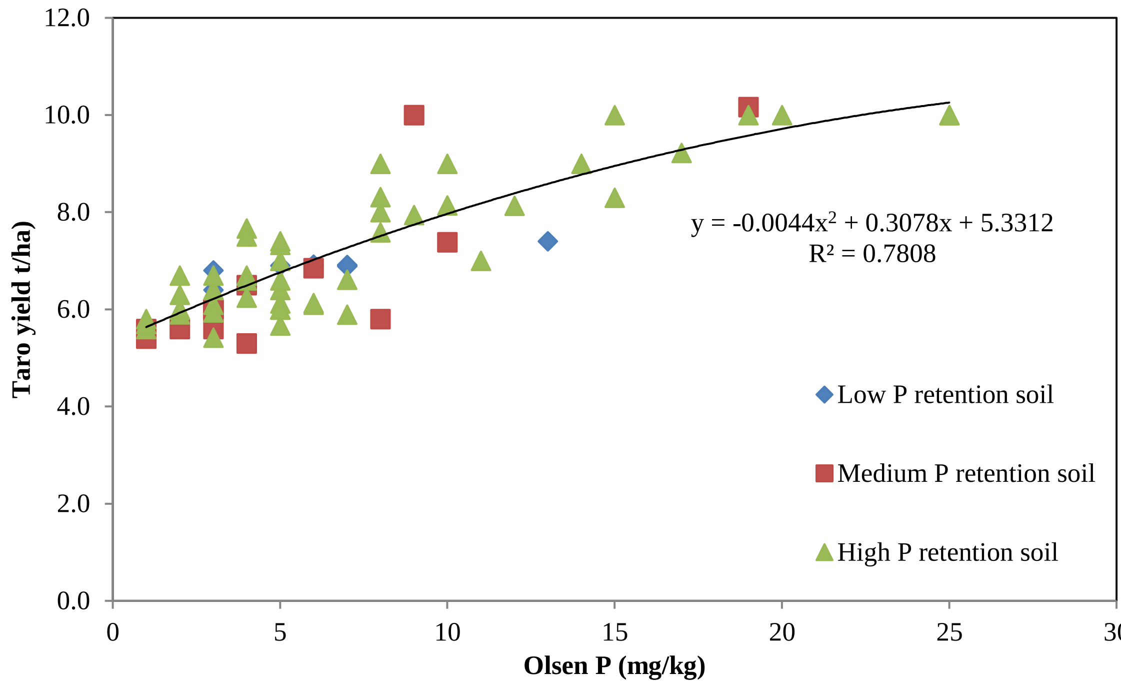


Figure 4.5 Relationship between Olsen P and taro yields for surveyed growers

Taro has high demands for potassium, as large amounts of K are exported in the harvested corms. Potassium deficient taro is characterized by slower growth rate, increased tendency to wilt, reduced size of leaf blades, and interveinal or marginal "scorching", a burnt appearance between the veins or around the leaf margins. As the deficiency progresses, the spots may coalesce, with the whole leaf turning yellow or brown. Potassium deficiency can be addressed by improved diagnosis of K deficiency, and measures to conserve and replenish soil K reserves (Miyasaka *et al*., 2002).With good yields of 10-15 t/ha, taro corms will be removing 34-54 kg K/ha from the soil at each harvest and maintenance fertiliser should be applied to replenish this (Anand, 2015; Bleming, 1996; Hartemink and Johnston, 1998). The relationship between soil exchangeable K and taro corm yield for surveyed farms was not strong (R^2 = 0.34). This may be due to available P likely to be the most limiting factor at most the sites surveyed.

The relationship between soil pH and taro corm yield for surveyed farms was weak and not significant ($R^2 = 0.25$). The lack of a strong relationship between soil pH and taro yield may also be due to Olsen P being more limiting. The desirable pH for taro ranges from 5.6 - 6.6 (Duke, 1978). In the current survey, growers had soil pH ranging from 5.2 - 6.6 (Table 4.2).

4.3.5 Fertiliser use

Semi-commercial growers used an average of 31 kg N, 17 kg P, 27 kg K and 15 kg S/ha, while commercial growers use 41 kg N, 26 kg P, 40 kg K and 27 kg S/ha per crop cycle (Figures 4.6 and 4.7). However, there was a wide range in fertiliser use between growers. For example, N fertiliser ranged from 16 to 25kg N/ha for semi-commercial growers and from 22 to 86 kg N/ha for commercial growers. Hartemink and Johnston (1998) demonstrated that fertiliser application increased taro yields from 8 to 23.3 t/ha when 100 kg N, 50 kg P and 100 kg K/ha was applied as compared to no fertiliser application. In their study nutrient uptake by whole taro plant was 91 kg N, 31 kg P and 215 kg K/ha. Based on their study it could be stated that the taro growers surveyed are potentially using insufficient quantities of N, P and K inputs in their farms, especially on areas were continual cropping has resulted in a decline in soil nutrient reserves.

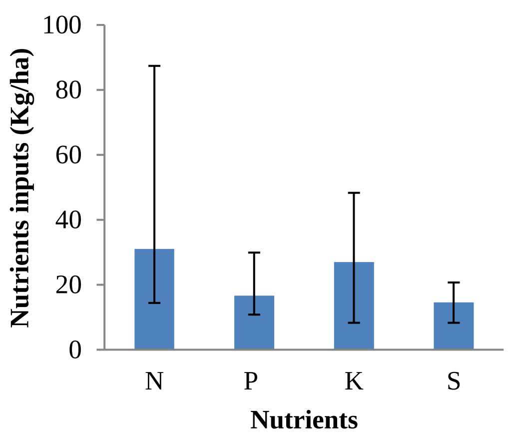


Figure 4.6 Nutrient inputs used by the semi-commercial taro growers (Error bars represent range for taro yields)

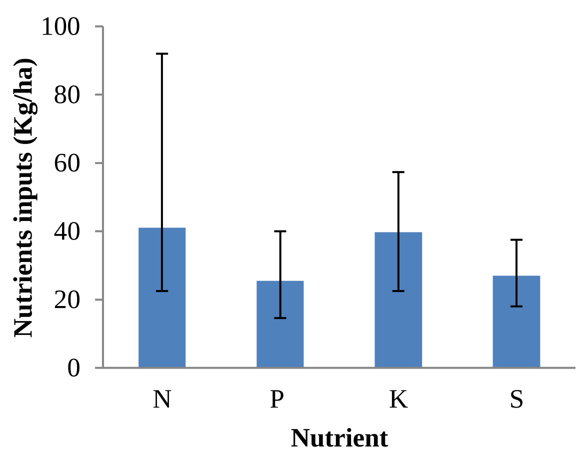


Figure 4.7 Nutrient inputs used by the commercial taro growers (Error bars represent range for taro yields)

4.3.6 Types of fertilisers used

Of the different type of fertiliser products used by the taro growers surveyed, the two most widely used products were a NPK (13-13-21) and urea. The proportion of farmers using NPK (13-13-21) and urea were 33% for each fertilise for semi-commercial growers and 66 and 10%, respectively, for commercial growers.

In the semi-commercial category 33% of the growers use NPK 13-13-21 fertiliser at the rate of 230 kg/ha, 33% use urea at the rate of 180 kg/ha, 17% use NPK 13-6-16 at the rate of 180 kg/ha and 17% use NPK 8-10-10 at the rate of 190 kg/ha. In the commercial category, 66% of the growers use NPK 13-13-21 at the rate of 273 kg/ha, 7% use NPK 13-6-16 at the rate of 250 kg/ha, 10% use NPK 8-10-10 at the rate of 400 kg/ha, 7% use NPK 15-15-15 at the rate of 150 kg/ha and 10% use urea only at the rate of 200 kg/ha (Figure 4.8 and 4.9).

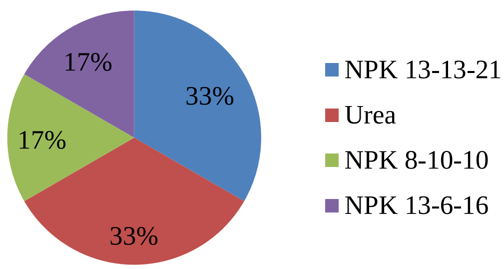


Figure 4.8. Fertiliser types used by semi-commercial growers.

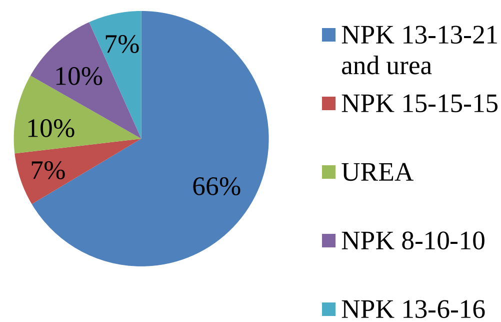


Figure 4.9. Fertiliser types used by commercial growers.

4.3.7 Timing of fertiliser application

The majority of the surveyed growers in both grower categories only used basal applications of fertiliser applied at planting (Figure 4.10 and 4.11). A small proportion of the farmers apply fertilisers in one and two split applications. When all of the fertiliser is applied at planting, then there is a high risk that some of the nutrients, especially N, will leach from the rooting zone during the growing period. For crops like taro with long growing periods (7 months) and which grow in high rainfall environments, only applying fertiliser at planting is likely to contribute to inadequate nutrient supply later in the growing period. Root formation and rapid root growth take place immediately after planting, followed by rapid growth of the shoot until 6-8 weeks after planting (WAP). This phase is known as establishment. At this phase, the plant is still developing its roots and is unable to use all the nutrients supplied at planting. This is followed by a grand growth phase (vegetative growth) in which taro plants accumulate dry matter very rapidly reaching a peak at 22 to 24 WAP (FAO, 2006). Therefore, the addition of the more mobile nutrients, N and K, should be applied in split applications prior to when the crop reaches its peak growth.

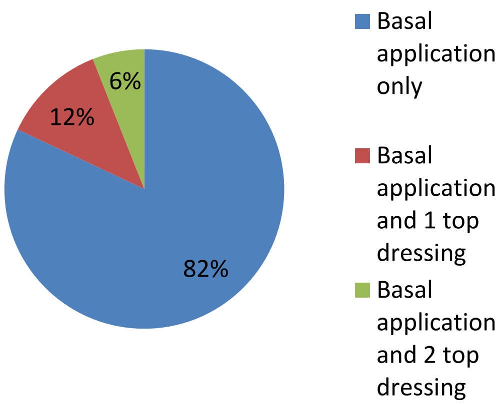


Figure 4.10. Timing of fertilisers used by semi-commercial growers

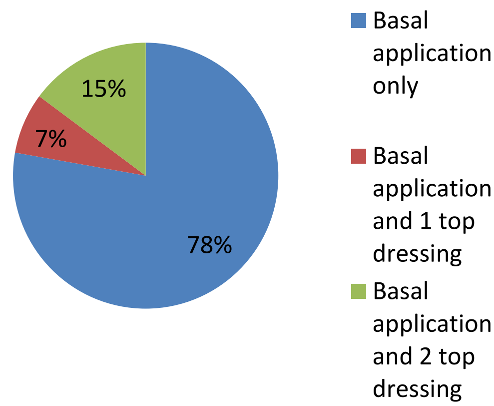


Figure 4.11. Timing of fertilisers used by commercial growers

4.3.8 Fertiliser placement methods used by surveyed taro growers

The majority of growers (52%) place fertilisers at the bottom/base of their planting hole (approximately 20 cm below soil surface), while 27% of the growers place fertilisers on top of the hole (beside the plant), 15% apply fertilisers in the middle of the planting hole (approximately 10 cm below the surface) and 6% mix fertilisers thoroughly in the planting hole (Figure 4.13). The majority of the farmers are using their own experience and advice from other farmers when making decisions about how to apply fertiliser, rather than advice from extension officers. When mobile nutrients, such as N, K and S, are surface applied they are able to move with soil water to reach the roots for uptake. However, if they are applied below at the bottom of the planting hole then these nutrients are at greater risk of leaching below the effective rooting zone (Figure 4.12). In contrast, less mobile nutrients, such as P, will only move a small distance through diffusion and if they are applied at the surface where roots are not developed then the plant may not take up these nutrients. If less mobile nutrients like P are applied at the bottom of the planting hole, then this may also limit the proportion of roots that are in close proximity to this nutrient source, which may also restrict availability to the crop. Most growers place fertiliser at the bottom of the planting hole at planting; this practice, in addition to the low rates of fertiliser used, will further limit nutrient availability to the crop. Therefore, fertiliser placement practice is likely to be another factor contributing to the low taro yields observed for most of the farms surveyed.

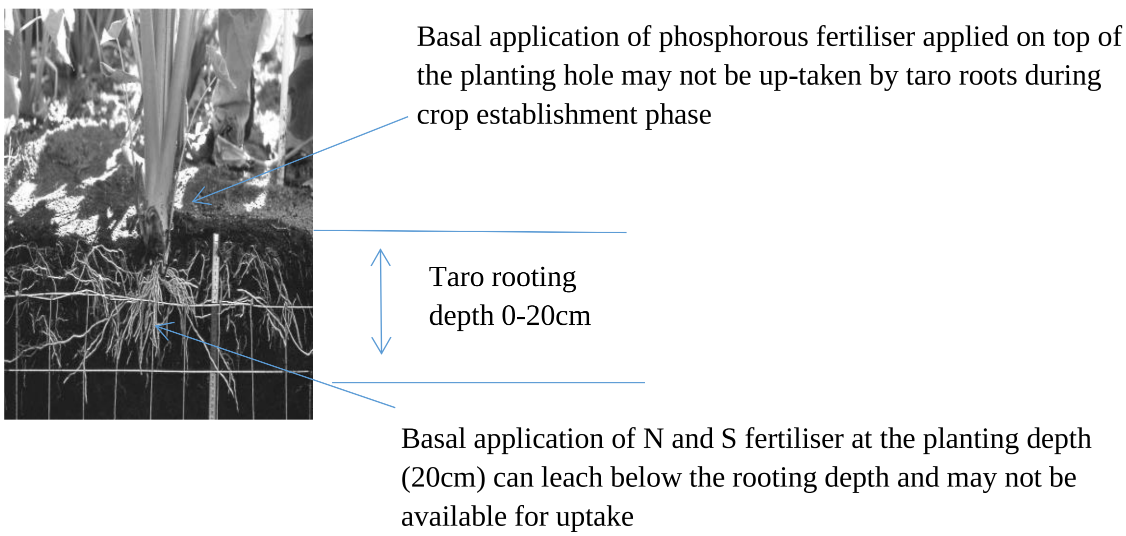


Figure 4.12 Taro rooting architecture

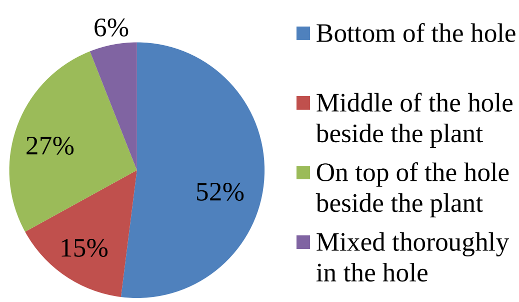
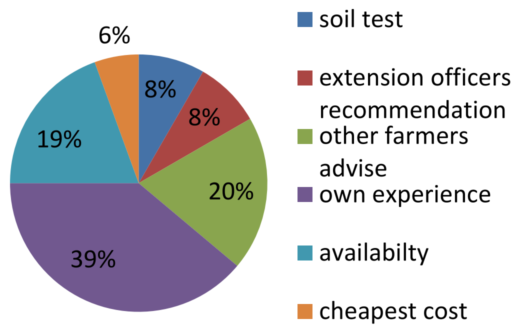


Figure 4.13 Fertiliser placement methods used by taro growers

4.3.9 Factors influencing growers' decisions on fertiliser use

There are a number of factors influencing fertiliser use decisions of the growers surveyed (Figure 4.14 and 4.15). For semi-commercial grower's fertiliser use was most frequently determined based on their own experience (39%), followed by other farmers' advice (20%) and then the availability of fertiliser material (19%). Only a small proportion of growers use soil tests (8%) or advice from extension officers to determine fertiliser requirements. For the commercial growers, fertiliser use decisions are also most frequently determined based on their own experience (30%) and by another farmer's advice (30%), but a higher percentage use soil tests (27%), compared to semi-commercial growers. However, only a small proportion of commercial growers used advice from extension officers (13%) to determine fertiliser requirements.

The failure of the majority of growers to use soil tests as a basis of fertiliser use may partly explain the low soil test values for most farmers surveyed. The limited reliance on advice on extension officers may be attributed to there being only three extension officers to serve 3,632 growers across the whole island. Studies by Nisha (2013) on Taveuni also stated that 94% of the farmers interviewed have never had the soil on their farm tested. Growers who are using their own experience and other farmers' advice may not be aware of how much nutrient inputs need to change when as soil fertility declines with continuous cropping. Fertiliser rates that were adequate when natural soil fertility was high, may be insufficient to replace nutrient losses and achieve good yields after many years of cropping. This is especially true for crops like taro that have high rates of nutrient removal in the harvested crop. Hartemink and Johnston (1998) stated that with corm yields of 23.3 t/ha, taro removed a total of 91 kg N, 31 kg P, 215 kg K, 74 kg Ca and 15 kg Mg/ha, which need to be replenished.



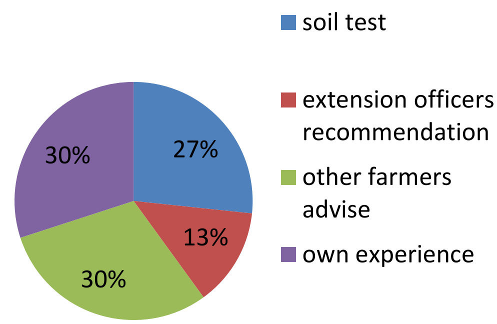


Figure 4.14 Decision on fertiliser use by semi-commercial taro growers

Figure 4.15 Decision on fertiliser use by commercial taro growers

4.4 Discussion

Taro yields of surveyed growers on Taveuni Island were mostly low (average of 6.9 t/ha), compared yields previously achieved when the industry commenced of approximately up to 15-20 t/ha (Sharma, 2015). The majority of taro growers surveyed had Olsen P levels of below 10 mg/kg, which implicates Olsen P as a primary limiting factor affecting taro yields on most farms surveyed. To achieve yields of 10-15 t/ha, soil Olsen P of > 20 mg P/kg have been recommended (Thiagalingam, 2000). The survey showed that no growers with Olsen P levels with less than 9 mg/kg, achieved yields greater than 9 t/ha. Therefore, it would be expected that yield gains are likely to be achieved by increasing Olsen P levels to a minimum of approximately 10 mg P/kg. The highest yields achieved were approximately 10 t/ha, even for farms with Olen P levels > 20 Olsen P. Therefore, it is likely that other key growth limiting nutrient, such as N and K, could be limiting further yield increases above 10 t/ha for sites with optimum soil P status. The majority of the growers (65%) also had low soil exchangeable K levels on their farms (< 0.4 me/100g). However, the relationship between soil exchangeable K and taro yields was not strong, which may be due to available P being the most limiting factor at most the sites surveyed.

On an average, semi-commercial growers use 31 kg N, 17 kg P, 27 kg K and 15 kg S/ha, while commercial growers use 41 kg N, 26 kg P, 40 kg K and 27 kg S/ha. Estimates of overall efficiency of these applied fertilisers are typically less than 60% (Baligar and Bennett, 1986, Manirique, 2008). Previous studies on phosphate adsorption on Fiji soils have shown that significant quantities of added P are strongly adsorbed by soils, especially by the Al and Fe hydrous oxide mineral, and only limited quantities (10-30%) of fertiliser P are utilised by plants (Dandy and Morrison, 1980; Morrison *et al*., 2005). While taking overall nutrient use efficiencies in account, it could be said that both categories of growers are using insignificant quantities of nutrients (Table 4.3), especially on sites with many years of continuous cropping. Most grower are applying less the 50% of the amount of nutrient required to achieve good taro yields. In addition, the fertiliser placement practices of most growers involving only placing fertiliser at the bottom of planting hole, it also likely to be further limiting nutrient availability for crop growth.

As previously discussed, Olsen P test (0-20 cm soil depth) showed a strong relationship with taro yield on the surveyed farms. However, the amount of P fertiliser required to achieve a change in soil test Olsen value will depend on the P retention of the soil. Therefore, the amount of P required for the surveyed farms to achieve Olsen P soil test levels considered optimum of taro yield will vary depending on soil P retention. For example, for a soil with a low P retention (< 30%) it may require an average about 169 kg P/ha to increase soil Olen P level from the survey average of 7 mg P/kg to an optimum level of 20 mg P/kg. However, for a high P retention soil (> 60%) this could take as much as 377 kg P/ha. These are very high rates and are higher than would be recommended for any single crop. Taro is planted at 1 m spacing, therefore, it may not be necessary to increase the soil P status of an entire field, but instead target fertiliser addition to the area in close proximity to individual plants. This would reduce the amount of P required to achieve an Olsen P of 20 mg P/kg in the soil close to the plant. Commercial and commercial growers are applying 17 and 26 kg P/ha, respectively, and this partially explains why low Olsen P levels are prevalent in most of the farms. The majority of growers don’t use soil tests as a basis of fertiliser use and this may have contributed to the low fertility and taro yields.

Table 4.3 Approximate phosphorus rates required to raise grower soil Olen P test level of an average of 7 mg P/kg to an optimum level of 20 mg P/kg (add reference)

	Low (<30%) P retaining soils	**Medium (30-60%) P retaining soils**	**High (>60%) P retaining soils**
Mean Amount of P required (kg P/ha) to raise Olsen P by 1 unit in the 0-20 cm soil depth	13	19	29
Total amount of P required (kg P/ha) to reach 20 mg/kg Olsen P	169	247	377

Fertiliser placement may also have an influence on the availability of the limited quantity of nutrient used, especially the less mobile nutrients like phosphorus. The majority of growers (52%) place fertilisers at the bottom/base of their planting hole (20 cm below soil surface). This practice is likely to increase the leaching of more mobile nutrients, particularly N. It will also reduce the ability of crop roots to access the fertiliser P, due to the short distances P can diffuse to plant roots in soils. Root formation and rapid root growth take place immediately after planting, followed by rapid growth of the shoot until 6-8 weeks after planting (WAP). At this establishment phase, the plant is still developing its roots and is unable to use all the nutrients that is supplied at planting. This is followed by a grand growth phase (vegetative growth) in which taro plants accumulates dry matter very rapidly reaching a peak at 22-24 WAP. Most N and K fertiliser should be applied during vegetative phase and should be avoided after 22-24 WAP.

4.5 Conclusion

Taro yields from the surveyed taro farms were very low (average of 6.9 t/ha), compared yields of approximately up to 15-20 t/ha previously achieved. Soil fertility, especially soil P and K status, was low for most farm sites tested. Fertiliser inputs for most farms were also low, compared to rates required to replace the amounts of nutrient removed in the crop at harvest. The low fertiliser inputs and in combination with continues cropping practices are likely to have contributed to both a decline in soil fertility and taro yields. The soil test that was most strongly correlated with yield was Olsen P, which suggests that P availability is likely to be a key limiting factor influencing taro yield at most of the surveyed sites. The average Olsen P of the sites surveyed was 7 mg P/kg, which is very low for most horticultural crops. At three sites, it was possible to achieve a yield of 10 t/ha when Olsen levels were below between Olsen P of 9 and 20 mg P/kg. However, no sites with Olsen P levels of less than 9 mg P/kg achieved yields greater than 9 t/ha. The practice of most taro growers to apply all fertiliser at planting at the bottom of the planting of hole may also reduce the efficiency of the applied nutrients. The results of the survey have shown that there is potential to improve taro yields through improving soil fertility status and fertiliser application practices. There is limited research information available, from field trials in Fiji, to identify the optimum fertiliser rates for taro crop growing on soils with low fertility due to continuous cultivation. Further research is required to quantify the fertiliser practices required to improve taro yields on Taveuni Island.

Chapter 5 Field Experiment 1

This chapter describes the results of the first season's field experiment carried out at three sites on Taveuni Island, Fiji. This study was conducted to identify the optimum fertiliser N and P requirements to improve taro yield. Fertiliser placement methods; either the typical farmer practice of placing fertiliser at the bottom of planting hole or mixing in the planting hole, were also compared. Additionally, the effects of splitting N fertiliser applications between 3 and 4 splits and growing Mucuna (*Mucuna pruriens*), a green manure crop, intercropped with taro, on the taro yield were also evaluated.

5.1 Rainfall Data

The distribution of average monthly rainfall for the three experimental sites over the two-crop cycles, used for Experiments 1 and 2, are shown in Figure 5.1. The 2017 annual rainfall for the Qeleni, Lagiloa and Delaivuna sites were 3544 mm, 3386 mm and 3533 mm, respectively. The monthly rainfall values were similar between the sites over the experimental period, accordingly, the average for the three sites are presented. The month of December in 2016 had the lowest rainfall across all sites, with an average of 144 mm. This rainfall is lower than the average for that time of year, being less than half the 10 year average rainfall of 356 mm. The taro suckers for Experiment 1 were planted in December 2016, so the low rainfall is likely to be have limited influence on the crop development at that time, because water requirements would have been low during this initial establishment phase. The highest monthly rainfall occurred in May 2017, with an average of 423 mm, which is more than double the 10 year average of 186 mm for that month. The months of May to August are typically the driest time of the year, with the 10 year monthly rainfall ranging from 102 to 186 mm/month. However, during the experimental period monthly rainfall during this period did not fall below 190 mm. This indicates that during the experimental period, soil moisture availability would have been less of a limiting factor for plant growth compared average conditions.

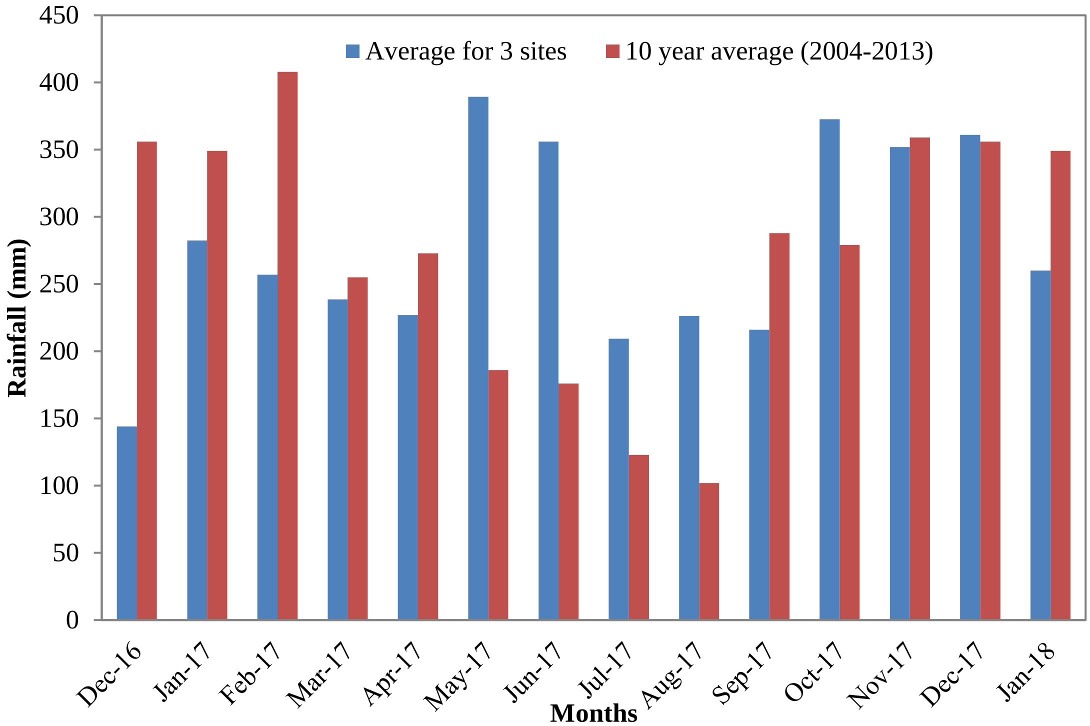


Figure 5.1 Average monthly rainfall for Qeleni, Lagiloa and Delaivuna sites and the 10 year monthly average rainfall for Taveuni

5.2 Site soil fertility status

Table 5.1 shows the mean soil test values prior to the treatment application. Delaivuna site had the highest P retention value of 74%, while the Qeleni site had the lowest P retention capacity of 12%. The pH values for Delaivuna and Qeleni sites were 5.7, while the Lagiloa site had a pH value of 5.6. The Total N (%) at Qeleni, Lagiloa and Delaivuna sites were 0.8, 1.2 and 0.5, respectively. The Olsen P values at Qeleni, Lagiloa and Delaivuna sites were 6, 8 and 6, respectively. The exchangeable K (me/100 g) levels at Qeleni, Lagiloa and Delaivuna sites were 0.39, 0.23 and 0.24, respectively.

Table 5.1 Mean soil test (0-20 cm soil depth) values for the three experimental sites prior to treatment application

Experimental Site	P-Retention (%)	pH	Total N (%)	Olsen P (mg P/kg)	Exchangeable K (me/100 g)
Qeleni	12	5.7	0.6	6	0.39
Lagiloa	56	5.6	1.2	8	0.23
Delaivuna	74	5.7	0.8	6	0.24

5.3 Taro fresh corm yield

5.3.1 Site effects on taro fresh corm yield

There was a statistically significant ($P < 0.05$) site effect on mean taro fresh yield between the three experimental sites. The mean yields for all treatments were 10.9 and 10.4 t/ha at the Lagiloa and Delaivuna, respectively, which were significantly higher than the mean yield of 9.5 t/ha at the Qeleni site.

Fresh taro yields for the control treatment (N0P0; 200 kg K/ha and 82 kg S/ha) were similarly low for all three sites, 5.6, 5.9 and 5.8 t/ha at Qeleni, Lagiloa and Delaivuna, respectively (Figure 5.2). As N and P rates increased, there was a general trend of yields increasing at all three sites. At the lower rates of N (0 and 100 kg N/ha), the Lagiloa site showed a greater yield response to increasing P rates, compared to the other two sites. This site had the highest soil total N, which may have contributed it having a higher plant available N status, which may explain the higher response to P at the lower rates of applied N. At all three sites, the highest yields where achieved at fertiliser N rates of 200 kg N/ha, with no yield advantage from further increasing N rate to 300 kg N/ha. Applying N at a rate of 200 kg N/ha with no added P (i.e. N120P0), significantly increased yield at all three sites, compared to the control treatment, achieving yields of 8.0, 9.6 and 10.2 t/ha at Qeleni, Lagiloa and Delaivuna, respectively.

At the Qeleni site, when N was applied at a rate 200 kg N/ha, increasing P rate to 120 kg P/ha achieved a yield of 12.7 t/ha, which was significantly higher than the 0 and 60 kg P/ha rates. At the Lagiloa and Delaivuna sites, when N was applied at 200 kg N/ha, the 120 kg P/ha rate achieved yields of 13.3 and 13.4 t/ha, respectively, which were significantly higher than the 0 kg P/ha rate but not the 60 kg P/ha rate. Qeleni site had lower initial soil Total N content (0.6%) while the other two site had > 0.8% Total N.

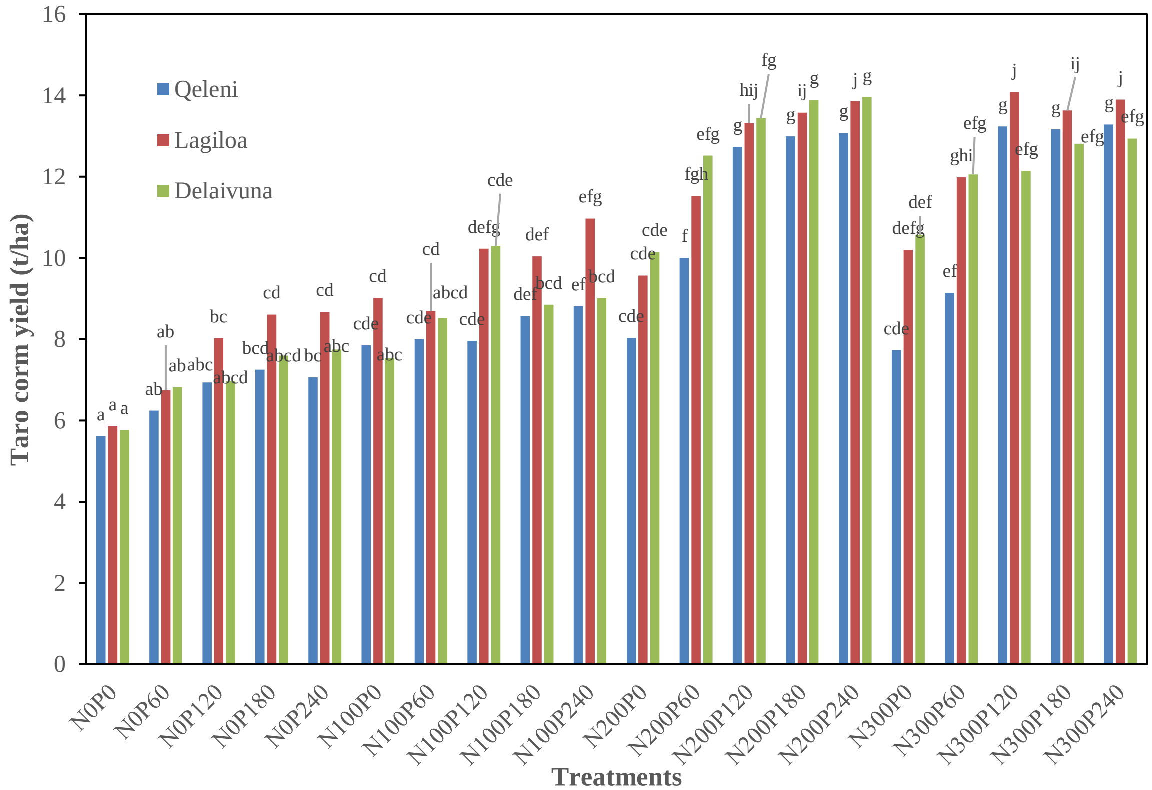


Figure 5.2 Treatment effect on taro yields at each site

(All treatments also received 200 kg K/ha and 82 kg S/ha in fertiliser. Bars with the same letter at each site are not significantly different from each other at 5% significance level.)

Overall, the yield responses to N and P addition were similar between the sites, therefore, these treatment effects are discussed in more detail for the three sites on average in the next section. All treatments, including the control treatments, received the same rates of K (200 kg K/ha) and S (82 kg S/ha), so the effects of these nutrients on yield were not evaluated in this experiment, however, the yield response to K fertiliser is assessed in Experiment 2, which is discussed in chapter 6.

5.3.2 Fertiliser treatment effects taro fresh corn yield

The overall effects of N and P fertiliser treatments on taro fresh corm yields on average for the three sites are presented in Figure 5.3. Fertiliser N applied at a rate of 200 kg N/ha, when no P was applied (N200P0), significantly increased yield compared to the control; from 5.8 to 9.3 t/ha. Further adding N in the absence of P did not result in further yield increases. While the yield achieved at the 200 kg N/ha rate was higher than 8.1 t/ha achieved with the 100 kg N/ha rate (N100P0), the difference was not significant. Likewise, applying P at a rate of 180 kg P/ha, when no N was applied, significantly increased yield compared to the control treatment, from 5.8 to 7.8, with no further yield increases observed when P was applied at 240 kg P/ha. However, the yield achieved at the 180 kg P/ha was not significantly higher than the two lower rates of P (60 and 120 kg P/ha).

The lowest rates of N and P inputs, to achieve the highest statistically significant taro yield were 200 kg N/ha and 120 kg P/ha. This treatment achieved a yield of 13.2 t/ha, which was more than double the control treatment yield. Further increasing these nutrients rates up to 300 kg N/ha and 240 kg P/ha did not result in additional yield increases. Across all the three sites, there was no additional benefit in increasing the N rate above 200 kg/ha and the P rate above 120 kg P/ha, when K and S rates were 200 kg K/ha and 82 kg S/ha, respectively.

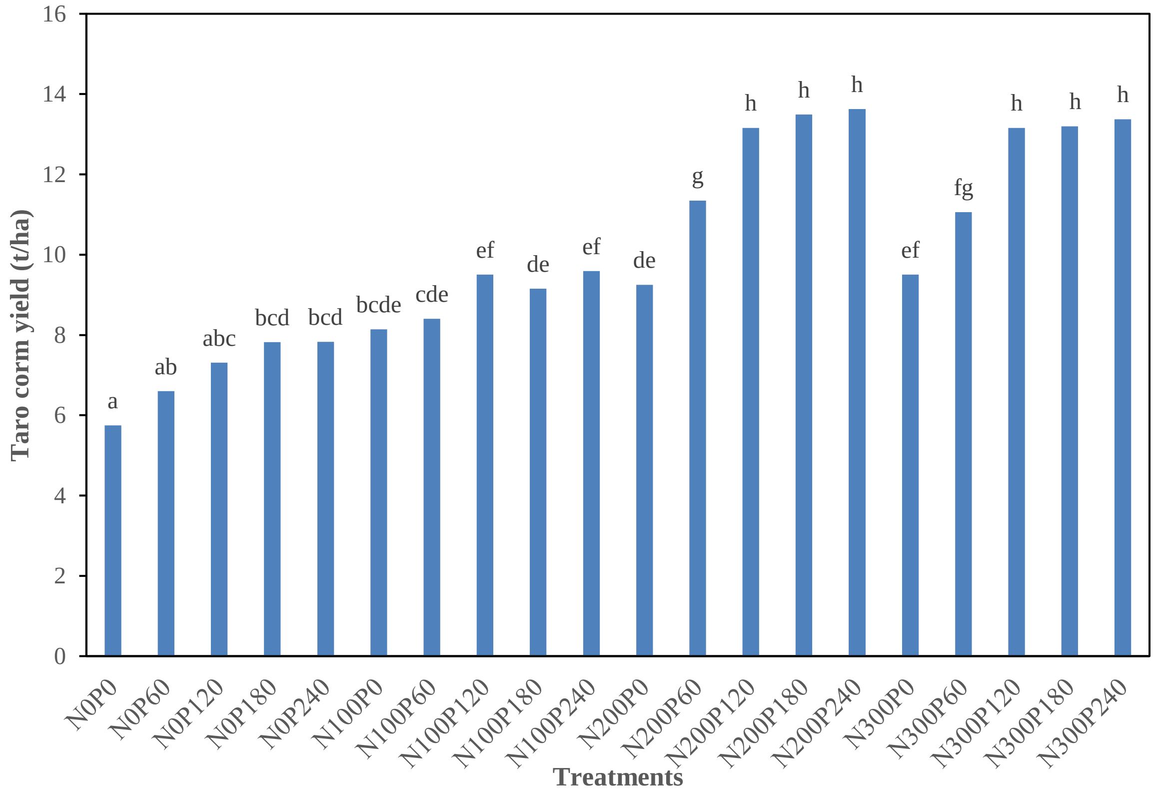


Figure 5.3 Effect of different treatments on taro corm yields across the three sites on average

(All treatments also received 200 kg K/ha and 82 kg S/ha fertiliser. Bars with the same letter are not significantly different from each other at 5% significance level)

Nitrogen fertiliser application rate had a strong positive relationship (R^2 =0.86) with taro yield at all sites, when 120 kg P, 200 kg K and 82 kg S/ha were also applied (Figure 5.4). In addition, P fertiliser addition had a strong positive relationship with taro yield (R^2 = 0.77), when 200 kg N, 200 kg K and 82 kg S/ha was also applied (Figure 5.5). Increasing N rates above 200 kg N/ha or P rates above 120 kg P/ha, did not significantly increase taro yields. At the 200 kg N/ha N fertiliser rate, when 120 kg P/ha was also used, yield increased to 13.2 t/ha, an increase of 81% compared to the N0P120 fertiliser treatment yield of 7.3 t/ha. When neither N nor P were applied (i.e. control treatment), the average yield was 5.8 t/ha. Therefore, the addition of P at a rate of 120 kg P/ha, when in the absence of N, had the potential to increase yield by 1.5 t/ha. In comparison, applying 200 kg N/ha without P fertiliser achieved a yield of 9.3 t/ha, which is 3.5 t/ha increase compared to the N0P0 treatment. Therefore, overall a greater response was observed for N fertiliser addition than for P fertiliser addition.

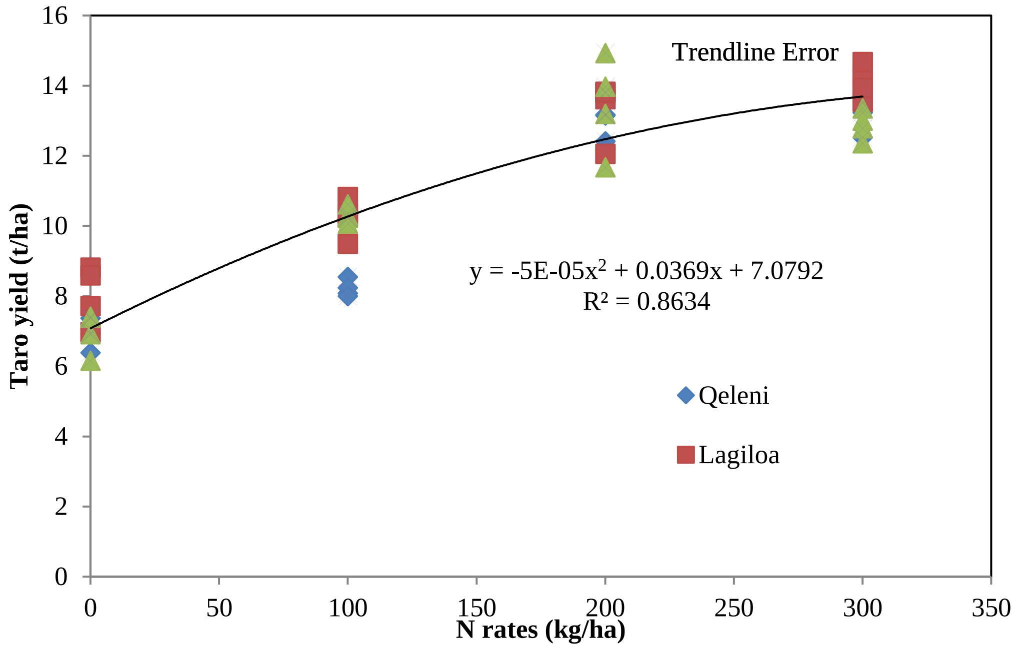


Figure 5.4 The effect of N fertiliser rates on taro corm yields

(All treatments also received 120 kg P, 200 kg K and 82 kg S/ha)

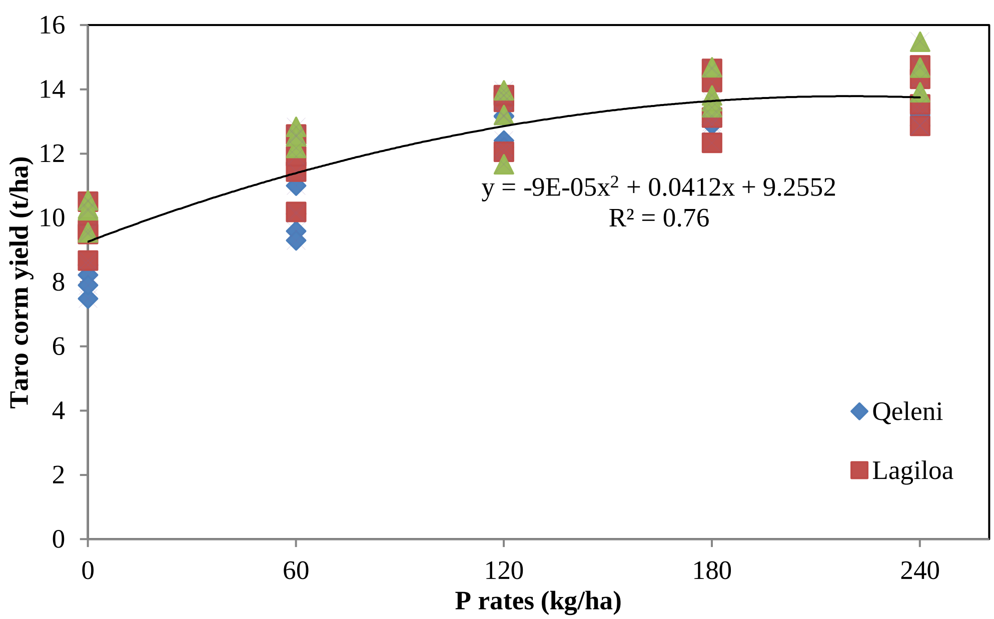


Figure 5.5 The effect of P fertiliser inputs on taro corm yield

(All treatments also received 200 kg N, 200 kg K and 82 kg S/ha)

Yield is dependent on combined N and P inputs (Figure 5.6). Multiple regression analysis of all the sites revealed that there was an overall significant ($P < 0.0001$) multivariate relationship ($R^2 = 78$; $F = 173.77$) between the rates of fertiliser inputs (N, and P) and the corm yield of taro as per the predictor model:

Taro yield (kg/ha) = 5.487 + 0.029 N (kg/ha) - 0.00005N^2 (kg/ha) + 0.023P (kg/ha) - 0.00007P^2 (kg/ha) + 0.000035NP (kg/ha).

This model indicates that optimum taro yield is dependent on both N and P inputs when 200 kg/ha K fertilisers are applied. Initially, increase in N and P inputs up to 200 kg N and 120 kg P/h, increases taro yield significantly but beyond these rates, the yield stagnates at between 13-14 t/ha. This indicates that further addition of N and P fertilisers above 200 kg N and 120 kg P/ha will not significantly increase taro corm yields. This model can be used to predict taro yield when 200 kg K and 82 kg S/ha is also applied to the crop.

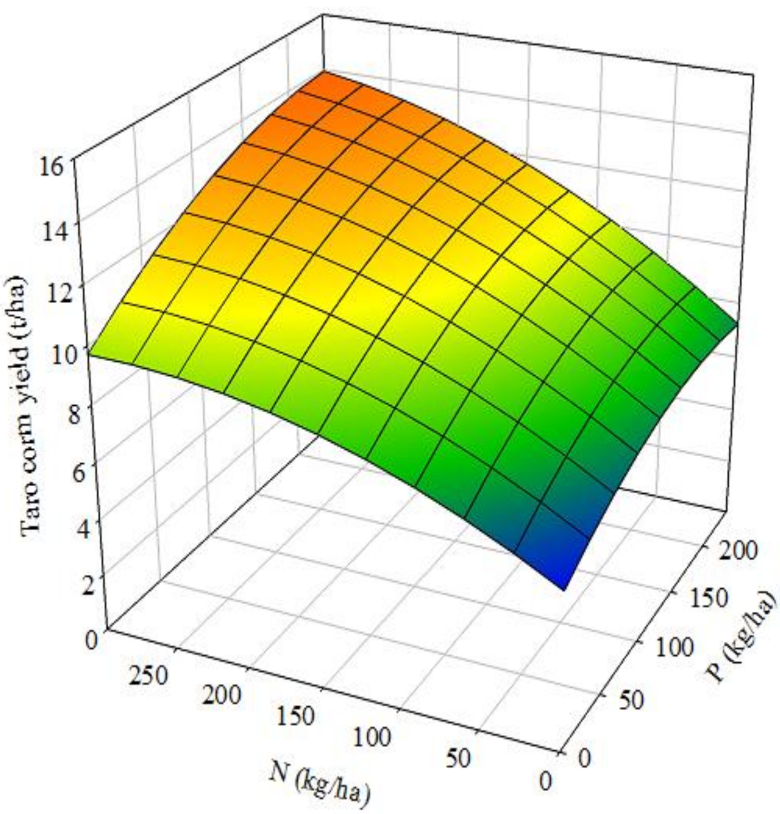


Figure 5.6 Corm yield as influenced by N and P fertiliser inputs

(All treatments also received 200 kg K and 82 kg S/ha)

5.3.3 Effect of split N applications on corm yields

In high rainfall environments there is a greater risk of N leaching from the soil, which can decrease the recovery of fertiliser N by the crop. To mitigate this, the Fijian Ministry of Agriculture recommendation is to apply N after the crop has established in three split applications at 5, 10 and 15 weeks after planting. This experiment compared this recommendation with a treatment that involved applying a portion of the N also at planting. The two different N split application strategies were 3 split application (5, 10 and 15 WAP) and 4 split applications (0, 5, 10 and 15 WAP), both applying a total of 100 kg N/ha in even applications, to assess the effect on taro yield. Both treatments also received 60 kg P, 200 kg K and 82 kg S/ha.

At all three sites (Qeleni, Lagiloa and Delaivuna) there were no significant (difference between the two split N application treatments (Figure 5.7). However, at Lagiloa and Delaivuna there was moderate to high statistical evidence ($P=0.09$ and 0.10, respectively) supporting that the 4 split application treatment resulted in higher yields of 10.2 and 10.6 t/ha, compared to the 8.7 and 8.5 t/ha, respectively, for the 3 split application treatment ($P<0.10$). This supports that there can be a yield advantage from applying a portion of the N fertiliser at planting. Applying a portion of the N fertiliser at planting, increased mean taro yield by 20.3% across the Lagiloa and Delaivuna sites. In comparison,applying 200 kg N/ha in three split applications (excluding planting) increased yield by 39.5%, for these sites. Therefore, applying 100 kg N/ha in four split applications, including at planting, gave about half of the additional yield increase achieved with an additional 100 kg N/ha (i.e. total of 200 kg N/ha) applied in three applications. These results indicate that N availability in the first 5 weeks after planting has a potentially strong positive effect on taro yield and, suggesting that N fertiliser addition should start earlier than the current recommendation.

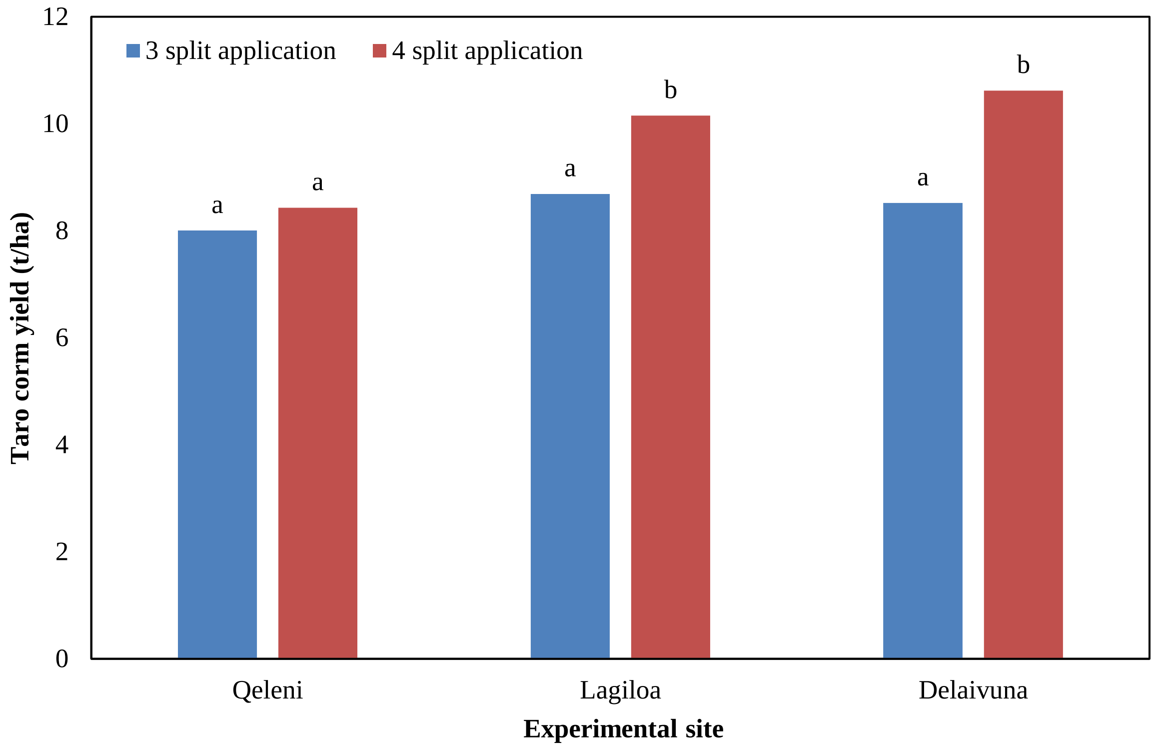


Figure 5.7 Taro corm yields as influenced by split application of 100 kg N/ha fertiliser

(All treatments received 60 kg P, 200 kg K and 82 kg S/ha)

5.3.4 Effect of phosphorus fertiliser placement method on taro fresh corm yield

Two different methods of P fertiliser placement, of 60 kg P/ha applied either at the bottom of planting hole or mixed in the planting hole, were also evaluated during this experiment (Figure 5.8). Both the treatments also received 300 kg N, 200 kg K and 82 kg S/ha. Mixing P fertiliser in the planting hole significantly (P=0.02) increased taro yield compared to compared to placing the fertiliser at the bottom of the planting hole at the Qeleni site, but not the other two experimental sites. At Qeleni, mixing P fertiliser in the planting hole achieved a yield of 9.1 t/ha, 23% higher than when fertiliser was placed at the bottom of the hole (7.4 t/ha). Overall yields were lower at Qeleni and this site was more responsive to P addition, when N rate was high, compared to the other two sites, which may indicate that yield at this was limited more by P availability. While all three sites had very low Olsen P values, the soil at Qeleni had the lowest total N level, probably reflecting lower soil organic matter status, which could mean a lower potential to supply available P from mineralisation. While applying P to the bottom of the planting hole (i.e. ~20 cm below the soil surface) is currently the main practice used by taro farmers in Taveuni, a disadvantage of this practice is that the P is placed below soil sampling depth (0-20 cm), which would prevent it from being accounted for in future soil tests. Therefore, mixing the P in the plant hole rather than applying at the bottom of the hole is expected to both improve P utilisation by the taro crop and enable the effect of P fertiliser addition to be monitored with soil tests.

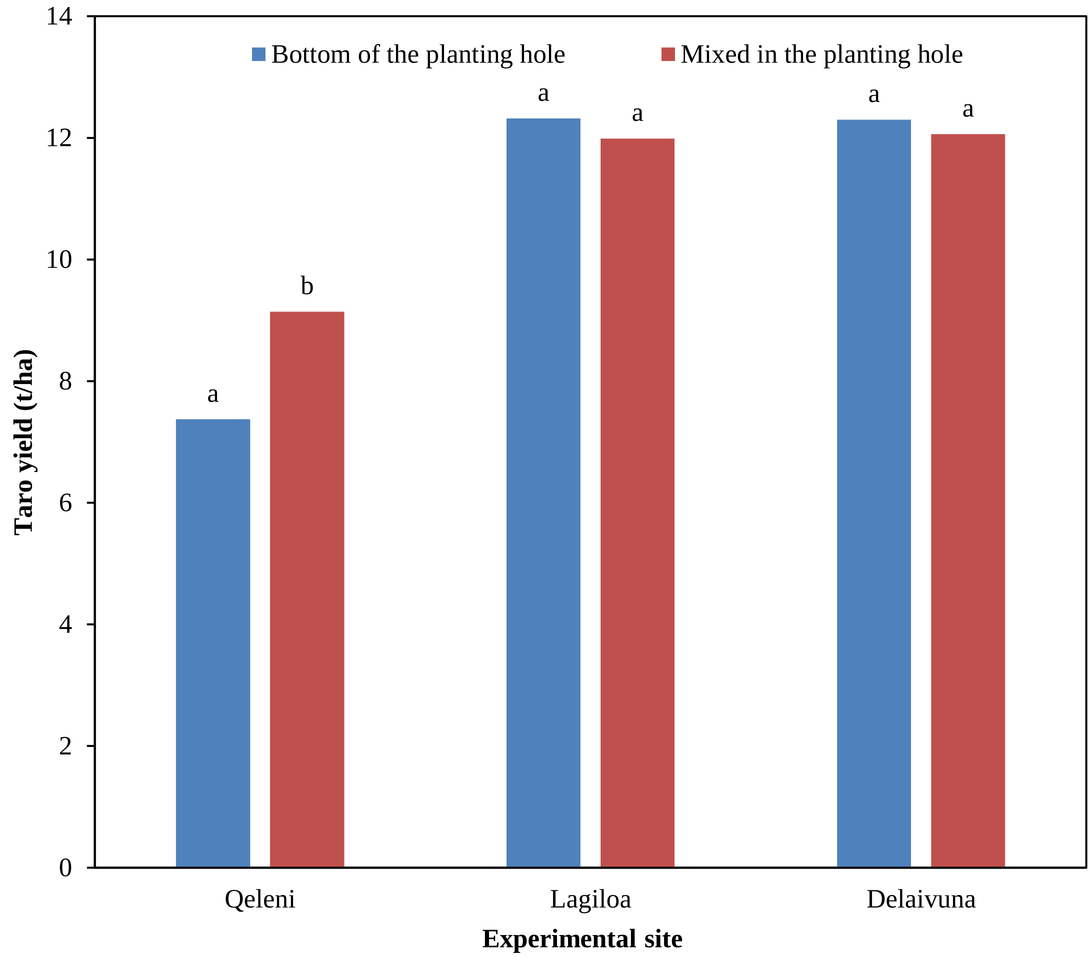


Figure 5.8 Effect of P fertiliser placement on taro corm yield

(all treatments received 300 kg N, 60 kg P, 200 kg K and 82 kg S/ha)

5.4 Taro sucker numbers

5.4.1 Site effects on taro sucker numbers

The effect of different N and P fertiliser treatments on the number of taro suckers produced was assessed for all treatments at all three sites (Figure 5.9). For the control treatment (N0P0), the number of suckers produced were 19,100, 30,600 and 28,400 suckers/ha, at the Qeleni, Lagiloa and Delaivuna sites, respectively. For most treatments, sucker numbers were lower at the Qeleni site, compared to the other two sites, which could also be due to the Qeleni site having a lower soil total N concentration. At all sites, there was a general trend of sucker numbers increasing with increasing N fertiliser rate, with the highest sucker numbers being achieved at the highest rate of N applied of 300 kg N/ha. For example, the N300P0 treatment resulted 103,400, 120,300 and 106,300 sucker/ha (i.e. 10.3, 12 and 10.6 suckers/plant), at the at the Qeleni, Lagiloa and Delaivuna sites, respectively, which were about 3.7-5.4 times the control treatment values. At the Qeleni site, there was no effect of P fertiliser rate on sucker numbers at any of the N fertiliser rates. At the other two sites, overall, there were minimal consistent effects of P rate on sucker numbers. Because the N and P fertiliser treatment effects on sucker numbers were similar across the three sites, they are discussed in more detail on average for all sites in the next section.

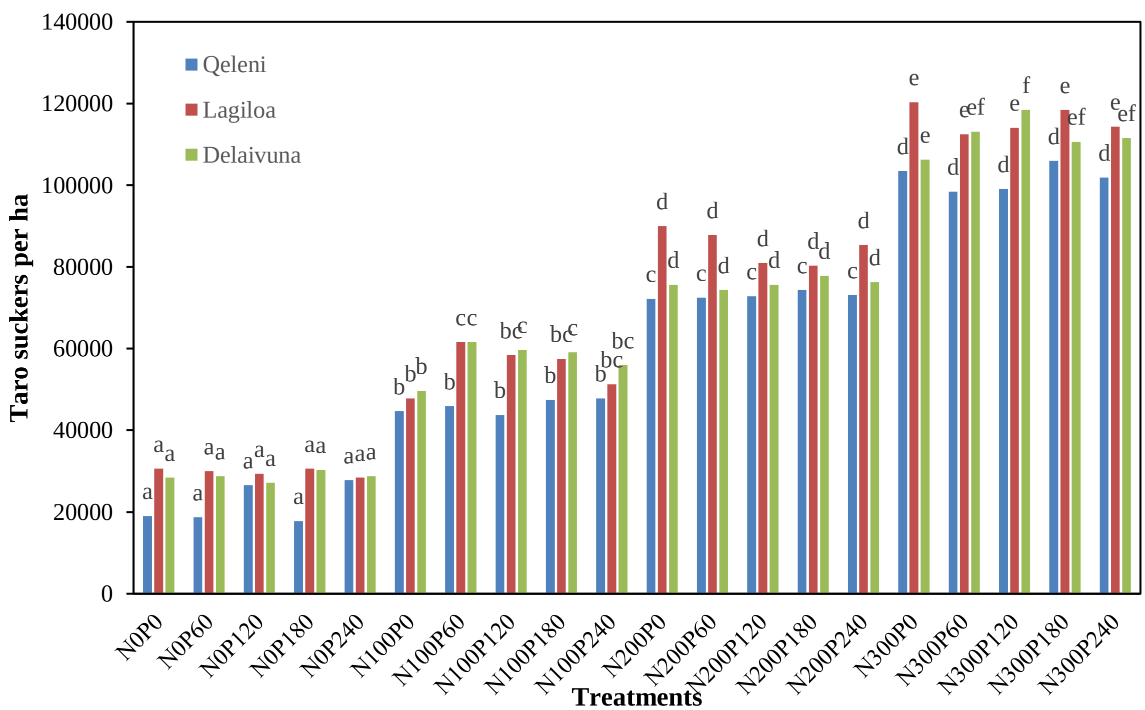


Figure 5.9 Effect of different treatments on taro sucker numbers

(All treatments also received 200 kg K and 82 kg S/ha in fertiliser. Bars with the same letter are not significantly different from each other at the 5% significance level within a site).

5.4.2 Effects of N and P fertiliser rates on taro sucker numbers

The effect of treatments on sucker numbers showed a highly significant difference ($P<0.001$) between N rates (Figure 5.10). There was a clear trend of sucker numbers increasing with N fertiliser rate, with there being significant differences between each N rate, being 26,800, 52,800, 77,900 and 109,900 suckers/ha for the 0, 100, 200 and 300 kg N/ha treatments, respectively. However, there were no significant differences between P rates on sucker numbers.

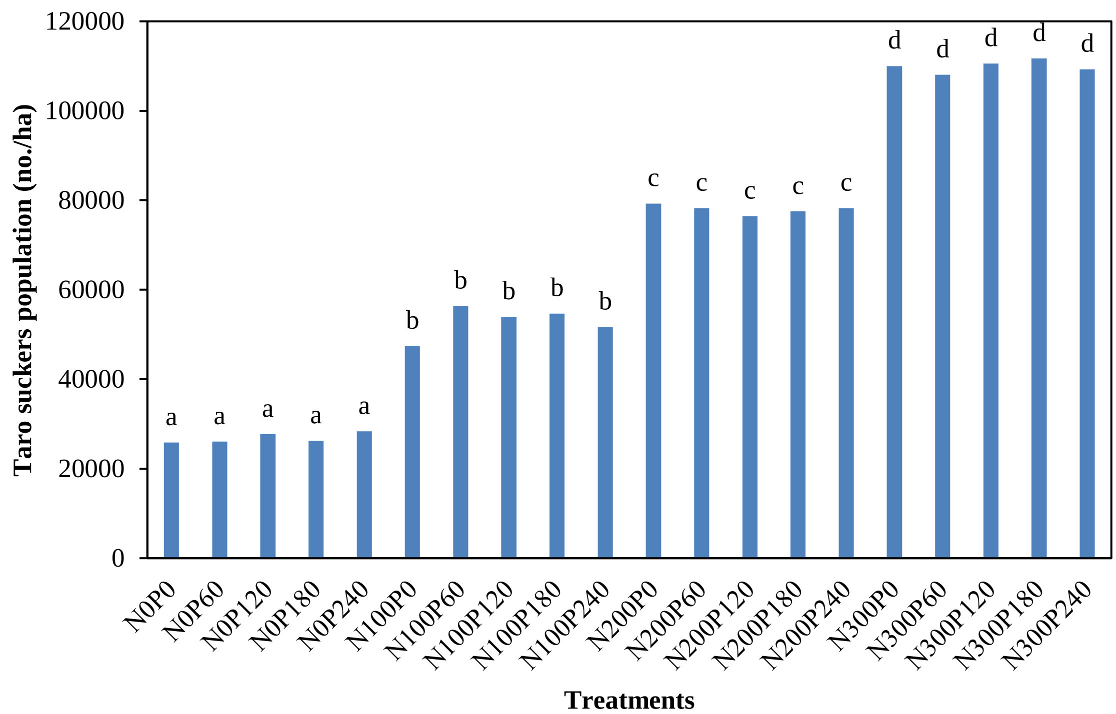


Figure 5.10 Effect of different treatments on taro sucker population across all 3 sites on average

(All treatments received 200 kg K and 82 kg S/ha in fertiliser. Bars with the same letter are not significantly different from each other at 5% significance level).

The relationship between N fertiliser rate and taro sucker numbers for the three sites on average was very strong ($R^2 = 0.94$, Figure 5.11). At a P rate of 120 kg P/ha, when not N fertiliser used then sucker numbers are an average of 27,700 sucker/ha (i.e. about 2.8 suckers/plant). At the highest rate of N used (300 kg N/ha), the number of suckers grown increased to 110,500 suckers/ha (i.e. about 11.1 suckers/plant). This equates to about 27,600 suckers/ha (i.e. ~2.8 suckers/plant) for every 100 kg N/ha applied. The relationship between

N rate and sucker numbers was linear up to the highest rate of N (300 kg N/ha) used in the experiment , consequently, it is not possible to ascertain at what rate of N the maximum number of taro suckers would be achieved. However, given that the highest taro yield was achieved at 200 kg N/ha, the only advantage for increasing N rate above 200 kg N/ha would be to increase sucker production. While all the rates of N used in the linear relationship presented in Figure 5.11 also received 120 kg P/ha, it is expected that this relationship will be similar irrespective of P rate. This is because P rate did not have a significant effect on sucker numbers for the three sites on average, as previously discussed.

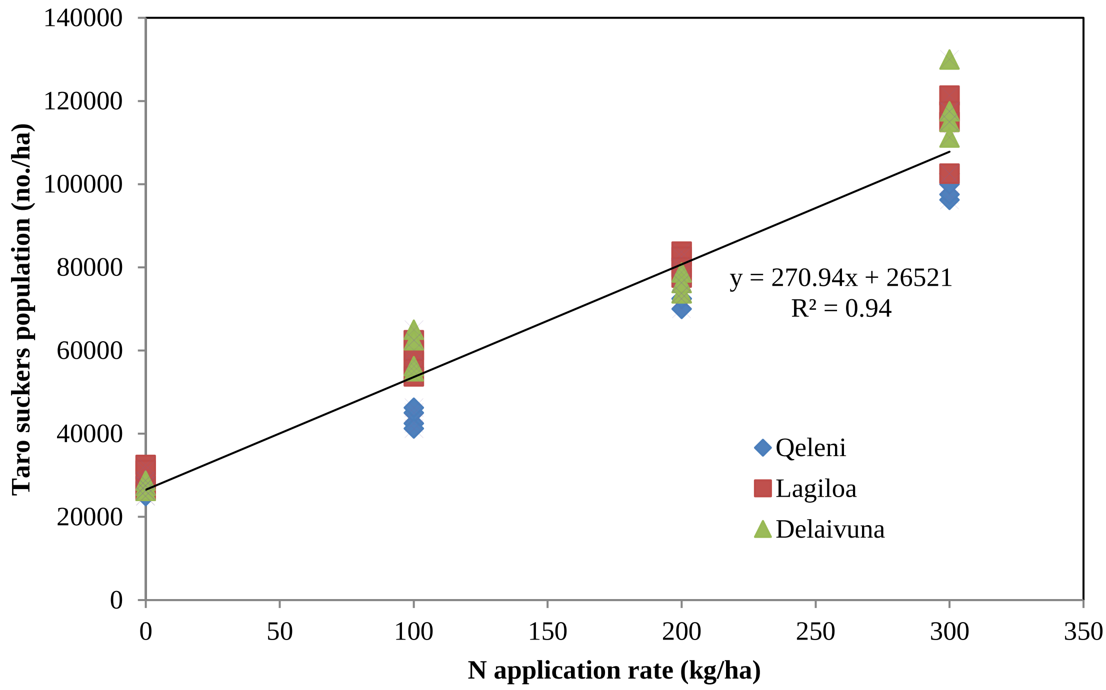


Figure 5.11 The effect of N application rate on Taro sucker population (all treatment received 120kg P, 200 kg K and 82 kg S/ha in fertiliser)

5.4.3 Effects of split applications of N fertiliser on sucker numbers

A comparative study was done to evaluate the effect of applying a total of 100 kg N/ha that was split applied in either 3 or 4 even applications on sucker numbers (Figure 5.12). The timings of the split applications are previously described (Section 5.2.3). Both of the split application treatments also received 60 kg P, 200 kg K and 82 kg S/ha. At all three sites, 4 split application of 100 kg N/ha resulted in significantly higher sucker numbers, compared to 3 split applications of same total rate of N. The increases in sucker numbers were similar across the three sites, being 11,300, 9,300 and 9,300 suckers/ha at the Qeleni, Lagiloa and Delaivuna sites, respectively. On average, across all three sites, 4 split applications of 100 kg N/ha resulted in an average sucker number of 64,000 suckers/ha, which was significantly higher than the 54,000 suckers/ha achieved by three split application of the N treatment. Based on the relationship between N fertiliser rate and taro sucker numbers (27,600 suckers per 100 kg N/ha) presented in Figure 5.11, this increase of 10,000 suckers/ha (i.e. 1.0 suckers/plant) would be equivalent to adding an additional 36 kg N/ha using three split applications. This adds a further benefit to that was observed with increased corm yields at two sites from applying N at four times, including at planting, rather than only 3 times.

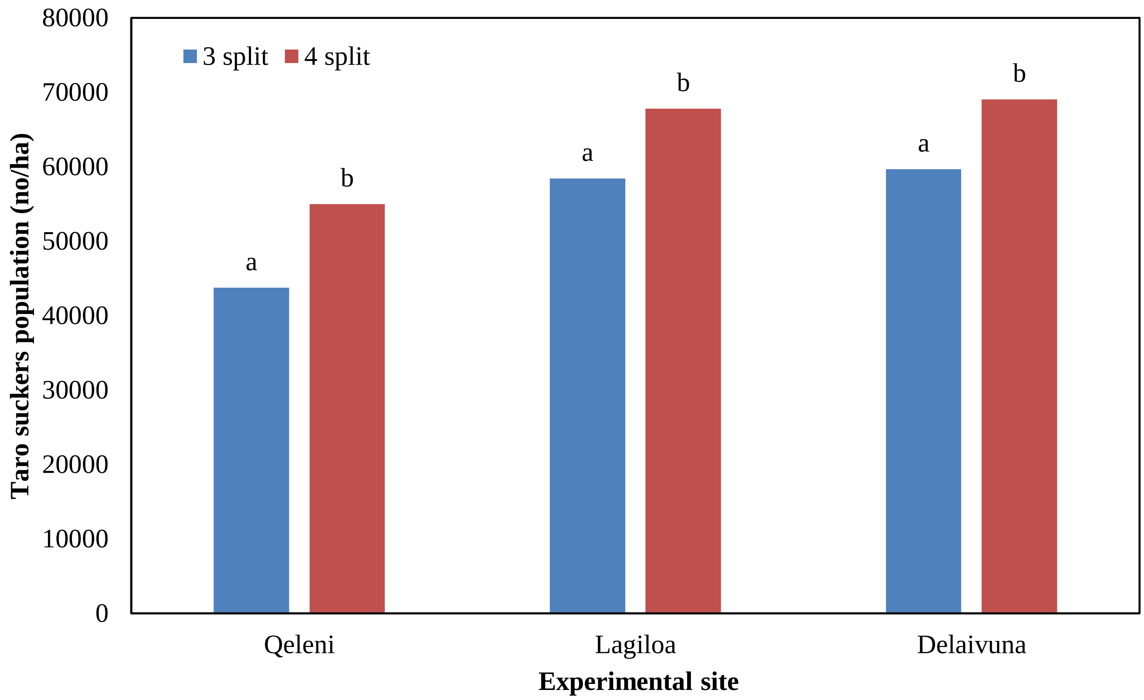


Figure 5.12 Taro sucker numbers as influenced by split applications of 100 kg N/ha

(All treatments received 60 kg P, 200 kg K and 82 kg S/ha in fertiliser).

5.5 Effect of Mucuna green manure

5.5.1 Effect of Mucuna green manure on taro fresh corm yield

The use of a Mucuna green manure crop treatment had a significant ($P<0.05$) effect on taro corm yields at all three sites (Figure 5.13). When Mucuna was grown with the 100 kg N and

60 kg P/ha fertiliser treatment (i.e. N100P60+Mucuna), the average yield across all three sites was 11.0 t/ha, significantly higher (P<0.05) than the yield of 8.4 t/ha for the same fertiliser treatment without Mucuna. The high P treatment, N100P240+Mucuna, achieved an average yield across all three sites of 13.2 t/ha, which was also significantly higher than the yield of 9.6 t/ha for the same fertiliser treatment without Mucuna. Thus, the Mucuna contributed to a 37% increase in corm yield. While the N200P240 treatment achieved a yield (13.62 t/ha) significantly higher than the N100P240 fertiliser treatment, it gave a similar yield to the N100P240+Mucuna treatment. This suggests that Mucuna incorporated with 100 kg N/ha crop has a yield benefit equivalent to a fertiliser treatment of 200 kg N/ha. In other words, the Mucuna gave a similar yield benefit of up to 100 kg N/ha, when P addition was high. In this experiment, Mucuna was only grown using either the 60 or 240 kg P/ha fertiliser rates. However, the taro yield response to P fertiliser increased with P addition up to 120 kg P/ha. Therefore, it is expected that the effect of Mucuna on corm yield at the120 kg P/ha rate, would be similar to that seen with the 240 kg P/ha treatment. This is assessed further in Experiment 2 in chapter 6.

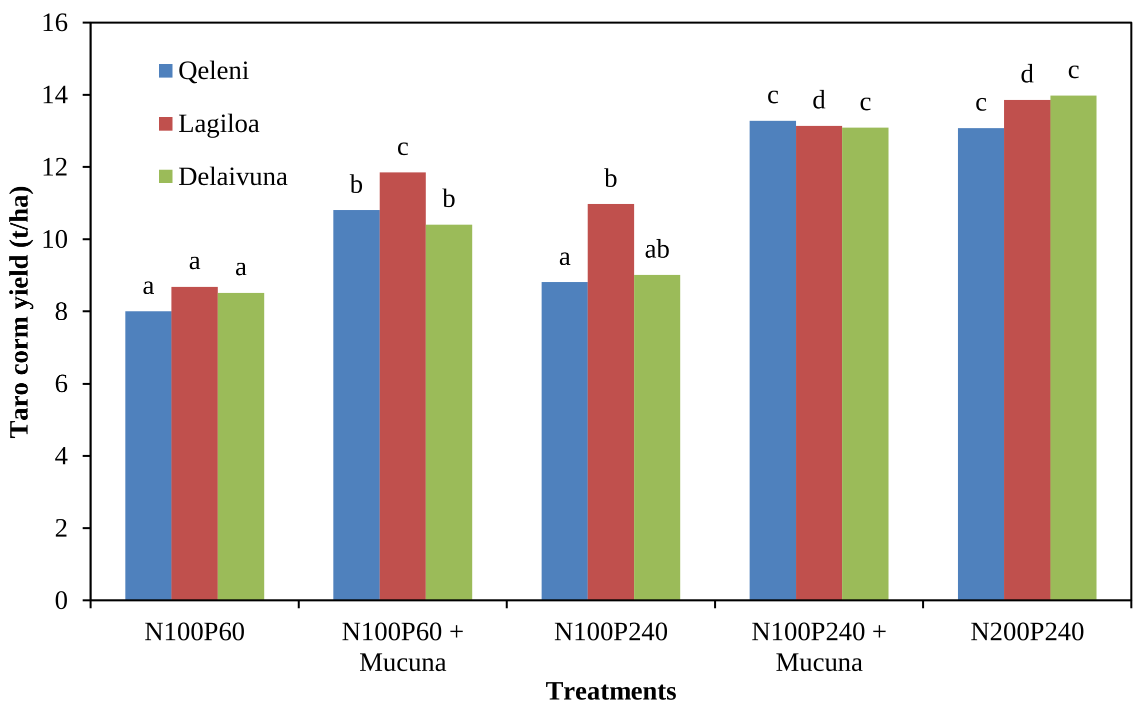


Figure 5.13 Effect of cover crop treatments on taro yield (All treatments received 200 kg K and 82 kg S/ha in fertiliser)

5.5.2 Effect Mucuna green manure on taro sucker numbers

The effects of the Mucuna green manure treatment on sucker numbers was highly significant at all three sites ($P < 0.001$) (Figure 5.14). The N100P60+Mucuna treatment achieved 77,400 suckers/ha (i.e. 7.7 suckers/plant) for the three sites on average, which was 46% higher ($P < 0.05$) than the 52,900 suckers/ha produced by the same fertiliser treatment without Mucuna. The high P treatment, N100P240+Mucuna, produced 79,800 suckers/ha, which was also significantly higher than the number of the suckers (55,100 suckers/ha) for the same fertiliser treatment without Mucuna, representing a 45% increase from Mucuna use. Only at the Delaivuna site was there a significant difference between the sucker numbers for the N100P60+Mucuna and N100P240+Mucuna, with the higher P treatment increasing sucker numbers by 13.6% (9,700 suckers/ha). Both the N100P60+Mucuna and N100P240+Mucuna treatments achieved similar sucker numbers to the N200P240 without Mucuna.

Overall, the effect of Mucuna used with 100 kg N/ha had a similar effect on sucker numbers as applying 200 kg N/ha without Mucuna. This 100 kg N/ha equivalent benefit from Mucuna is similar to the findings of the previous section. There was no effect on sucker numbers from increasing P rate from 60 to 240 kg P/ha, but as seen previously (Figure 5.10), sucker numbers were not influenced by P fertiliser addition.

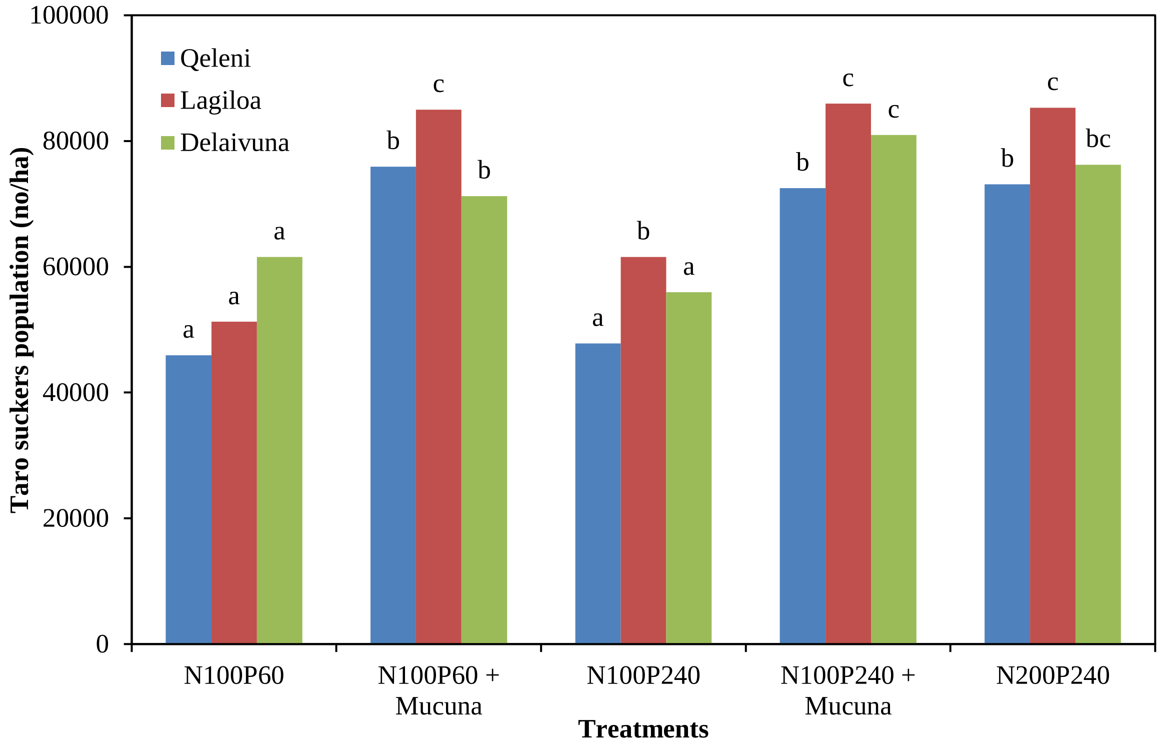


Figure 5.14 Effect of Mucuna cover crop treatments on taro suckers

(All treatments received 200 kg K and 82 kg S/ha in fertiliser)

5.6 Discussion

This experiment showed consistent results, across three field sites, of the influence that N and P fertiliser addition had on both taro corm yield and sucker number production. All three sites had low initial soil fertility as a result of continuous long-term (i.e. > 10 years) cropping. Therefore, the crop responses seen to nutrient inputs are reflective of this context. While this experiment did not study the effect of K and S, these nutrients were supplied to all treatments at high rates to reduce the likelihood that their soil status would limit crop growth. When neither N or P fertiliser were applied, the average corm yields were very low at all sites, being on average 5.8 t/ha. As well as being a low yield, average corm yield was about 0.6 kg/corm, which is well below the >1 kg/corm size required by export markets. As a result a high proportion of this control (N0P0) treatment yield would be rejected for sale; therefore, marketable yield would have been only 40%.

Taro yields increased significantly as N and P fertiliser rates were increased up to 200 kg N/ha and 120 kg P/ha to an average site corm yield of 13.1 t/ha. This is a total yield gain of 7.4 t/ha compared to the control treatment, on average for the three sites. Adding 200 kg N/ha without P fertiliser gave a corm yield of 9.4/ha, which was 3.4 t/ha higher then compared to no N or P fertiliser treatment. Whereas adding 120 kg P/ha fertiliser with no N fertiliser achieved a corm yield of 7.3 t/ha, which was only 1.5 t/ha higher than the no N and P fertiliser treatment. Therefore, N fertiliser addition had a larger influence on increasing yield than P fertiliser addition; however, the combined effect of adding both nutrients was greater than the sum of their individual effects. All sites had very low initial Olsen P values that were less than 10 mg P/kg soil, which would explain why yields were responsive to P fertiliser addition up to a rate. In addition, all sites have been used for long-term (i.e. > 10 years) cropping, which is reflected in the low soil total N levels across all three sites. Accordingly, this would contribute to low levels of N being available from mineralisation from soil organic matter and result in the crop being responsive to N fertiliser addition.

Rates of 200 kg N and 120 kg P/ha were shown to have the highest significant influence on increasing corm yields. In comparison, the Fijian Ministry of Agriculture recommended N and P fertiliser use for taro are only 50% and 33% of these rates, respectively. This Ministry recommendation is based on experiments that were conducted in early 1980's, on the research fields of Koronivia Research Station, which has different soil types, rainfall and would have been less intensively cropped, compared to the three experimental site used in the current study. However, the grower survey conducted showed that on average farmers were using even lower rates of N and P than those recommended by the Ministry and much lower than those identified in the current study as being optimum. On average, Taveuni growers were only using 18% of the optimum N and P rates. In addition, on average they were only using 34 kg K/ha (17%), compared to 200 kg K/ha used on all treatments in this experiment. The current practice of very low rates of nutrient inputs on sites that have experienced long-term cropping; probably explain the low yields achieved by farmers in recent years. A main finding of the current study of is that very low soil fertility and very low nutrient returns by farmers is the main factor causing the decline in taro yields in Taveuni.

Suminarti *et al*., (2016) achieved a taro corm yield of 16.7 t/ha in Indonesia using fertiliser rates of 127 kg N and 164 kg K/ha in rain fed dry land farming system. Before planting they had applied 9 t/ha poultry manure with an estimated 90 kg N and 163 kg P/ha, bringing total applied N to the crop to 217 kg N/ha. The soils in their experiment was silty clay loam, with soil pH of 6.5; organic C content of 0.63%; and K content of 1.0 me/100 g (soil P values are not mentioned). Daniells *et al*. (2009), in irrigated fertiliser response studies on dry land taro in Australia, achieved optimum taro yields of 32.6 t/ha (95% corms with marketable weight), which was more than double the yields achieved in the current study. This yield was achieved with the addition of 340 kg/ha N, 320 kg/ha P and 540 kg/ha K. In his study with the addition of 240 kg/ha N, 270 kg/ha P and 360 kg/ha K, taro yields were 31.2 t/ha (89% marketable yield). The K rate used in this study is much higher than that used in the current study, which may indicate that K could have limited yield potential at the higher N and P rates used in the current study, particularly as the initial soil test K level were low (<0.4 me/100 g) at all three sites.

There was a strong linear relationship between N fertiliser use and taro sucker population up to the maximum rate of N used, which was 300 kg N/ha. The maximum number of suckers achieved was ~110,500 suckers/ha (i.e. 11.1 suckers per plant) on average across the three sites. There was an average increase of ~27,600 suckers/ha per 100 kg N applied. Nitrogen promotes above ground vegetative growth (Manirique, 1984), which was observed in this experiment. Across all 3 sites, a 4-split application of N improved sucker numbers compared to 3 split applications. Addition of P had no significant effect on sucker numbers, however, there are no literature to support this. In this study all treatments received 200 kg K and 86 kg S/ha, so it is not possible to determine the influence of these nutrients on sucker numbers. The use of four split applications provides a strategy that farmers can use to improve both corm yield and sucker numbers with lower inputs of N fertiliser.

Mixing P fertilisers in the planting hole increased taro yield compared to placing the fertiliser at the bottom of the planting hole at one of the three sites. At the Qeleni site, mixing 60 kg/ha P fertiliser in the planting hole increased yield by 1.7 t/ha (23%). Corm formation in taro is upwards from where the bottom of the sucker is planted. The fibrous root system develops from the base of the initial corm (Onwueme, 1999) and plant progressively grows more roots out from the side of the corm as it develops upwards toward the soil surface. This pattern of root development, and the very low initial Olsen P levels, would help explain why there was a yield advantage from applying P throughout the planting hole, rather than just at the bottom of the hole. In this experiment, the two P fertiliser placement methods were only compared at the lowest rate of P of 60 kg P/ha, therefore, it is not known whether P placement would have also made a difference at higher rates. Another consideration with P fertiliser placement, is that if all the P is applied at the bottom of the planning hole (at about 20 cm depth) future soil sampling at 0-20 cm depth may not detect the presence of this added P, which could potentially underestimate the available P status of the soil.

Inter-cropping taro with Mucuna as a green manure crop was estimated to provide an equivalent benefit, in terms of increased corm yield and sucker numbers, as applying up to an additional 100 kg N/ha. This indicates that the amount of N accumulated by the Mucuna crop, as well as the rate and timing residue decomposition/mineralisation, were valuable to the taro crop. While N uptake and dry matter yield of the Mucuna were not assessed in this experiment, they were assessed in the subsequent experiment (Chapter 6). In this experiment, Mucuna growth was terminated by chopping the plants with a knife at 16 WAP (flowering stage) and the residues were allowed to decompose on the soil surface providing a mulching effect. In another Fijian study, Lal (2013) found that the N accumulated by a Mucuna crop was 145 kg N/ha at 26 WAP. Other studies of N accumulation by Mucuna have shown that it can accumulate very high quantities of N, between 145- 412 kg N/ha (Buckles *et al*., 1998; Steinmaier and Ngoliya, 2001; Martini, 2004; Lal, 2013). It has also been estimated that between 70-96% of total N accumulated of Mucuna N is fixed from atmospheric N and the remainder coming from available soil N (Sanginga *et al.,* 2001; Chikowo *et al.*, 2004; Goh and Chin, 2007; Ngome *et al.*, 2011). Some of the benefit provided by the Mucuna may also have been due to improved weed suppression and a mulching effect of Mucuna crop (Lal, 2013, Anand 2015).

All sites in the experiment had soil pH levels that are considered below optimum for taro growth and, therefore, there may be potential to further increase yields above the highest yields observed in this experiment through the use of liming to increase soil pH. In addition, the only rate of K used in this experiment was 200 kg K/ha and, therefore, establishing a taro yield response to K use was not determined. Therefore, the subsequent experiment includes the use of lime and different rate of fertiliser K as treatments. With the high rates of P applied in some of the fertiliser treatments, it is also worth investigating whether there is any carry-over effect of this on yield of a subsequent taro crop.

5.7 Conclusion

On Taveuni Island, taro corm yields on long-term continuous cropping sites can be substantially improved by increasing fertiliser use above the rates currently used by farmers and above the rates recommended by the Ministry of Agriculture. Corm yields were responsive to N and P across all three sites in this experiment, with high rates of both of these nutrients required to achieve the highest yields. Taro sucker numbers were responsive to N but not P, with there being a linear relationship between sucker numbers and N fertiliser use up to the highest rate of N used. Therefore, following natural disasters, such as cyclones or droughts, when sucker numbers are limited, then the use of N fertiliser, with minimal P fertiliser, may be a cost-effective way to help re-establish the taro industry and minimise the inflation in sucker prices, given that N fertiliser is relatively cheap compared to P fertiliser. Increases in sucker numbers were also observed from applying a portion of the fertiliser N at planting, rather than waiting until 5 WAP to apply the first application, which is the Ministry of Agriculture recommendation. The effectiveness of P fertiliser on corm yield can also be improved by mixing the fertiliser in the planting hole at planting, rather than applying at the bottom of the planting hole. Corm yields and sucker numbers were improved by inter-cropping taro with a Mucuna green manure crop, which showed an ability to maintain higher yields with lower N fertiliser inputs. Further research is required to quantity the effect of liming and different K fertiliser rates on taro corm yield and sucker numbers. It will be useful to also assess whether the high P fertiliser rates used in this experiment improve soil P status for subsequent crops.

Chapter 6 Field Experiment 2

6.1 Introduction

This chapter describes the results of the second season's field experiment carried out at three sites on Taveuni Island. Results from Experiment 1 quantified the response of taro corm yields and sucker numbers to N and P fertiliser addition, when K and S fertilisers were applied at a constant rate to all treatments. This chapter reports the results from a follow-on trial assessing the response of taro corm yield and sucker numbers to different rates of K fertiliser. This experiment also gave the opportunity to investigate whether the high rates of P fertiliser applied in the previous experiment had any significant carry-over effect on the succeeding crop. The influence of P fertiliser placement methods, either mixing in the planting hole or placed at the bottom of planting holes (i.e. farmers practice), on taro corm yield, was also evaluated. The effect of Mucuna, as a green manure crop intercropped with taro, provided corm and sucker yield related benefits in the first experiment, which was further investigated in this experiment. Lime was also included as a treatment in this experiment. A constant supply of calcium is required in the root environment for continued root growth. Calcium deficiency in taro is characterized by reduced root and shoots growth and can predispose plants to soil-borne diseases when roots die back and become open to invasion by pathogens (Miyasaka *et al. 2002)*. Two sources of lime, Fijian lime and imported New Zealand (NZ) lime, were compared. Fiji extracted lime is $17.75/40 kg bag while NZ lime is $12.78/20 kg bag.

Treatments were allocated based on the previous treatments used in Experiment 1 and some treatments were repeated. This was done to evaluate the carry over effects of P and N addition from Experiment 1. Results of this experiment aim to contribute to the development of appropriate nutrient management recommendations for improving taro production in a sustainable manner.

6.2 Taro corm yield

6.2.1 Mean taro yields at experimental sites

Mean taro yields across the three experimental sites are shown in the Figure 6.1. The average site yields were 9.5, 10.4 and 10.9 t/ha at the Qeleni, Delaivuna and Lagiloa sites, respectively. On average, the yields were significantly higher at the Lagiloa site, compared to the other two sites. A possible reason for this is that Lagiloa site received more sunshine because it is on a sloping site facing in a northerly direction and it also has less shading compared to the other two sites. Lagiloa site was situated on a north-east direction and had less shading effect as compared to other sites.

6.2.2 Fertiliser treatment effect on taro yield at each site

At all three trial sites there was a significant treatment effect on taro yields, with all treatments being significantly different ($P < 0.05$) from the Control (N0P0K200) treatment, which produced yields of 5.9, 5.4 and 7.6 t/ha at the Qeleni, Delaivuna and Lagiloa sites, respectively (Figure 6.2).

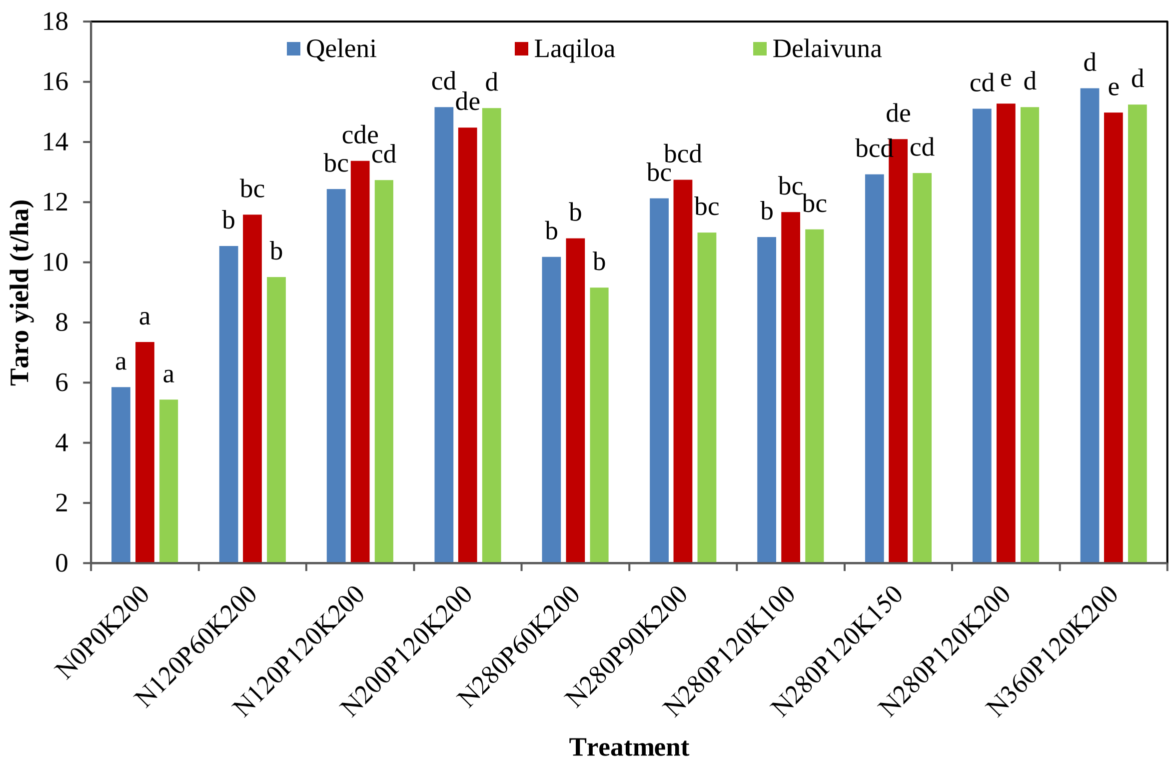


Figure 6.1. Effect of the main fertiliser treatments on taro yield at each site

(Values with the same letter are not significantly different from each other at 5% significance level. The effects of P fertiliser placement, Mucuna green manure and lime treatments are presented later in this chapter).

The highest taro corm yields at these sites were 15.1, 15.2 and 15.3 t/ha, respectively, for the N280P120K200 treatment, however, this treatment was not significantly higher than the

N200P120K200 treatment, which had a lower rate of N applied. Overall, the yield responses to N, P and K addition were similar between the sites, consequently mean treatment effects are discussed in more detail across all three sites.

6.2.3 Overall fertiliser treatment effect

The overall effects of N, P and K fertiliser treatments on taro yields across all sites are shown in Figure 6.3. Increasing the inputs of these major nutrients increased taro yield. At the highest rates of P and K (120 kg P and 200 kg K/ha), there was a significant ($P < 0.05$) increase in yield with increasing N addition up to 200 kg N/ha, however, higher rates of N did not further significantly increase yield.

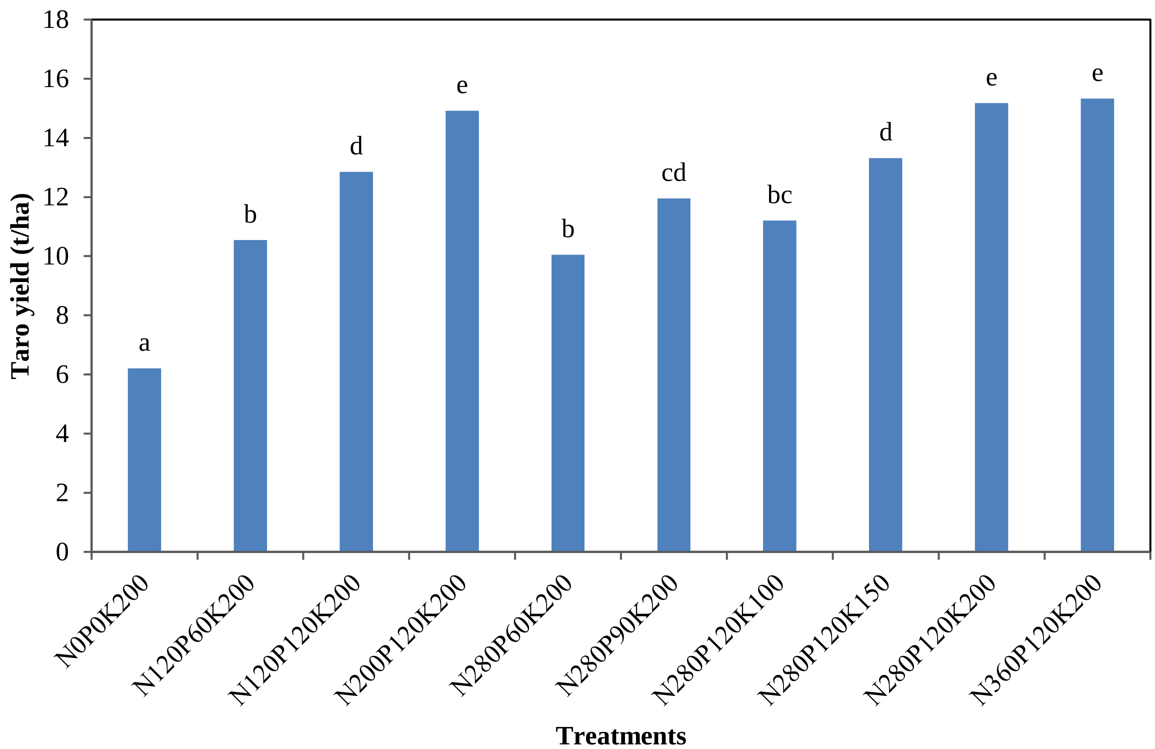


Figure 6.2. Effect of the main fertiliser treatments on taro yields for the three sites on average

(Values with the same letter are not significantly different from each other at 5% significance level. The effects of P fertiliser placement, Mucuna green manure and lime treatments are presented later in this chapter).

When N and K were applied at high rates (280 kg N and 200 kg K/ha), taro yield increased with increasing rates of P up to 120 kg P/ha, the highest rate of P used in this experiment. At the highest rates of N and P used (280 kg N and 120 kg P/ha), taro yield increased significantly with increasing K rates up the highest rate of K used (200 kg K/ha). All treatments received the same rate of S (82 kg S/ha) so it was not possible to determine the influence that S fertiliser addition had on yield.

6.2.3.1 Effect of N fertiliser rates on taro corm yields

On average, N fertiliser addition had a strong positive effect ($R^2 = 0.60$) on taro yield when 120 kg P, 200 kg K and 82 kg S/ha were also applied (Figure 6.4). There were significant ($P < 0.05$) increases in yield up to a N fertiliser rate of 200 kg N/ha. Increasing N rate from 120 to 200 kg N/ha, significantly ($P<0.05$) increased yield by 15.5% on average, from 12.9 to 14.9 t/ha. Further increasing N rates above 200 kg N/ha, up to as high as 360 kg N/ha, had no significant effect on yield. When no N or P fertiliser were applied, average taro corm yields across the three sites was 6.2 t/ha, which increased by 140% to 14.9 t/ha when 200 kg N and 120 kg P/ha were applied.

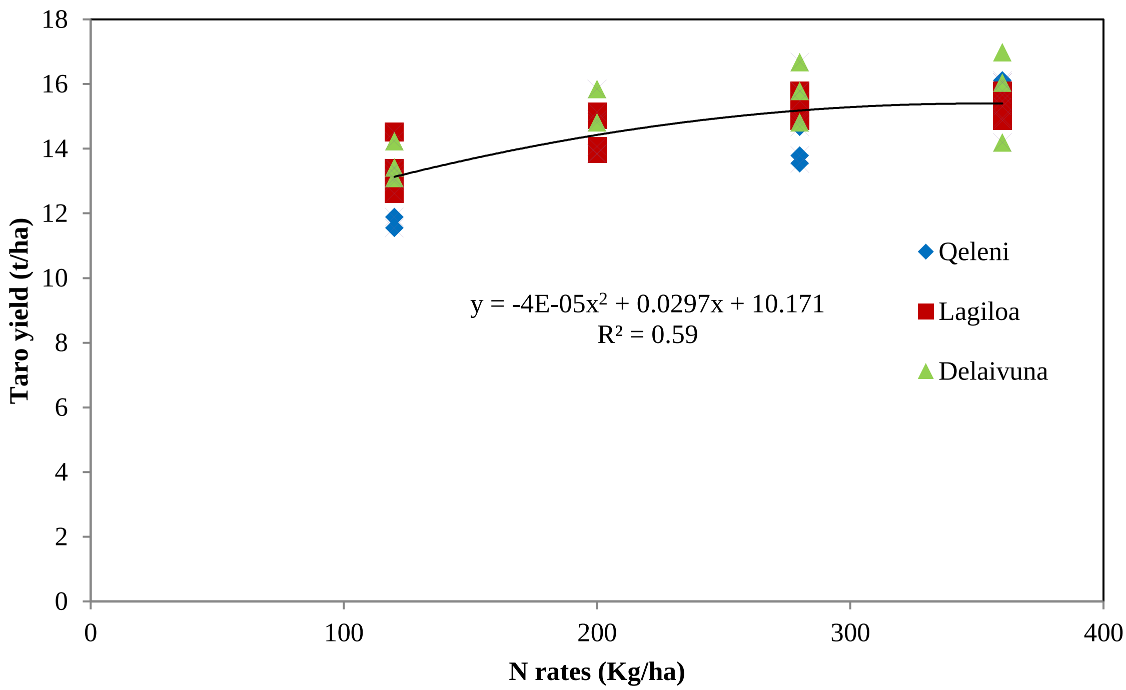


Figure 6.3. The effect of N fertiliser rates on taro corm yields when 120 kg P/ha, 200 kg K/ha and 82 kg S/ha were applied.

6.2.3.2 Effect of P fertiliser rate on taro corm yield

On average, P fertiliser addition had a strong significant effect ($P < 0.05$) on taro yield ($R^2 = 0.83$) when high rates of N, K and S were also applied (Figure 6.5). The average taro corm yield across all the three sites, when 60 kg P/ha fertiliser was applied was 10.1 t/ha. Application of 90 and 120 kg P/ha fertiliser, produced 12.0 and 15.2 t/ha of taro corms on average, which 19 and 53% higher than the 60 kg P/ha treatment, respectively. The yield response to added P was near linear up until the highest rate of P used, which was 120 kg P/ha in this experiment. In the first field experiment (Chapter 5), rates of P fertiliser of up to 240 kg P/ha were used, but on average across the three sites there wasn't a statistically significant increase in corm yields above 120 kg P/ha. Therefore, it is not possible to identify from the current experiment at what P rate the maximum corm yield would have occurred at. However, a limit of 120 kg P/ha was selected for the current experiment based on the results of the previous experiment and because applying more than 120 kg P/ha is considered to be potentially excessive from both a cost and environmental perspective, with the risk of P loss via runoff increasing with increasing P fertiliser rate. Therefore, applying rates higher than 120 kg P/ha are unlikely to be recommended, especially if a substantial yield response above 120 kg P/ha is not reliably expected, a result of the earlier experiment (see Chapter 5).

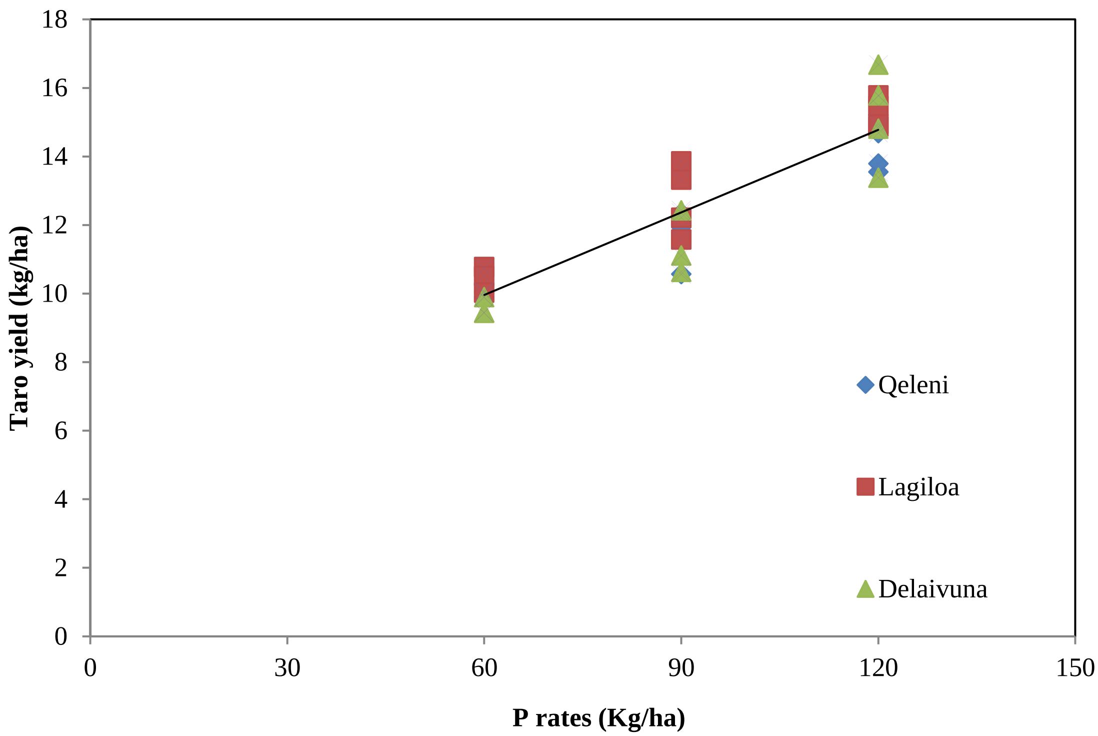


Figure 6.4. The effect of P fertiliser inputs on taro corm yield when 280 kg N/ha, 200 kg K/ha and 82 kg S/ha were also applied.

6.2.3.3 Effect of K fertiliser rate on taro yield

On average, K fertiliser addition had a strong significant effect ($P < 0.05$) on taro yield ($R^2 = 0.76$) when 280 kg N, 120 kg P and 82 kg S/ha were also applied (Figure 6.6). There was a linear relationship between K fertiliser and taro yields up to a rate of 200 kg K/ha, which was the highest rate used. Increasing K from 150 to 200 kg K/ha increased taro yield by 14.3%, from 13.3 to 15.2 t/ha. When K was applied at 200 kg K/ha, with no additional N and P, yield was 6.2 T/ha, which increased to 14.9 t/ha, when 200 kg N and 120 kg P were applied. The average corm yield across the three sites for the 100 kg K/ha treatment, when high rates of N, P and S were also used, was 11.2 t/ha. Application of 150 and 200 kg K/ha produced corn yields of 13.3 and 15.2 t/ha, which were 19 and 36% higher than 100 kg K/ha treatment, respectively. In this experiment there were no treatments without K applied. However, when K was applied at 100 kg N/ha (with 280 kg N, 120 kg P and 82 kg S/ha) corm yield was constrained to 11.2 t/ha. This indicates that high yields are not achievable when K is applied without N and P. Once the availability of N and P have been improved, then ensuring adequate K supply is also important for achieving further yield increases. For high taro corm yields (i.e. > 14 t/ha) at these sites, then high K addition is required along with N, P and S. It is not possible to determine the rate of K at which maximum yield was achieved because there was a linear relationship between K rate and corm yield up to the highest rate of K used in this experiment. This suggests that yields in this study were constrained by K inputs and that higher yields may be possible with higher K rates. The highest rate of K used in this experiment, of 200 kg K/ha, was the only rate of K used in the first experiment. Further research is required to identify the K rate at which maximum corm yields can be obtained.

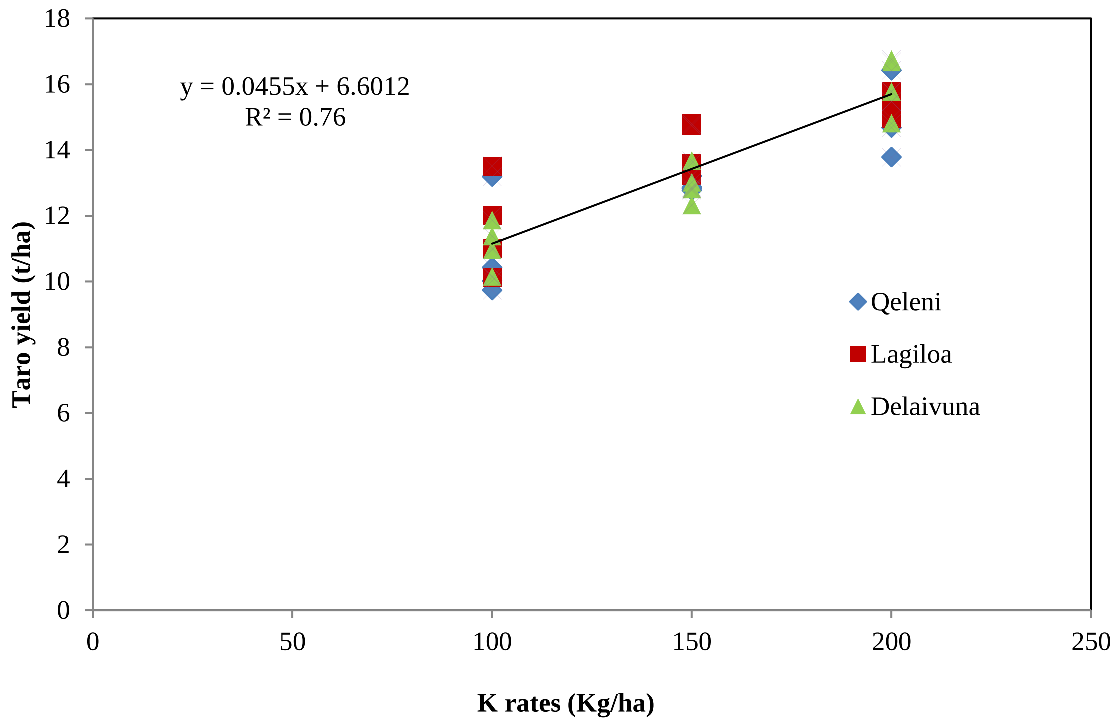


Figure 6.5. The effect of K fertiliser inputs on taro corm yield when 280 kg N/ha, 120 kg P/ha and 82 kg S/ha were also applied.

6.2.3.4 Interactive effect of N, P and K on taro yield across all sites

Multiple regression analysis between nutrient supply and yields across all sites revealed that there was an overall significant ($P < 0.001$) multivariate relationship ($R^2 = 0.80$; $F = 165.08$) between the rates of fertiliser inputs (N, P and K) and the corm yield of taro:

Taro yield (kg/ha) = -0.577 - 0.00393 N (kg/ha) + 0.06357 P (kg/ha) + 0.03219 K (kg/ha).

This model will be applicable for farms with low Olsen P levels (5-8 mg/kg) and moderate K levels (~0.40 me/100 g) as was the case at the field sites in this study. This model indicates that optimum taro yields are dependent on N, P and K inputs. Initially, increasing N, P and K inputs up to 200 kg N, 120 kg P and 200 kg K/ha (when 82 kg S/ha is also applied), increased taro yield significantly but beyond these rates the marginal yield increases are small and/or insignificant. This indicates that there is strong evidence for a yield response using up to the aforementioned N, P and K rates.

6.3 Taro suckers

6.3.1 Treatment effect on sucker numbers across the 3 sites

The effect of different N, P and K fertiliser treatments on the number of taro suckers produced at each site is shown in Figure 6.10. Overall, there was a similar trend in the response to fertiliser treatments at all three sites. Therefore, the treatment effects are discussed using the average sucker number response across all sites.

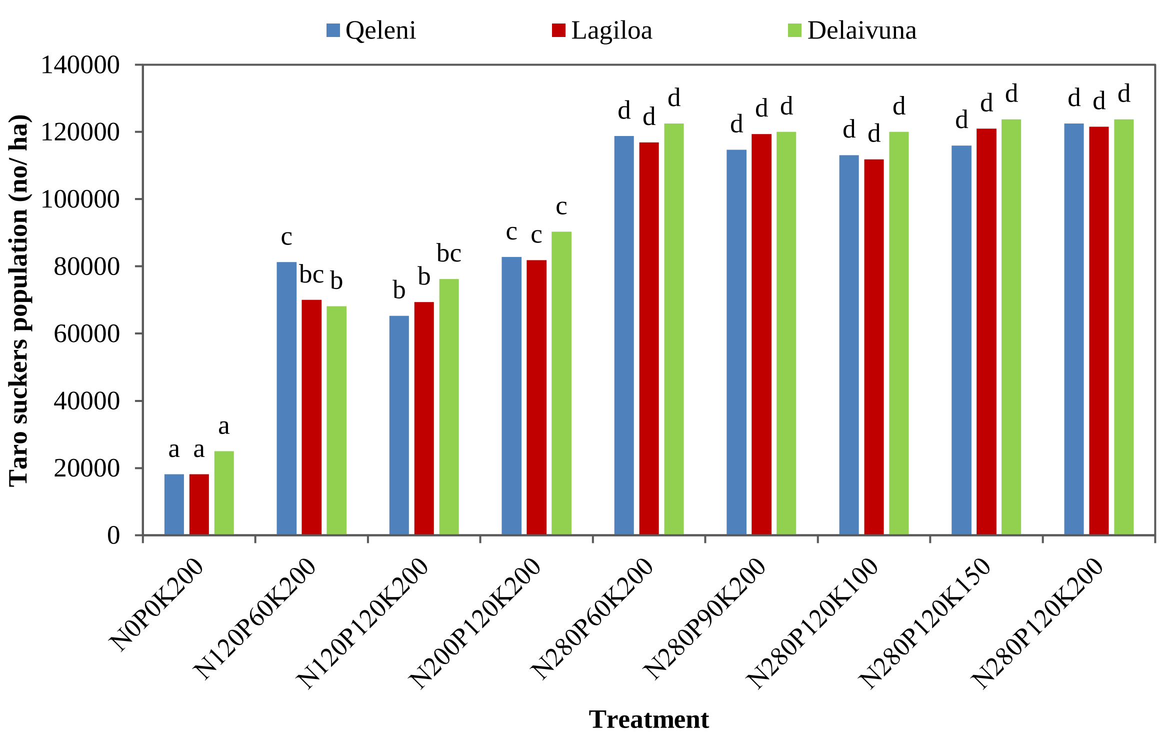


Figure 6.6. The effect of the main fertiliser treatments on taro sucker numbers at each site.

6.3.2 *Overall fertiliser treatment effects on taro sucker population*

The effect of N, P and K fertiliser treatments on taro sucker numbers showed a highly significant difference ($P < 0.001$) between N rates (Figure 6.11). The highest taro sucker populations ($P<0.001$) were achieved at fertiliser rates up to 280 kg N, 60 kg P and 100 kg K/ha (when 82 kg S/ha was also applied). The effect of each nutrient on sucker numbers is discussed in more detail in the following sections

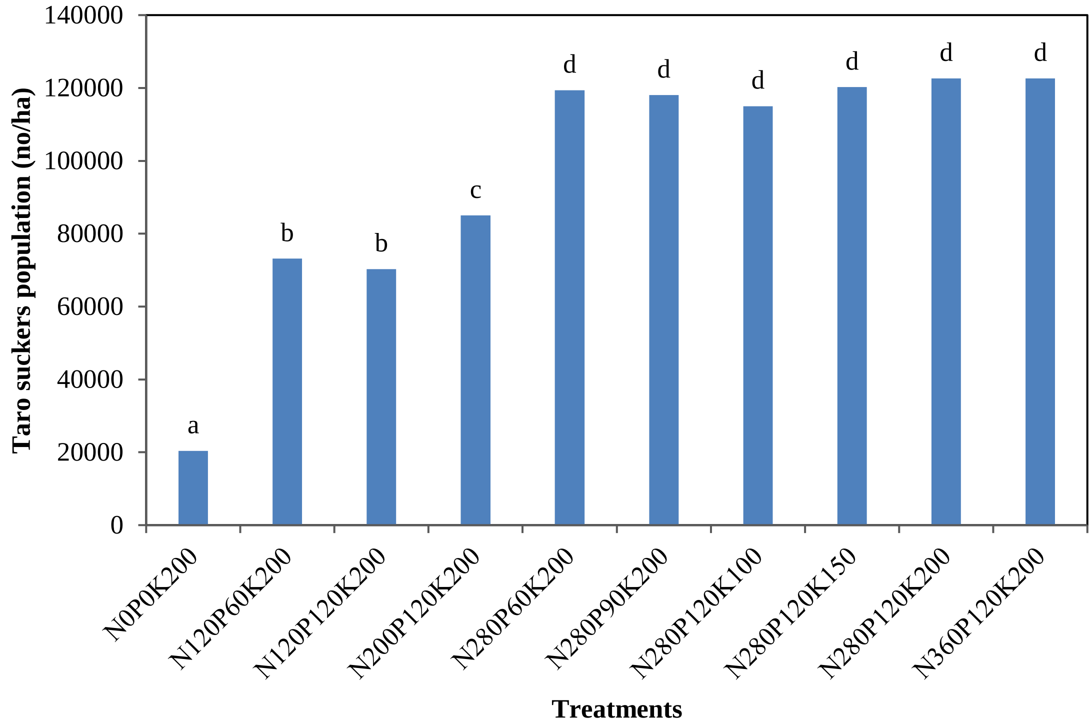


Figure 6.7. Effect of the main fertiliser treatments on taro sucker numbers for three sites on average

(Values with the same letter are not significantly different from each other at 5% significance level).

6.3.3 *Effect of N fertiliser rates on taro sucker population*

On average, N fertiliser addition had a strong positive effect ($R^2 = 0.84$) on taro sucker numbers, when 120 kg P, 200 kg K and 82 kg S/ha were also applied (Figure 6.12). Sucker numbers increased with increasing N fertiliser rate up to 280 kg N/ha. Further increasing N rates up to 360 kg N/ha, had no significant ($P < 0.05$) effect on further increase in sucker population. When 120 kg N/ha fertiliser was applied, average taro sucker numbers across the three sites was 70,312, which increased by 74% to 122,604 when N fertiliser rate was increased 280 kg/ha N fertiliser. In the first experiment, sucker numbers increased significantly with N fertiliser rates up to 300 kg N/ha, which was the highest rated of N used in that experiment. These results suggest that there is unlikely to be a further significant benefit from applying more than 300 kg N/ha, and that a rate of 280 kg N/ha is sufficient for maximising sucker numbers.

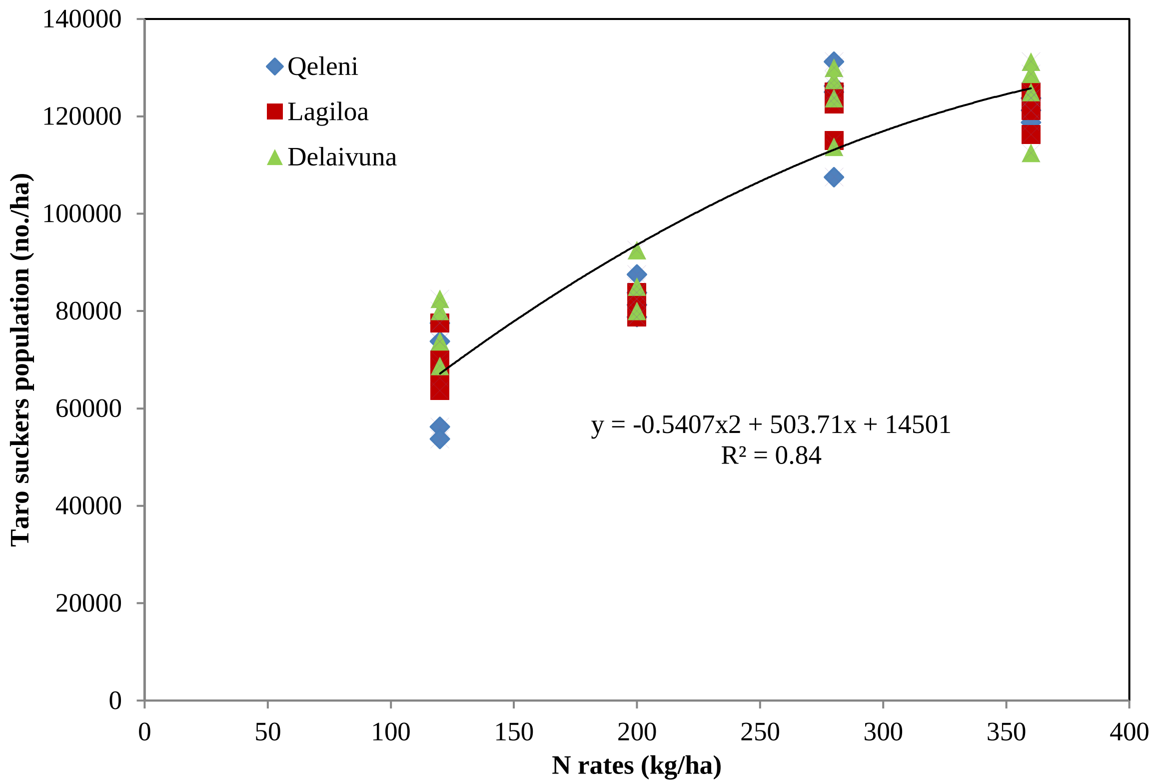


Figure 6.8. Taro sucker population in response to N application rates with base fertiliser of 120 kg P, 200 kg K and 82 kg S/ha.

6.3.4 Effect of P fertiliser rate on taro sucker population

The effect of P fertiliser rates on sucker population was not statistically significant ($P > 0.05$; Figure 6.12); there was no benefit for sucker numbers above 60 kg P/ha. This result is in agreement with the first experiment, which also showed that increasing the P rate had negligible influence on sucker population at harvest. Taro suckers are vegetative components, which are attached to the taro corms. This vegetative growth is not strongly influenced by increasing P availability compared with the influence of N supply. Taro responds positively to N fertilisers (De La Pena and Plucknett, 1972; Manrique, 1994; Silva et al., 1990). Plant growth and Foliar N concentration increases with N applications up till 560kg/ha rate.

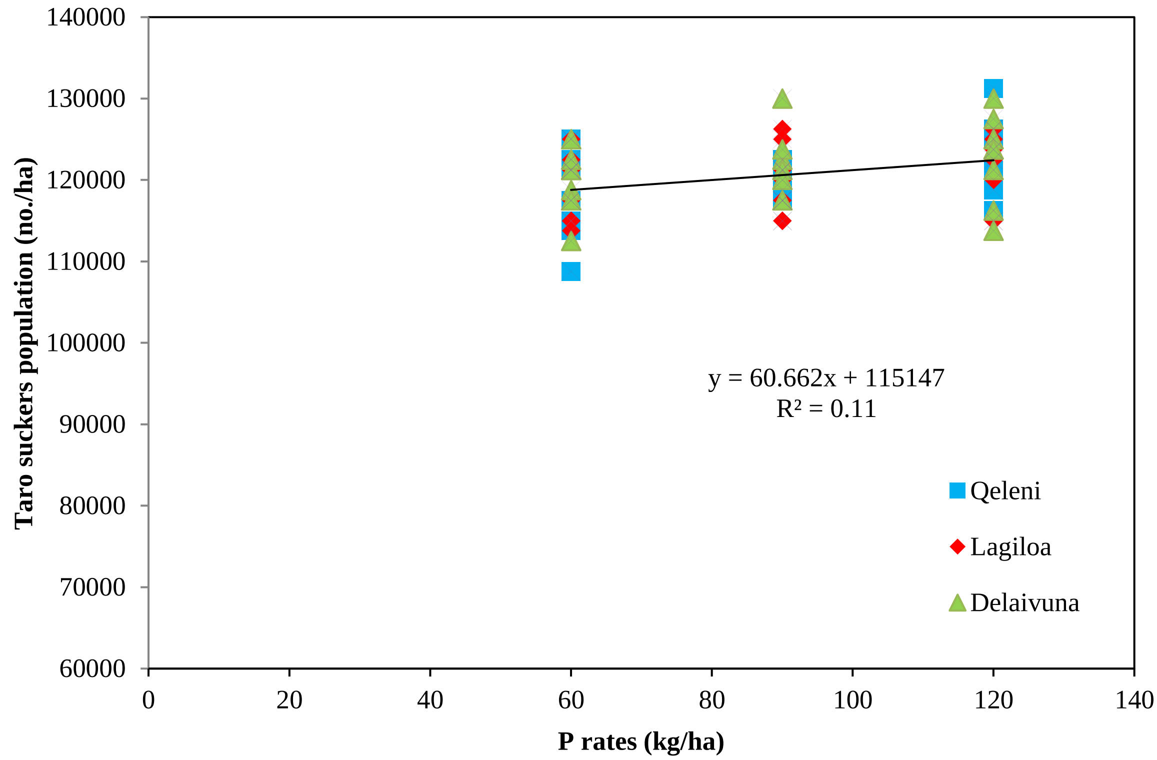


Figure 6.9. Taro sucker populations at different P application rates with base fertiliser of 280kg N, 200 kg K and 82 kg S/ha.

6.3.5 Effect of K fertiliser rate on taro sucker population

The effect of K fertiliser application rates on taro sucker population was statistically significant (P = 0.018) across the three sites on average (Figure 6.14.). Suckers numbers increased significantly when K fertiliser rate was increased from 100 to 200 kg K/ha. When 100 kg K/ha fertiliser was applied, mean taro sucker number was 115,000/ha, which increased by 7% to 122,604/ha at 200 kg K/ha. However, differences in sucker numbers between different K rates were not significant. While percentage increase in sucker numbers from increasing K rate from 100 to 200 kg K/ha, is small and on its own may not justify using the higher rate, this benefit is in addition to the increase in corm yield also achieved at a rate of 200 kg N/ha.

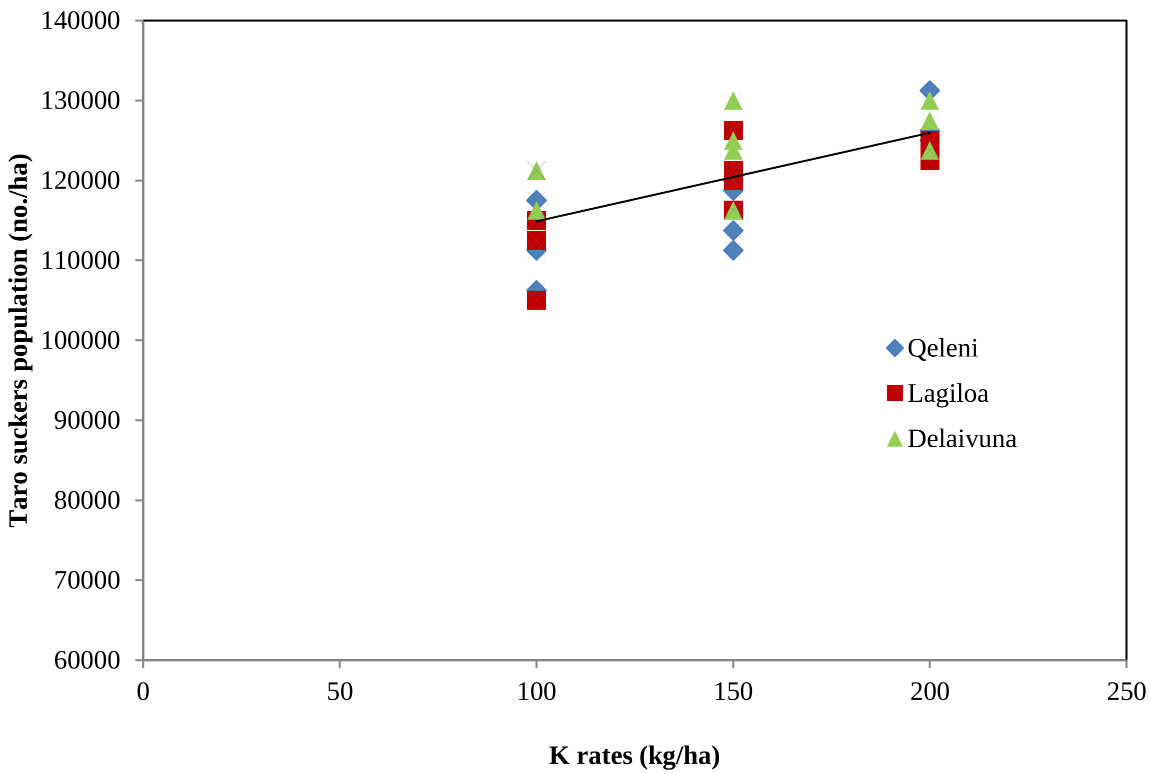


Figure 6.10. Taro sucker population in response to K application rates with base fertiliser of 280 kg N, 120 kg P and 82 kg S/ha.

An important aspect of improving fertilisers use efficiency, is understanding nutrient uptake and allocation within the taro plant during the growing season. Table 6.1 shows the effect of the N0P0K200 and N280P120K200 treatments on the nutrient content of various plant components. With the N0P0K200 treatment the N content of leaves, petioles, corm and suckers were 2.17%, 0.52%, 0.24% and 0.22% respectively. These concentrations increased markedly using the N280P120K200 treatment, providing N contents of 3.63, 1.53, 0.74 and 0.54% respectively. The P content of leaves, petioles, corm and suckers were 0.17, 0.21, 0.14 and 0.22%, respectively, for the N0P0K200 treatment. Whereas, for the N280P120K200 treatment the P contents increased to 0.23, 0.25, 0.22 and 0.26%, respectively. In general, this treatment had higher N, P, K, Ca and Mg content in all plant components, as compared to treatment N0P0 (Table 6.1). The weighted average plant taro N concentrations doubled with fertiliser use, from 0.33% for the N0P0K200 compared to 0.88% for the N280P120K200 treatment.

With the N0P0 treatment the dry matter content of leaves, petioles, corms and suckers were 0.17, 0.46, 2.06 and 1.78 kg/ha respectively. In contrast the dry matter content of N280P120 treatment for leaves, petioles, corms and suckers were 0.39, 0.86, 5.76 and 4.06 kg/ha respectively. When no N and P fertiliser was applied, total N, P and K uptake of taro at harvest was 14.94, 7.70, and 47.08 kg/ha, respectively, of which 33% N, 37% P and 33 K was taken up by the taro corms (Table 6.2). With N280P120 treatment the total N, P and K uptake of taro at harvest was 91.86, 26.28 and 123.39 kg/ha respectively and of which 46% N, 48% P and 39% K was taken up by the taro corms. Hartemink and Johnston (1998) stated that fertiliser application had an effect on nutrient uptake by taro plant. In their study, fertilised (N100P50K100) taro removed a total of 91 kg N, 31 kg P, 215 kg K, 74 kg Ca and 15 kg Mg/ha.

Nutrient use efficiency for N, P and K were 32.5%, 21% and 61% respectively when 280 kg N, 120 kg P and 200 kg K were applied. The high efficiencies for N and K may have been due to split applications of nutrients at critical growth stages. Hartemink *et al.*, (2000) found N use efficiency to be 10% in their experiment and this was due to high rainfall event after N application which might have leached most of the N and K nutrients

At harvest, removal of corms and suckers from the field results in the loss of nutrients. With optimum fertiliser rates, 64.5 kg N, 23.2 kg P, 94.7 kg K, 29.0 kg/ha Ca and 23.4 kg Mg/ha is exported through removal of corms and suckers. Leaves and petioles decay and recycle nutrients. However, farmers in Taveuni often pile all harvested taro plants in a corner of the fields, enabling them to clean and pack all marketable corms at one site rather than picking corms throughout the field. This means corms are easy to collect and are not lost under crop residue. This results in nutrients in the petioles and leaves recycled at one location rather than across the field. Consequently all plant components are effectively removed at harvest, removing nutrients. Replenishment efforts should look at total nutrients removed rather than nutrients removed in the corm only.

Table 6.1. Nutrient content of various taro plant component and the weighted average.

Treatment	Plant component	Nutrient content (%)				
		N	**P**	**K**	**Ca**	**Mg**
N0P0K200*	Leaf	2.17	0.17	1.9	1.77	0.28
	Petiole	0.52	0.21	2.42	0.37	0.26
	Corm	0.24	0.14	0.75	0.12	0.13
	Sucker	0.22	0.22	0.97	0.41	0.31
	Average	0.33	0.18	1.05	0.32	0.22
N280P120K200*	Leaf	3.63	0.23	1.83	1.70	0.4
	Petiole	1.53	0.25	2.51	0.4	0.38
	Corm	0.74	0.22	0.84	0.13	0.16
	Sucker	0.54	0.26	1.14	0.53	0.35
	Average	0.83	0.24	1.11	0.35	0.26

* Treatments also received 82 kg S/ha

Table 6.2. Nutrient uptake by various plant component

Treatment	Plant component	Dry matter (t/ha)	Nutrient uptake (kg/ha)				
			N	**P**	**K**	**Ca**	**Mg**
N0P0K200	Leaf	0.17	3.69	0.29	3.23	3.01	0.48
	Petiole	0.46	2.39	0.97	11.13	1.70	1.20
	Corm	2.06	4.94	2.88	15.45	2.47	2.69
	Sucker	1.78	3.95	3.56	17.27	7.298	5.52
	Total	4.47	14.94	7.70	47.08	14.48	9.87
N280P120K200	Leaf	0.39	14.16	0.90	7.14	6.63	1.56
	Petiole	0.86	13.16	2.15	21.59	3.44	3.27
	Corm	5.76	42.62	12.67	48.38	7.49	9.22
	Sucker	4.06	21.92	10.56	46.28	21.52	14.21
	Total	11.07	91.86	26.28	123.39	39.08	28.25

* Treatments also received 82 kg S/ha

6.3.6 Spatial variation in Olsen P levels

The practice of applying P fertiliser to the planting hole in taro production is expected to result in high spatial variation, particularly when high rates of P are required. However, it is important to quantify this variability to assess the potential impact of this on the availability of P for subsequent crops. Spatial variation in Olsen P levels of soil samples collected at three distances from the centre of the planting hole are presented in Figure 6.11. These samples were collected from treatment plots that had received P fertiliser at a rate of 120 kg P/ha and mixed in the planting hole.

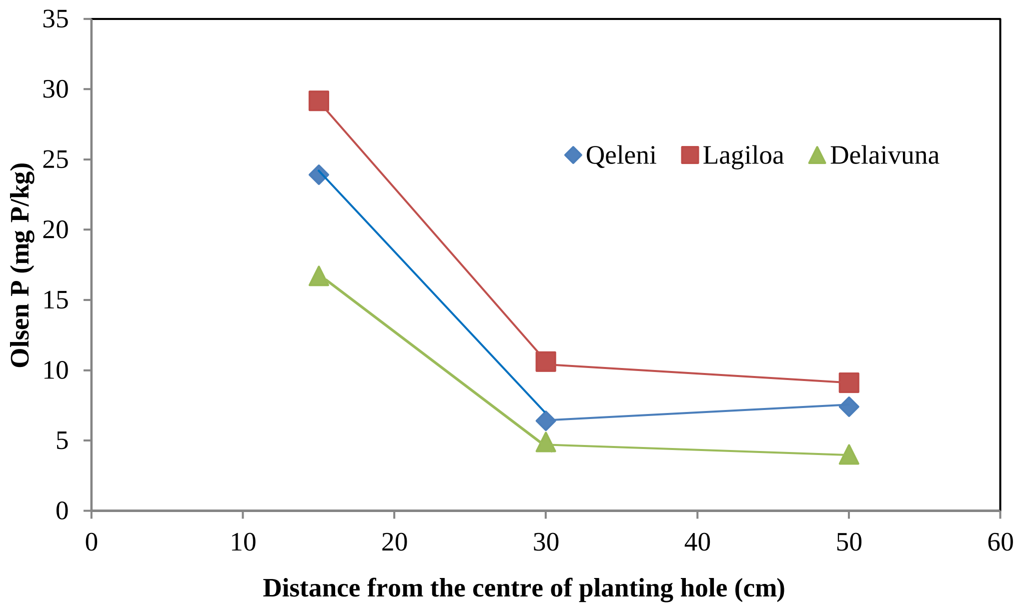


Figure 6.11. Spatial variation in Olsen P levels at the three experiment sites when P fertiliser (120 kg/ha) is mixed in the planting hole.

At all three sites, soil Olsen P levels were significantly ($P < 0.05$) higher at 15 cm from the centre of the planting hole, compared to distance of 30 and 50 cm. At the soil sampling located the closest to the planting hole, the Olsen P levels were 16.9, 23.9 and 29.2 mg P/kg at the Delaivuna, Qeleni, and Lagiloa sites, respectively. There was no difference between Olsen P levels for soil samples collected at 30 and 50 cm away from the planting hole. At both the these distances Olsen P levels were close to or at the initial Olsen P levels, being 4.9, 6.4 and 10.6 mg P/kg at a distance of 30 cm and 4.1, 7.4 and 9.1 mg P/kg at a distance of 50 cm, for the Delaivuna, Qeleni, and Lagiloa sites, respectively. This indicates that the potential benefit of P fertiliser use in terms of increased soil P availability status for subsequent crops is confined to the area near the planting hole. However, if a standard sampling technique, of collecting a bulked sample of from a number (typically 12-18) of randomly collected soil cores, was used then this high degree of spatial variation created by the P placement method would not be seen.

When P fertiliser is mixed in the taro planting hole, a high degree of spatial variability in Olsen P levels results. Therefore, it is useful to estimate the areas of a field influenced by P fertiliser addition, as this will provide an indication of the likely influence that previous P fertiliser use will have on subsequent crops. In this experiment, the field areas of influenced from applying and mixing 120 kg/ha basal P fertilisers in planting holes (1 x 1 m spacing), are shown in Figure 6.12. When the Olsen P results are average across the three trial sites, then ~5% of total field area is expected to have soil Olsen P levels at or above 23.3 mg P/kg, another ~23% of the field area is expected to have Olsen P levels between 23.3 and 7.3 mg P/kg, while the remaining ~72% of the field will have Olsen P levels between 7.3 and 6.9 mg/kg. On the other hand, if soil samples were taken randomly across these fields, average soil Olsen P is estimated to be 7.8 mg P/kg (weighted averages against % area covered at each location). These results show that even after a high rate of P fertiliser is used, the application method has result in the majority of the field still having Olsen P levels similar to the original very low levels. This may have been the reason why previous P applications, used in Experiment 1, had no significant influence on yield in this experiment. Fertiliser placement may cause non-uniform nutrient distribution in the soil, making it difficult to determine whole-field fertility by traditional sampling strategies (Fernandez and Schaefer, 2012). In Taro systems it may take multiple crops in succession before the majority of the field area has achieved a moderate to high Olsen P level.

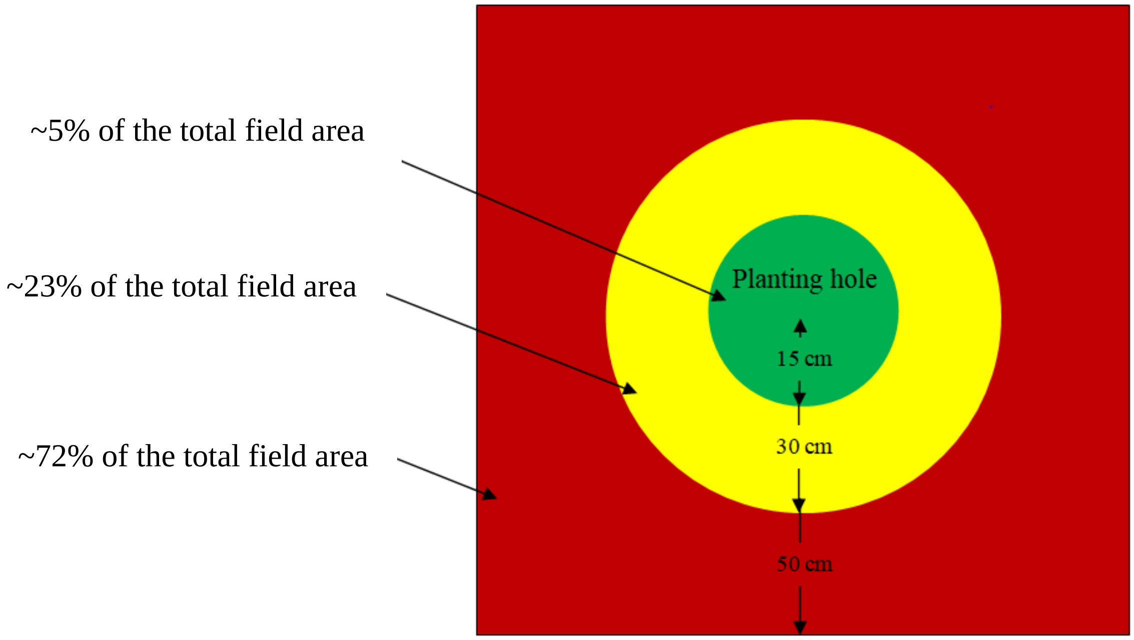


Figure 6.12. Area around the planting hole representing each soil sampling zone.

6.4 Effect of P fertiliser placement method on taro yield and Olsen P

In this experiment two different methods of P fertiliser placement were compared, either 120 kg P applied at the bottom of planting hole or 120 kg P mixed in the planting hole. The method of applying P at the bottom of the planting hole is a common practice with farmers on Taveuni Island because it reduces the time involved with planting. However, this practice confines the added P to a small part of the root, which could limit the availability of the P to developing roots. In addition, his P is added at a depth of about 20 cm, which is at the bottom of the soil sampling depth of 0-20 cm and, therefore, may not be detected in future soil sampling and, thereby, underestimate soil fertility. Both the treatments also received 280 kg N, 200 kg K and 82 kg S/ha. On average, mixing P fertilisers in the planting hole achieved a significantly ($P < 0.001$) higher taro yield, compared to placing the fertiliser at the bottom of the planting hole. The effect of the two treatments was similar across the three sites. Placing the P fertiliser at the bottom of the whole achieved an average yield across the three sites of 11.0 t/ha, which increased by 38% to 15.2 t/ha when the P was mixed in the planting hole. In the first experiment, only Qeleni site showed that mixing the P fertiliser in the planting hole increased taro corm yields significantly. This may have been due to lower rate of P fertiliser (60 kg P/ha) used in the first experiment to compare the two P fertiliser placement methods.

Corm formation in taro is upwards from where the bottom of the sucker is planted. The fibrous root system develops from the base of the initial corm (Onwueme, 1999) and as the corm develops, the majority roots are located between the bottom of the planting hole and the soil surface, rather than below the bottom of the planning hole. Because P is a relatively immobile nutrient in soils, roots need to be located in close proximity to the soil P for plants to access it. These factors could help explain why mixing P in the planting hole had a greater influence on yield, compared to placement at the bottom of the planting hole.

The effect of P fertiliser placement method on soil Olsen P from soil samples taken at the 0-20 cm depth about 15 cm from the centre of the taro planting hole is shown in Figure 6.14. On average across the three sites, mixing 120 kg P/ha fertiliser in the planting hole achieved significantly (P= 0.01) higher soil Olsen P level in the 0-20cm soil depth, as compared to when it was applied at the bottom of planting hole. When P fertiliser was placed at the bottom of the planting hole the Olsen P test value was 11.7 mg P/kg, which almost doubled to 23.0 mg P/kg same rate of P fertiliser as mixed into the planting hole. Although the same rate of P was added in both placement treatments, these result support that applying P fertiliser to the bottom of the planting hole will have minimal influence on the Olsen P test because it is being added near the limit of the soil sampling depth. Therefore, this practice over time could lead to an underestimation of the availability of P to plants and incorrectly lead to the conclusion that the P fertiliser addition is having negligible influence the available P status of the soil.

6.4.1 Residual P effect on taro yield

Residual effect of previous P fertiliser application on taro yields is shown in Figure 6.13. There was no significant difference in taro yield of the second crop when 0 and 240 kg P/ha applied in the first crop. Despite high rates of P fertiliser applied in the first experiment there was no significant P carry over effect the on the yields of the succeeding crop. This may be due to a lower rate of P (90 kg P/ha) used in the second experiment while 120 kg P/ha was likely to be near optimum rate for taro yield. Farming systems in Taveuni are characterised by no tillage system; land is cleared, and planting holes are dug manually for planting the crops. P Fertilisers is applied to this planting hole rather than broadcasted over the field, which causes stratification zones of applied fertilisers. The next crop is often planted 0.5 m away from the previous crop and this may have caused low carry over effect of previous high P applications on taro yield.

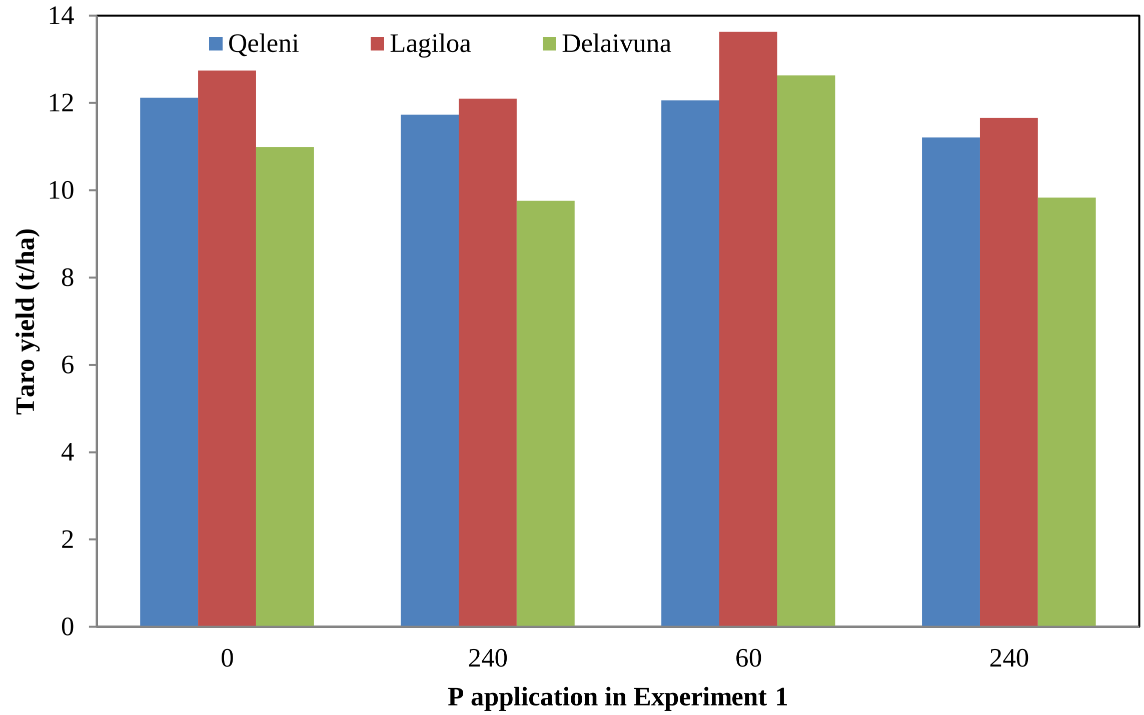


Figure 6.13. Residual effect of previous P fertiliser application on taro yields.

(All treatments were applied with 280 kg N/ha and 200 kg K/ha in this experiment. The first 2 treatments across all the sites were applied with 90kg P/ha during the second experiment. The 3rd treatment received 120 kg P/ha while the last treatment received 60 kg P/ha).

6.4.2 Effect of P fertiliser rate on soil Olsen P

The effect of P fertiliser rates on Olsen P levels at ~15 cm from the centre of the planting hole are shown for the three sites in Figure 6.14. All rates of P were mixed in the planting hole prior to planting of the taro. There was significant ($P < 0.05$) increase in soil Olsen P levels with the 120 kg P/ha rate compared to no P fertiliser, at all sites, compared to 60 kg P/ha at two sites and compared to 90 kg P/ha at one site. Olsen P was least responsive to P addition at the Delaivuna site, which is likely to be due to this site also having the highest P retention capacity of 86%. The 120 kg P/ha rate increased Olsen by from 5.6 to 16.9 mg

P/kg, which was a 11.3 mg/kg increased. The Qeleni and Lagiloa sites had P retention values of 12.1% and 57.8%, respectively. The Olsen P values at these two sites increased from 5.6 and 8.2 to values of 23.9 and 29.2 mg P/kg, respectively, from an application of 120 kg P/ha. At these two sites the 120 kg P/h treatment achieved Olsen P values between 20 - 30 mg P/kg, which would indicate moderate to high soil P availability status, considered optimum of taro production

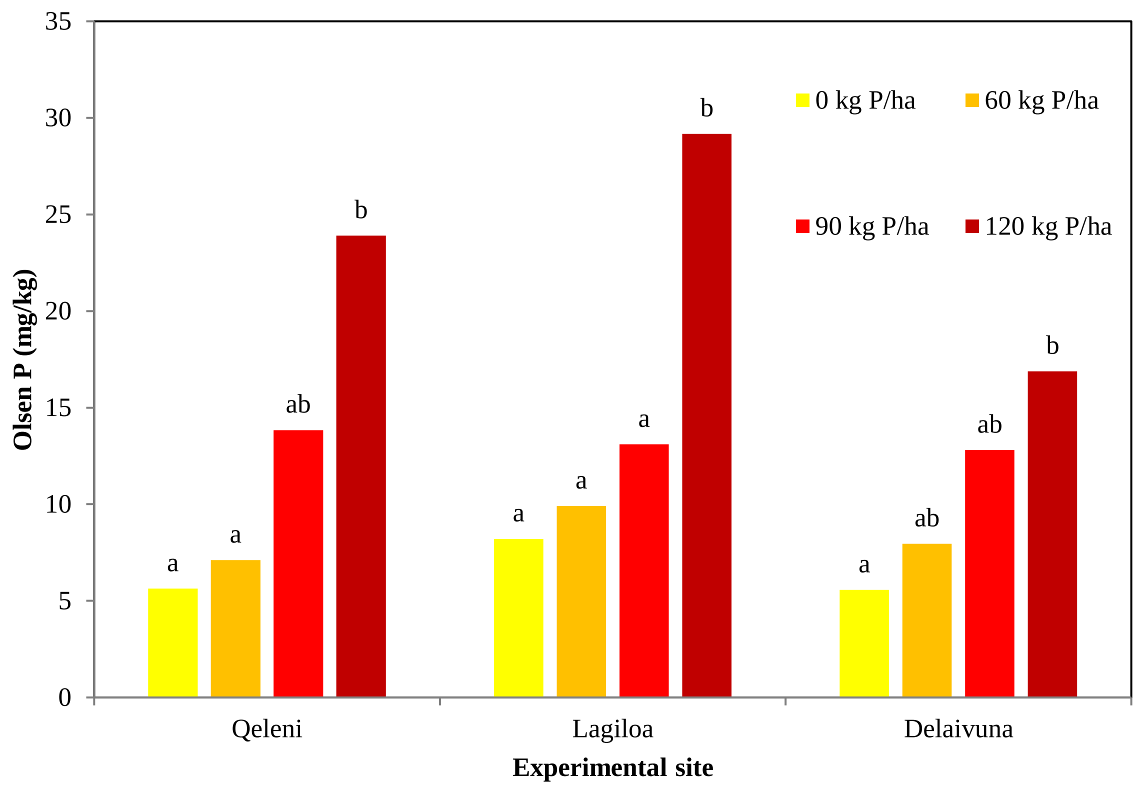


Figure 6.14. Effect of P fertilisers on changes in soil Olsen P levels.

All treatments were also applied with 280 kg N/ha and 200 kg K/ha and samples were collected 15 cm away from the planting hole.

6.5 Effect of K fertiliser on soil exchangeable K levels

Potassium fertiliser was applied in two even split application, at planting and again at 10 WAP. At planting, the K fertiliser was applied in the planting holes and mixed with the soil. At the 10 WAP, individual applications of K fertiliser were surface applied around each taro plant up to 15 cm from the centre of the plant. Increasing the K fertiliser rate from 200 and 150 kg K/ha increased the average exchangeable soil exchangeable K levels at the three sites, with the largest increase (54%) being for the Delaivuna site (Figure 6.15). However, the differences were not significantly (P < 0.05) different at any of the three sites, possibly due to high soil test variation between plots. Also, there were no treatments without K fertiliser applied, so the comparison was just between two relatively high rates of K, for which an observable difference in soil test values is less likely. Soil samples were collected about 15 cm away from the centre of the planting hole at a soil depth of 0-20 cm depth at 28 WAP. On an average exchangeable K levels across the sites was 0.32-0.49 me/100g which is considered optimum for most crops.

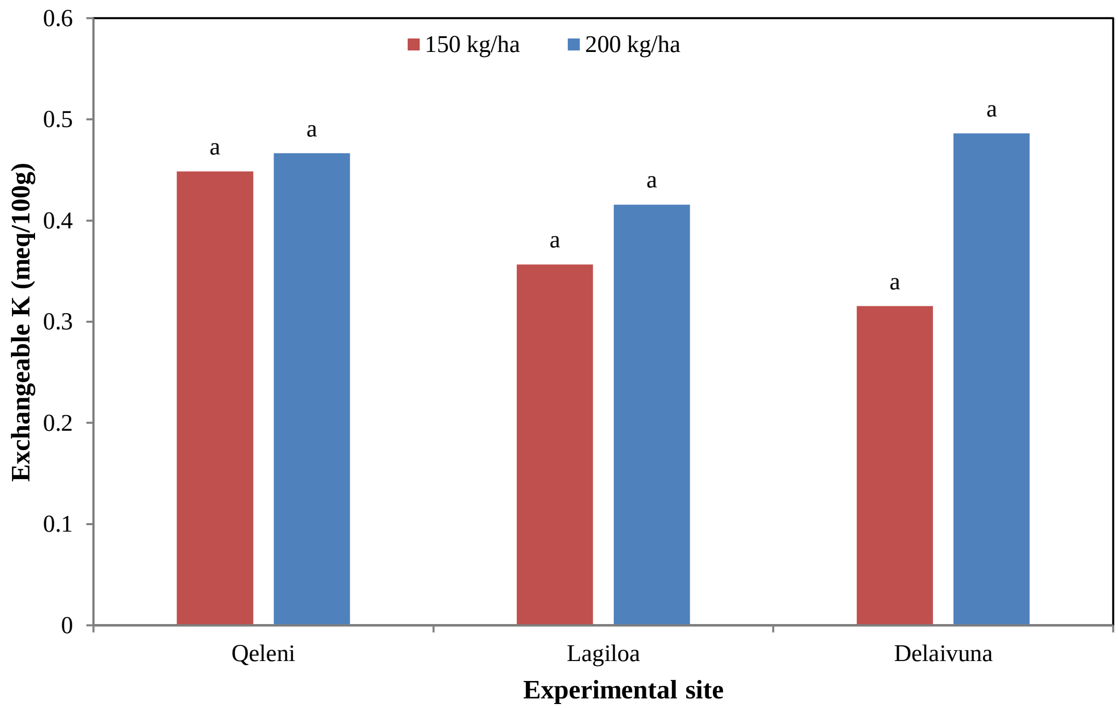


Figure 6.15. Influence of K fertiliser applied at two rates on soil exchangeable K levels

As was the case with Olsen P, soil exchangeable K levels was also measured at two other distances (30 and 50 cm) in addition to the 15 cm distance from the centre of the planting hole, for the highest rate of K used (200 kg K/ha). Even though half of K fertiliser was mixed in the planting hole, there was no significant difference in soil exchangeable K levels between the three sampling distances (Figure 6.16). This may have been due to the applied K being more mobile in the soil, compared to phosphate, therefore, and being more prone to leaching losses. Also, a higher proportion of the K added is likely to have been removed by plant update, compared to the P added in fertiliser. Consequently, there is expected to be less surplus K fertiliser remaining in the soil, which would explain why there is not the same increase in soil test levels with proximity the taro plant, as was seen for Olsen P.

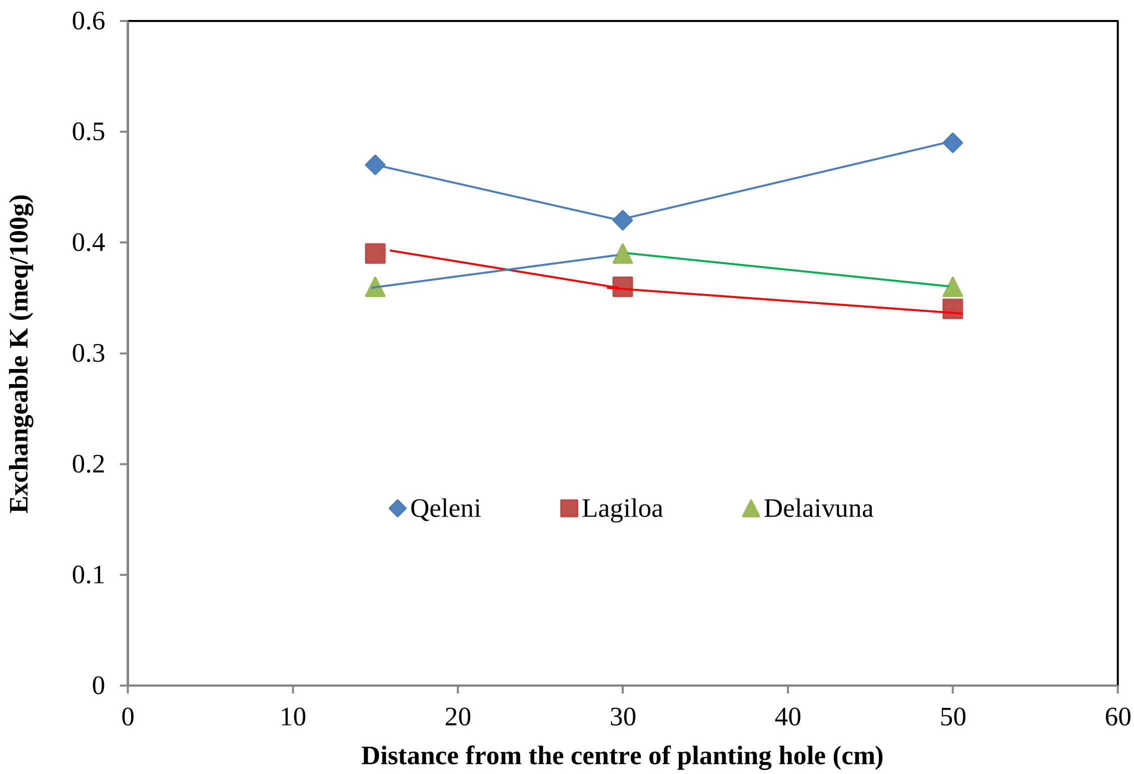


Figure 6.16. Soil exchangeable K distribution along the field when 200 kg K/ha was applied.

6.6 Influence of liming

6.6.1 Influence of liming on soil pH

Figure 6.17 shows the influence of liming on soil pH across the three sites. Lime treatments were broadcasted on to the soil surface during land preparation. The initial soil pH at Qeleni, Lagiloa and Delaivuna were 5.8, 5.2 and 5.7, respectively. Application of lime significantly ($P < 0.05$) increased soil pH in the 0-20 cm depth by 0.3 units, but there was no significant difference between the 1 and 2 ton/ha New Zealand (NZ) lime treatments on soil pH. In addition, there were no significant difference between the effect of the local Fijian lime and the imported NZ lime, both at 2 ton/ha, on soil pH. Both the local lime and imported NZ lime are sold in Taveuni and costs $443.75 and $639t respectively. The results of this study indicate that the local lime as effective at changing pH as the NZ lime and is half the cost. The Fijian government, through its Ministry of Agriculture, has also further subsidised local lime and growers can buy it at a third of the actual price, which will be an additional cost savings.

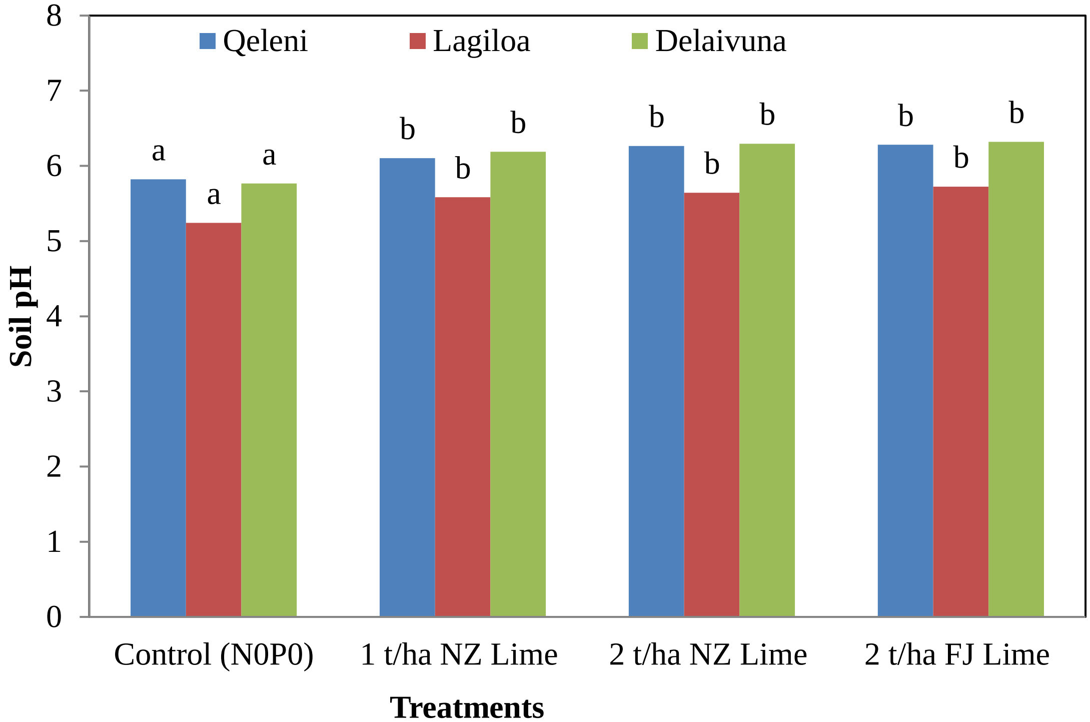


Figure 6.17. Influence of lime application on soil pH at 0-20 cm depth

(Weighted average of the three distances)

6.6.2 Influence of liming on Taro corm rot

Corm rots are caused by *Pythium* sp., *Sclerotium rolfsii*, and *Phytophthora colocasiae* (Plucknett et al., 1970) and are a major production constraint with estimates of yield losses as high as 36% (Miyasaka, *et al*., 2001). In most cases, farmers do not detect the aboveground symptoms until about 5 months after planting, or 2 to 3 months before harvest. When the first above ground symptom appeared, over a half of the corm is often already badly affected and as a consequence unmarketable (Burdani, 2001).

The whole plant becomes stunted, the leaf stalks are short, the leaf blades become curled, and instead of being deep healthy green they become yellowish and pale blueish-green. The only chemical presently registered for the control of taro corm rots in Hawaii is metalaxyl (Ridomil Gold), which is recommended as a single application near planting.

In the current experiment, the proportion of the crop with corm root rot when no N and P fertiliser was applied were similar for each trial site, ranging from 9.4-13.0% of the total yield across the three sites on average (Figure 6.18). While not significantly different from the other two sites, the Lagiloa site had the highest amounts of rots and also had the lowest initial soil pH of 5.2, compared to 5.8 for Qeleni and Delaivuna. When N and P fertiliser was applied at rates of 280 kg N and 120 kg P/ha, then the incidence of root rot was reduced by nearly half, to 6.0-6.3%. However, this was only significantly different compared to the no N and P fertiliser treatment at the Lagiloa site. In this experiment, the high N and P rates did not have higher corm rots when compared to no N and P inputs. Triple super fertiliser was used in these experiment and Ca content of this fertiliser was 16%.

All lime treatments, which also received N and P fertiliser, had significantly ($P < 0.05$) lower corm rots compared to no N and P fertiliser treatment at all three sites. However, there were not significant differences between the different lime treatments. At the three lime treatments and three sites, root rot incidence was only 2% or less. While this is lower than for the N and P fertiliser treatment with no lime, it was not shown to be significantly different. Calcium content of the liming materials may have also contributed to lower corm rots. Calcium is important in stabilizing cell membranes and cell walls. It activates enzymes and is required as an intermediary between environmental signals and plant responses. A constant supply of this cation is required in the root environment for continued root growth. Calcium deficiency can predispose plants to soil-borne diseases when roots die back and become open to invasion by pathogens (Miyasaka *et al*., 2002).

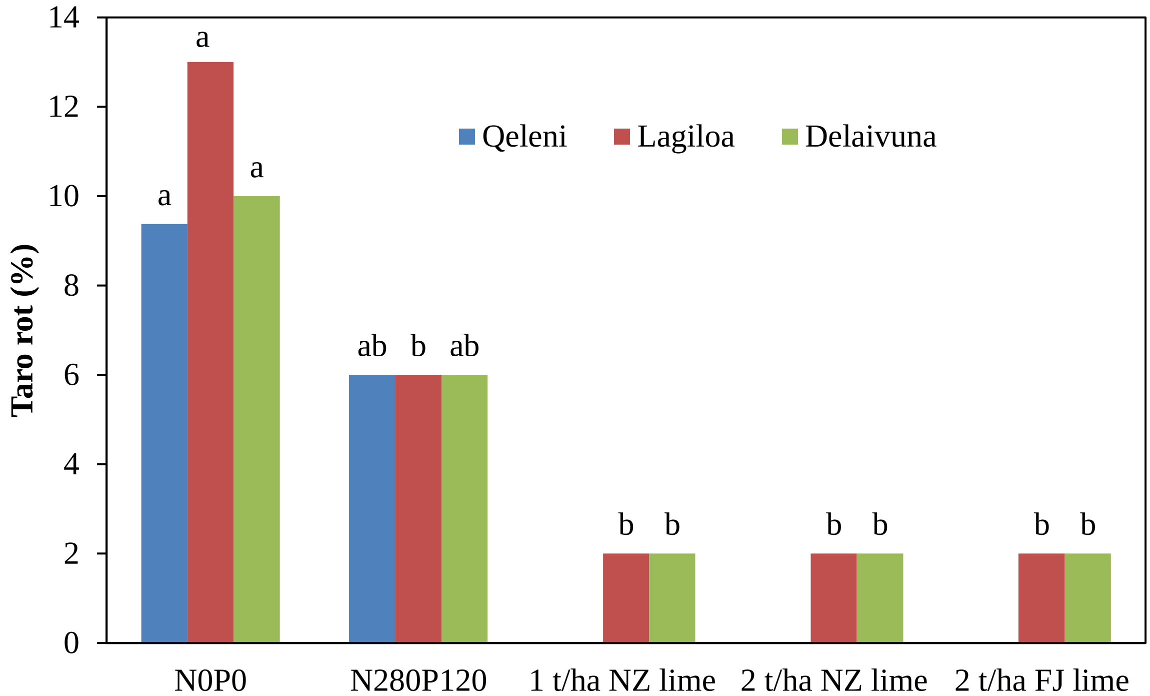


Figure 6.18. Treatment effect on taro corm rot (%).

*(*means followed by the same letters at each site are not significantly different from each other at 5% significance level. All treatments also received 200 kg K/ha and 82 kg S/ha*

6.7 Cover cropping

6.7.1 Effect of Mucuna on taro yields and sucker numbers

The use of a Mucuna green manure crop treatment had a significant ($P<0.05$) effect on taro corm yields at all three sites (Figure 6.19). The experimental plots which were planted with Mucuna and applied with 120 kg N and 60 kg P/ha fertilisers had average yields of 12.04 across the 3 sites, which was significantly higher ($P < 0.05$) than the yield of 10.54 t/ha for the same fertiliser treatment without Mucuna. Mucuna contributed to 14% increase in corm yield as compared to the same fertiliser treatment without Mucuna.

When Mucuna was grown with the 120 kg N and 120 kg P/ha fertiliser treatment, the average yield across all three sites was 15.5 t/ha, which was significantly higher ($P <0.05$) than the yield of 12.8 t/ha for the same fertiliser treatment without Mucuna. Mucuna contributed to 21% increase in corm yield as compared to the same fertiliser treatment without Mucuna.

However, when Mucuna was grown with the 280 kg N and 120 kg P/ha fertiliser treatment, the average yield across all three sites was 15.0 t/ha, which was equivalent to the yield of 15.2 t/ha for the same fertiliser treatment without Mucuna.

While the 280 kg N/ha and 120 kg P/ha fertiliser treatment without Mucuna achieved a yield (15.2 t/ha) significantly higher than the 120 kg N and 120 kg P/ha fertiliser treatment without Mucuna, it was not higher than the 120 kg N and 120 kg P/ha treatment with Mucuna. This supports that Mucuna incorporated with 120 kg N/ha crop has an equivalent benefit, in terms of increased yield, as a fertiliser treatment of 280 kg N/ha.

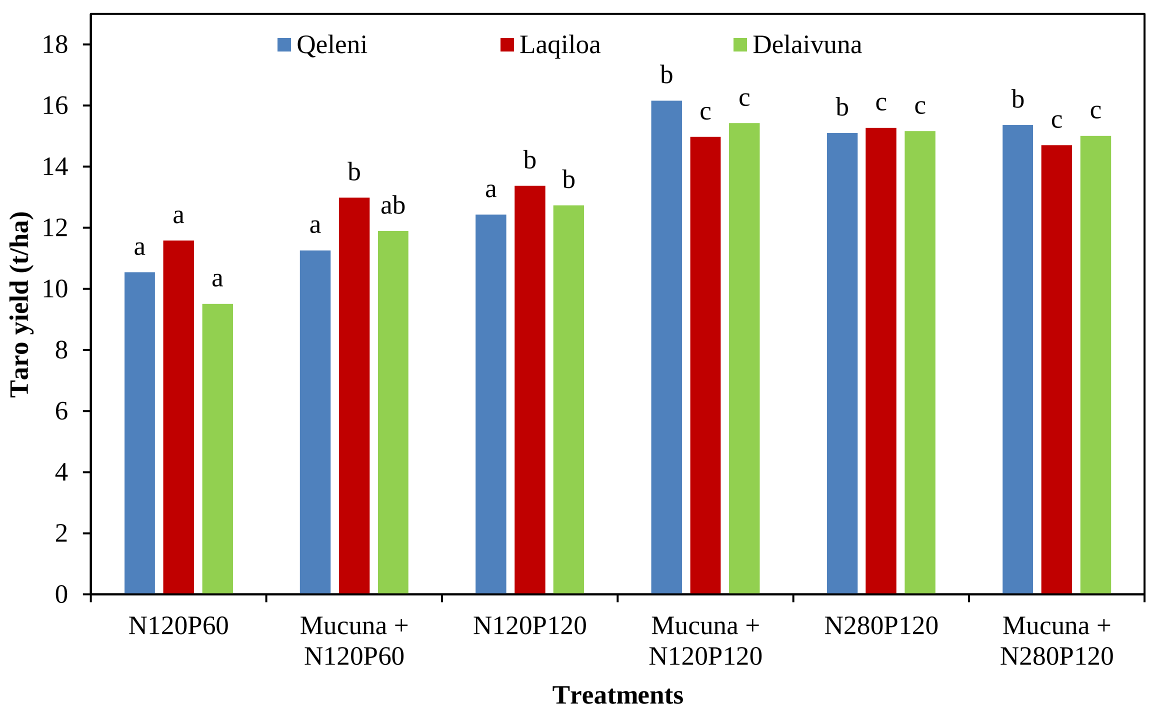


Figure 6.19. Effect of fertiliser and Mucuna green manure crop treatments on taro yield.

All treatments also received 200 kg K and 82 kg S/ha.

The effects of fertiliser and Mucuna green manure crop treatments on sucker numbers are shown in Figure 6.20. There were no significant differences in taro sucker populations between the treatments N120P60 and N120P120 and Mucuna with N120P60. Taro sucker population seems to be least affected by additional phosphorous treatment. Low soil P status of experimental sites may have limited Mucuna growth and N uptake. Table 6.3 (Page 133) shows that N concentration of Mucuna biomass with treatment that received 120 kg N and 60 kg P/ha had 2.74% N content (190 kg/ha N uptake), whereas treatments that received 120 kg N and 120 kg P/ha had 3.30% N (228 kg N/ha uptake). When Mucuna was grown with the 120 kg N and 120 kg P/ha fertiliser treatment, the average sucker population across all three sites was 99,667 suckers/ha, which was significantly higher ($P < 0.05$) than the 70,300 suckers/ha achieved for the same fertiliser treatment without Mucuna. Mucuna contributed to 42% increase in sucker yields as compared to the same fertiliser treatment without Mucuna. All treatments received 200 kg/ha K and 82kg S/ha.

The highest number of suckers was produced when Mucuna was grown with the 280 kg N/ha, 120 kg P/ha and 200 kg K/ha fertiliser treatment (120,200 suckers/ha), which was also same as the number of the suckers (122,633 suckers/ha) for the same fertiliser treatment without Mucuna.

Unlike with corm yield, the use of Mucuna with the 280 kg N and 120 kg P/ha produced significantly ($P<0.05$) more suckers than Mucuna treatment with 120 kg N and 120 kg P/ha treatment. This confirms previous findings that for optimum sucker production, 280 kg N/ha with or without Mucuna treatment is recommended.

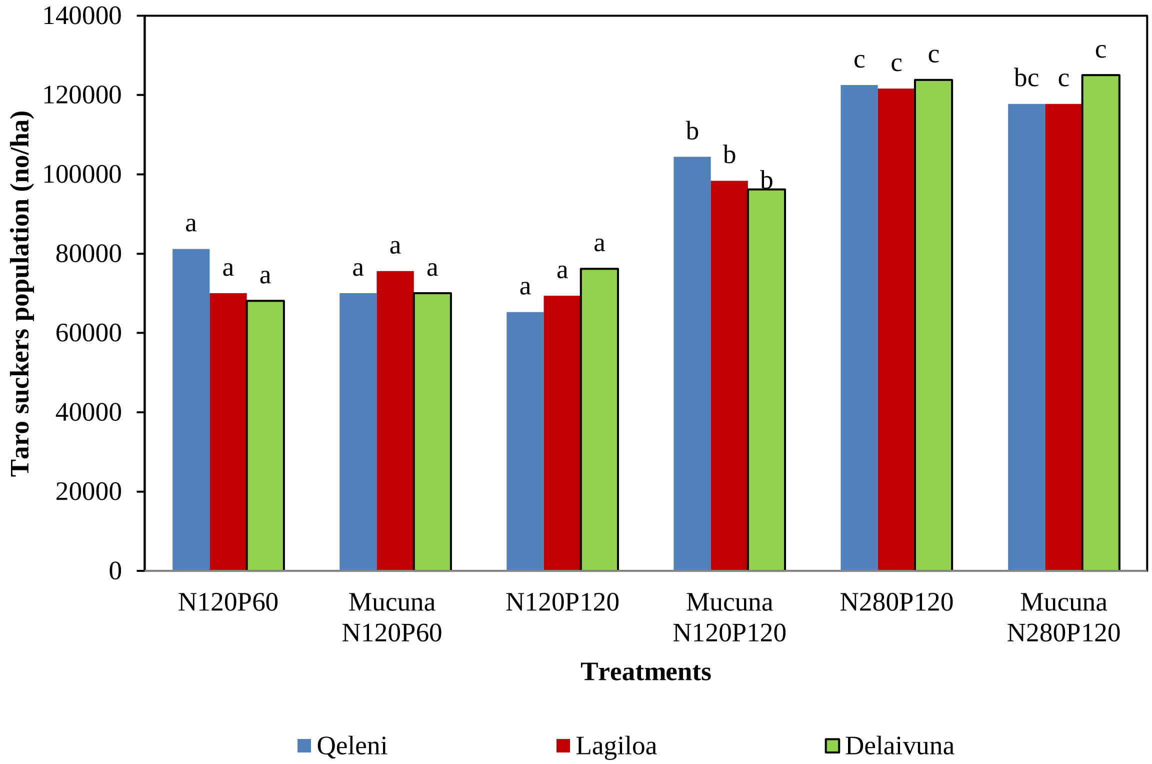


Figure 6.20. Effect of fertiliser and Mucuna green manure crop treatments on taro yield.

All treatments also received 200 kg K and 82 kg S/ha.

6.7.2 Nutrient content and accumulation for Mucuna green manure crop treatments

The dry matter yield and the macro-nutrient content of the three Mucuna cover crop treatments with different N and P rates at 120 DAP are given in Table 6.3. Taro was harvested at 30 WAP. At 120 DAP Mucuna had reached its peak growth and was flowering. There were no significant ($P < 0.05$) differences the biomass production (dry matter basis) of the different cover crop treatments, which ranged from 6.9 – 7.2 t DM/ha. In a study in Ghana, Fosu *et al.* (2004) stated that dry matter yields for Mucuna ranged from 5 to 15 t/ha depending on the amount of rainfall and fallow duration. In separate studies Lathwell (1990) and Sanginga *et al.* (1996) reported Mucuna dry matter yields of 6.7 t/ha and 7.7 t/ha, respectively, which are similar to the current study.

Mucuna cover crop with higher rate of P application (120 kg/ha P) showed significantly ($P < 0.05$) higher total N content indicating that uptake of N by Mucuna cover was influenced on uptake of P. Mucuna cover crop with 120 kg N and 60 kg P/ha, had 2.74% N content, in comparison to the Mucuna treatment with 120 kg N and 120 kg P/ha treatment had 3.30% N content. Vanlauwe *et al.*, 2000 in his study in Nigeria conformed that mean N concentration of Mucuna vegetation at 126 DAP was 2.31%. His experimental plots had total soil N of 0.80% in top 0-9 cm of soil and 0.37% in the 9-21 cm subsoil profile and no N fertilisers were applied. The treatments in this experiment received 120kg/ha N and this may have been the reason for higher N concentrations.

Table 6.3. Nutrient content of Mucuna cover crop

Treatment	Dry matter (t/ha)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Mucuna + N120P60	7.2 a	2.74 a	0.30 a	0.92 a	0.67 a	0.35 a
Mucuna + N120P120	6.9 a	3.30 b	0.34 a	1.02 a	0.78 ab	0.29 a
Mucuna + N280P120	7.0 a	3.60 *b*	0.34 *a*	1.02 *a*	0.96 *b*	0.32 *a*
LSD	0.129	0.43	0.14	0.17	0.21	0.09

* Within a fallow duration column means followed by the same letter are not significantly different from each other at 5% significance level. All treatments also received 200 kg K and 82 kg S/ha.

The macro-nutrient accumulations by the different Mucuna treatments are shown in Table 6.4. Mucuna treatment with highest N and P application rate had a significantly ($P < 0.05$) higher accumulation of N and Ca compared to lowest N and P application treatment. The N and Ca accumulated by Mucuna + N120P60 treatment was 2.7 and 3.60%, respectively, while the N and Ca accumulated by Mucuna + N280P120 treatment was 3.60 and 0.78%, respectively. There were no significant differences between treatments in the accumulation of other nutrients.

In other studies (Sanginga *et al.* (2001)Chikowo *et al.* (2004) Goh and Chin (2007) and Ngome *et al.* (2011), Mucuna has been shown to fix from the atmosphere a high proportion (71-96%) of the N accumulated in the plant. In the current study, N fixation was not estimated, however, it is likely that a substantial proportion of the N accumulated in some Mucuna treatments was contributed to by fixation. For example, the N120P120+Mucuna treatment accumulated 108 kg N/ha (i.e. 47%) more N than was applied in fertiliser. However, not all of the fertiliser N would have been available to the Mucuna, as the taro crop was also competing for this source of N. Therefore, fixation is likely to have been greater than 47%, if it is also assumed that the supply of N from soil organic N mineralisation was not high. Given that the sites had previously be used for cropping for many years (> 10 years), it is likely that the soil supply of mineral N (background and from mineralisation) was not large. For example, when no N fertiliser was applied (e.g. the N0P0K200 treatment), then taro N accumulation was only 14.9 kg N/ha (Table 6.2). This supports that the supply of mineral N from the soil alone was low at the experimental sites during the period of the experiment.

Jemo *et al.* (2007) conducted a study on N uptake by Mucuna at 120 DAP in Southern Cameron and concluded that Mucuna can accumulate 206-314 kg N/ha. Martini (2004) stated that nitrogen accumulation in Mucuna biomass at 60, 90 and 120 DAP were 171, 303 and 421 kg/ha, respectively. In these study nutrient accumulation was measured at 120 DAP and were lower than the findings of Martini (2004) and Jemo *et al (2007)*. The duration of the fallow crop and time of sowing influenced the biomass production and nutrient uptake (Buckles *et al.*, 1998 and Lal, 2013).

Table 6.4. Nutrient accumulation by Mucuna green manure crop treatments

Treatment	**N (kg/ha)**	**P (kg/ha)**	**K (kg/ha)**	**Ca (kg/ha)**	**Mg (kg/ha)**
Mucuna + N120P60	190 *a*	23.6 *a*	63.4 *a*	48.1 *a*	22.3 *a*
Mucuna + N120P120	228 *ab*	20.9 *a*	73.1 *a*	56.5 *a*	20.9 *a*
Mucuna + N280P120	260 *b*	24.4 *a*	71.1 *a*	68.1 *b*	24.9 *a*
LSD	32.15	9.95	14.30	15.50	5.74

* Within a fallow duration column means followed by the same letter are not significantly different from each other at 5% significance level. All treatments also received 200 kg/ha K and 82 kg S/ha.

6.7.3 Effect of Mucuna green manure crop on weed suppression

Mucuna was planted in selected treatments at the same time as the taro was planted. Weeds surveys were conducted on Mucuna treatments plots and non Mucuna plots at 4 and 8, 12, 16 and 20 WAP. During each survey, a 1 m x 1 m quadrant was placed in 3 randomly selected areas within each plot. Weeds within the quadrants were identified and counted. Following each weed assessment, weeds were removed by hand from each plot as part of weed control. Taro crop had formed full canopy

The five species of weeds observed under mucuna cover crop and selected non-cover crop treatments across all the sites were Crowsfoot (*Eleusine indica*), Thick head (*C. crepidioides*), Nut sedge (*cypruss rotundus*), Hawaiian rose (*Clerodendrum philippinum*) and Tar weed (*Cuphea carthgenensis*) (Figure 6.21). Crowsfoot and Thick head infestation were the more numerous weed species (approximately 70% of total weed biomass). According to Queensland Government Department of Agriculture, Fisheries & Forestry (2012), Crowsfoot colonises thin open turf, particularly on worn areas with compacted soils and some populations are Glyphosate resistant. In Taveuni, it was observed to be Paraquat resistant, thus making it difficult to control. Thick head (*C. crepidiodes)* is an invasive herb included in the Global Compendium of Weeds and classified as one of the most aggressive weeds occurring in tropical and subtropical regions (Randall, 2012). It is a pioneer species with the capability to produce large amounts of hairy wind-dispersed seeds. Both Crows foot and Thick head are hard to control in taro fields. Taro in Taveuni is grown with no tillage system and farmers are total reliant on herbicides for weed control. Studies by Gurnah (1985) have shown that taro was sensitive to weed competition through most of its growth stages, but that it was more sensitive during early growth (16 WAP). Early weed competition can result in smaller taro corms. Suckering was also severely reduced by weed competition. Typically, 7-9 weeding events are required to keep the crop to provide adequate control of weeds.

There were no significant differences ($P < 0.05$) in dry weed biomass at 8 WAP between Mucuna and treatments without Mucuna. It was observed that Mucuna germinated 2 WAP and there was only 30% ground cover at 8 WAP. Across all sites the treatments with Mucuna had significantly ($P < 0.05$) lower weed biomass at 12, 16, 20 and 24 WAP as compared to non Mucuna treatments (Figure 6.22, 6.23 and 6.24). On an average at 12 WAP, across the three sites, the Mucuna cover crop treatment had 224 kg DM/ha weed dry matter, compared to 750 kg DM/ha for the treatments without Mucuna. Taro plants are grown at 1mx1m spacing and at 20 WAP the plants had formed full canopy which intercepted most of the sunlight. Taro leaves and corm develop synchronously up to maximum canopy attainment at about 20 weeks. Leaf area increases during this stage due to increase in the rate of leaf production, leaf number and leaf size. At this stage weed growth was suppressed due to low sunlight interception and shading effect of developed canopies.

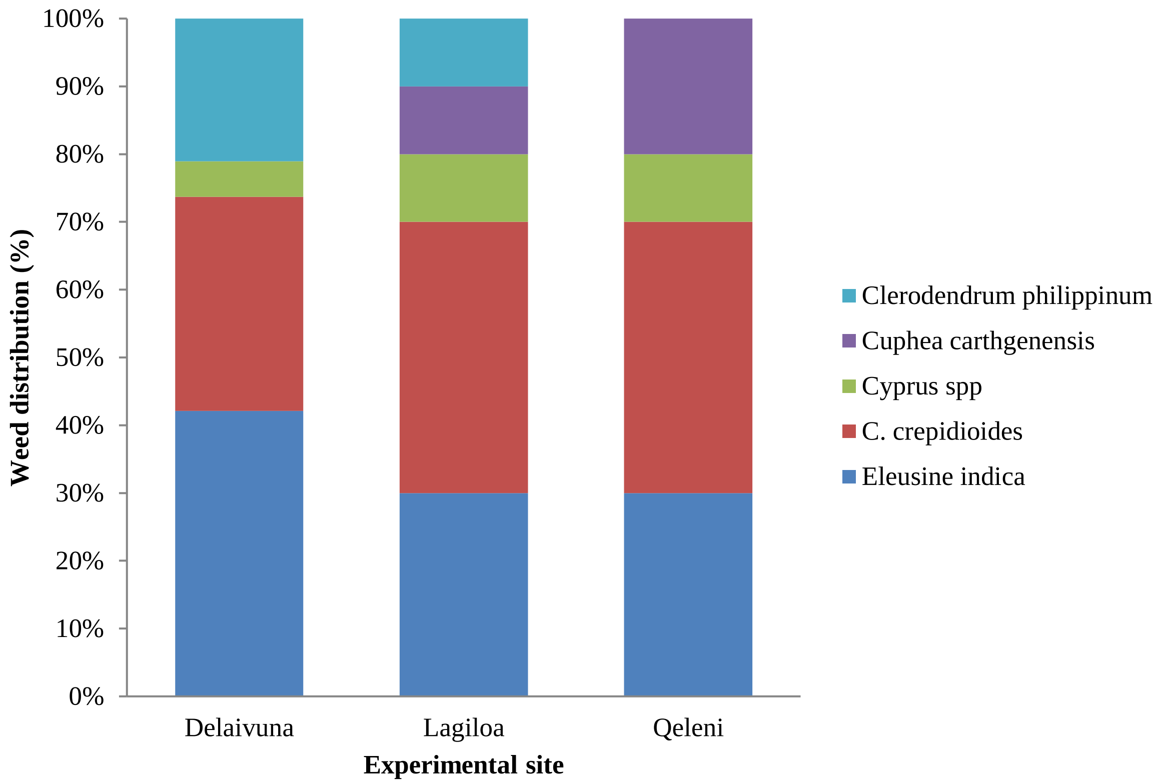


Figure 6.21. Weed types at the 3 experimental sites sampled from control plots at 12 WAP

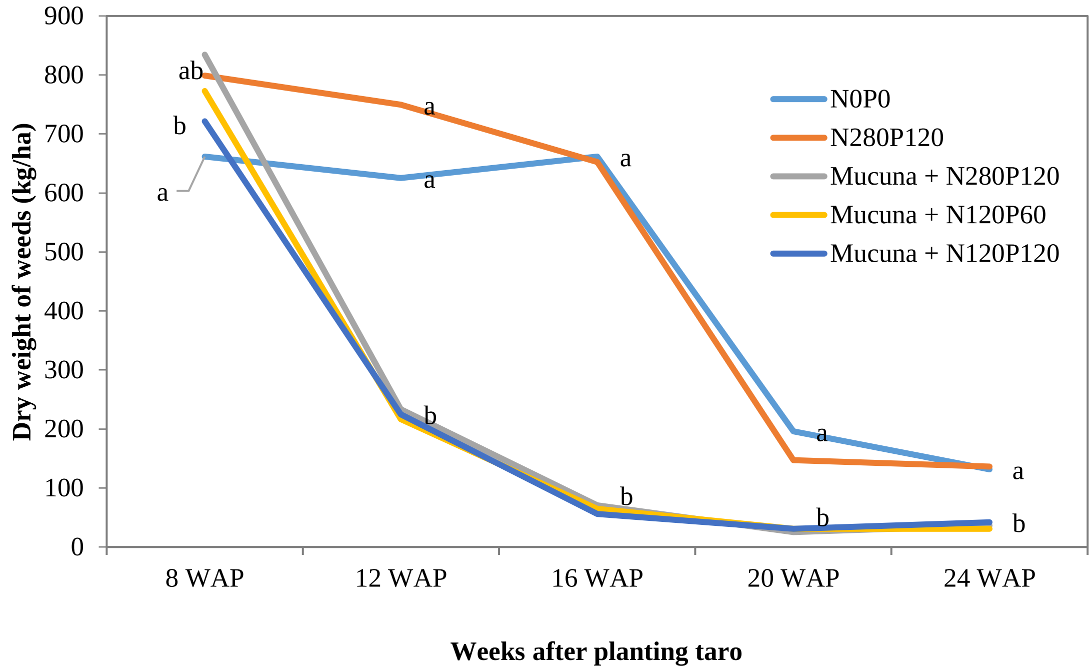


Figure 6.22. Effect of different treatments on weed biomass at Qeleni site

*(*means followed by the same letters at each duration are not significantly different from each other at 5% significance level.)*

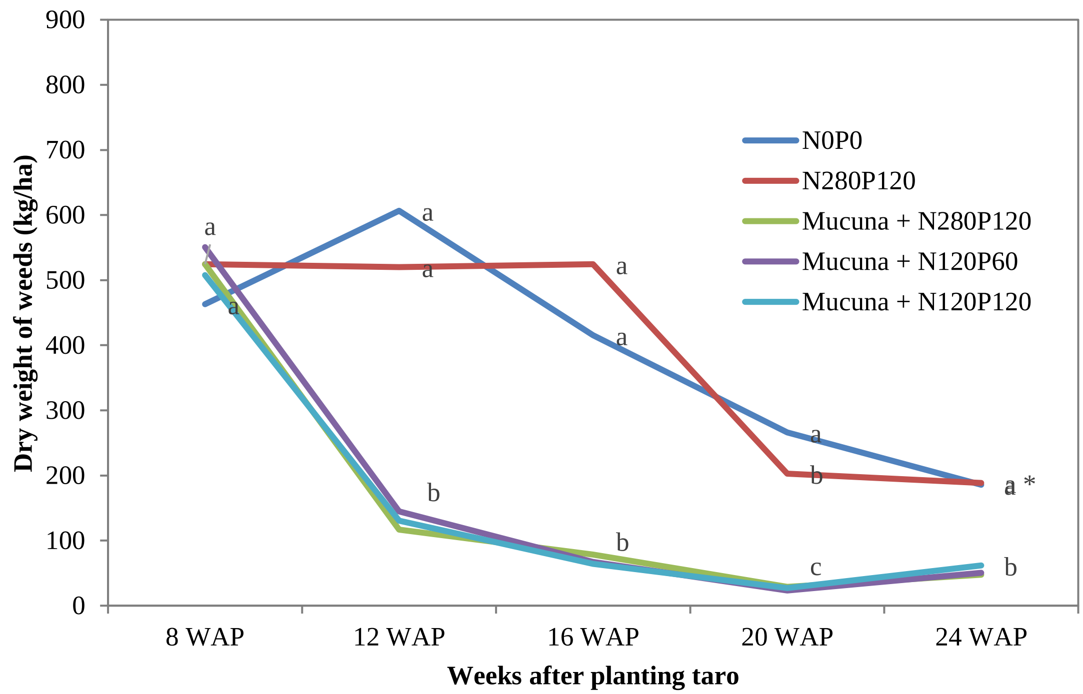


Figure 6.23. Effect of different treatments on weed biomass at Lagiloa site.

*(*means followed by the same letters at each duration are not significantly different from each other at 5% significance level).*

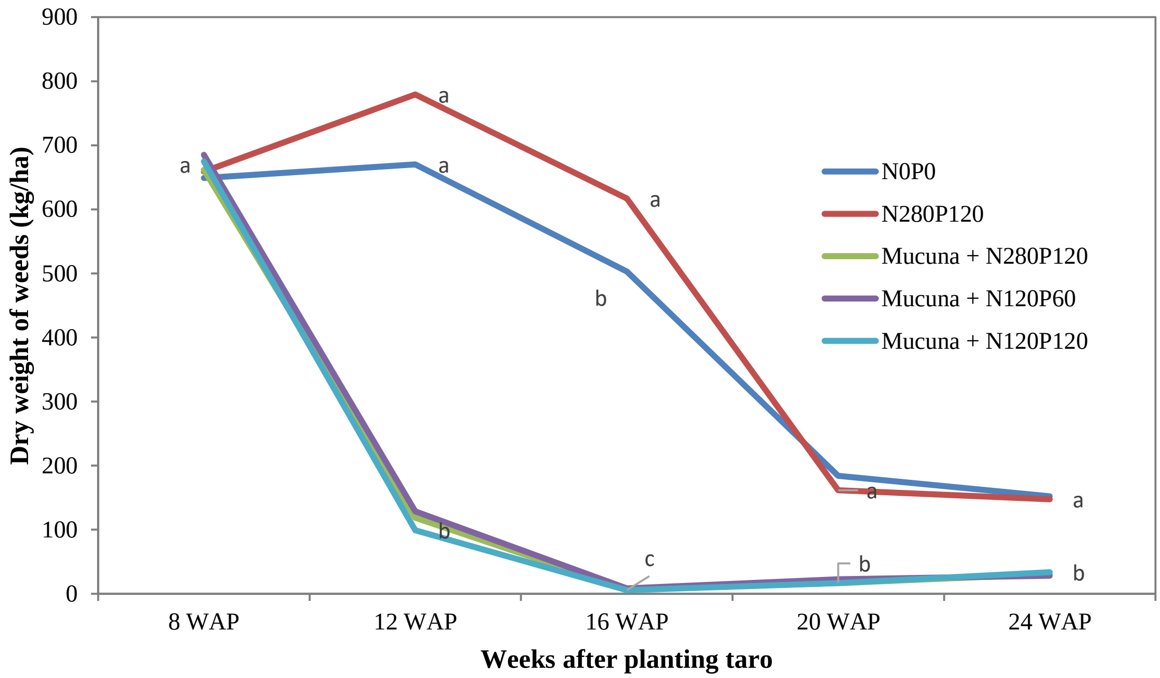


Figure 6.24. Effect of different treatments on weed biomass at Delaivuna site.

*(*means followed by the same letters at each duration are not significantly different from each other at 5% significance level.)*

6.8 Discussion

The response of taro corm yields to N, P and K fertiliser was similar across all three sites. The plant availability of soil N and P were major limiting factors to yield at all three sites. When no N and P fertiliser was applied, average corm yields were very low at 6.2 t/ha, even when K and S fertiliser inputs were high. The addition of up to 200 kg N/ha and 120 kg P/ha, resulted in substantial yield increase of 240% to 14.9 t/ha. Further increasing N fertiliser rates did not significantly increase yield. In addition, all sites have been used for long-term (i.e. >10 years) cropping, which would contribute to low levels of N being available from mineralisation from soil organic matter result in the crop being responsive to N fertiliser addition. All sites had very low initial Olsen P values that were less than 10 mg P/kg soil, which would explain why yields were responsive to P fertiliser addition. The response of taro yield to N and P addition was consistent with Experiment 1 results (Chapter 5). Taro yield was also responsive to K fertiliser use, with significant increases in yield up to the highest rate of K used (200 kg K/ha). Application of 150 and 200 kg K/ha produced corn yields of 13.3 and 15.2 t/ha, which were 19 and 36 % higher than 100 kg K/ha treatment, respectively.

Daniells *et al*., 2009 did fertiliser response studies in Australia and stated that 300 kg N, 120 kg P and 720 kg K/ha produced optimum yields of 33.7 t/ha. They also stated that 200 kg N, 80 kg P and 480 kg K/ha produced 31.1 t/ha and 32.6 t/ha taro yield respectively. Their experiment states that further yield improvements can be achieved with higher K use.

There was a near linear increase in taro sucker populations from N fertiliser applications up to a rate of 280 kg N/ha of N fertiliser. On average across the three sites, taro sucker numbers increase from ~20,000 when no N fertiliser was applied, up to ~123,000 for the 280 kg N/ha rate. This provided and increase of approximately 368 suckers/ha of kg N applied. Further increasing N rates up to 360 kg N/ha, had no significant ($P < 0.05$) effect on additional yield increases. Hartemink *et al.* (2000) stated that above-ground biomass (tops) of taro was not significantly increased up to 200 kg N/ha but applications of 300-400 kg N/ha yielded 8–11 t/ha more taro tops.

Potassium fertiliser rate also had an influence on taro sucker numbers, but to a lesser extent than N. Taro sucker production was not influenced by P fertiliser application rates. While taro corm yield did not significantly increase above 200 kg N/ha, there were further benefits for sucker numbers up to 280 kg N/ha. Therefore, depending of the availability of sucker numbers/price of suckers there may be an advantage for farms to us rate of N up to 280 kg N/ha. For example, increase N rate from 200 to 280 kg N/ha increased sucker numbers by ~38,000 suckers/ha. Fiji is frequently affected by cyclones and droughts and after each extreme event the taro industry suffers shortages of planting materials. Application of high rates of N (280 kg N/ha) will ensure abundance of taro suckers for quick rehabilitation of the industry.

Mixing P fertilisers in the planting hole had a significantly higher taro yield compared to placing the fertiliser at the bottom of the planting hole at one of the three sites. Mixing 120 kg P/ha fertiliser in the planting hole increased yield by 4.14 t/ha (38% increase). The apex of the taro corm represents the plant's growing point and is usually located close to ground level while the base of the corm represents the initial corm that was attached to the planting material. Corm formation in taro is upwards from where it was planted. The fibrous root system develop from the base of the initial corm (Onwueme, 1999) and as the corm develops, more roots are on the soil surface than at the bottom of the planting whole and this may have been the reason for low yields when P fertiliser was applied at the bottom of the hole.

Despite high rates of P fertiliser were used in first experiment there was no significant P carry over effect the on current taro yields. At all three sites, soil Olsen P levels were significantly ($P < 0.05$) higher at 15cm distance away from the planting hole, compared to 30 and 50 cm distances. There was no significant difference between measured soil Olsen P levels at 30 and 50 cm distance away from the planting hole. This indicates that residual P fertiliser are confined to the places where it was applied to and are not evenly distributed throughout the field. Applying fertilisers in planting hole caused non-uniform distribution of nutrients along the field and traditional soil sampling strategies will not show where the applied nutrients are. Taro in Taveuni is planted at a spacing of 1m x 1m and when 120 kg/ha P fertilisers are applied in these planting holes, than 4.9% of total field area will have soil Olsen P levels of 23.9, 9.1 and 16.9 mg P/kg at Qeleni, Lagiloa and Delaivuna sites, respectively. In addition, 23.4% of the field area will have Olsen P levels of 6.4, 10.6 and 4.9 mg P/kg while 71.7% of the field will have Olsen P levels of 7.4, 9.1 and 4.1 mg P/kg at these sites respectively. On the other hand, if soil samples were taken randomly across these fields, then average soil Olsen P levels at Qeleni, Lagiloa and Delaivuna sites will be 8.0, 10.4 and 4.9 mg P/kg, respectively (weighted averages against % area covered at each location). This may have been the reason why no previous P application rates had any carry over effects on the later crop. This study shows that this can be a substantial mistake when the overestimation of soil fertility indicates no need for P fertiliser application is required and when actual soil test levels may be yield limiting. Fertiliser placement may cause non-uniform nutrient distribution in the soil, making it difficult to determine whole-field fertility by traditional sampling strategies. In no tillage system, overall soil P build up strategies will require high rates of P fertiliser application over time.

Inter-cropping taro with Mucuna as a green manure crop incorporated with 120kg N/ha, 120 kg P/ha and 200 kg K/ha has an equivalent benefit (14.91 t/ha), in terms of increased corm yield, as the treatment 200 kg N, 120 kg P and 200 kg K/ha treatment without Mucuna (15.51 t/ha). This may have been due to N fixation, weed suppression and mulching effect of

Mucuna crop (Lal, 2013, Anand 2015). In the subsequent experiment, N uptake and dry matter yield of Mucuna was measured. The choice of cover crop and ways of reducing competition between the crops is very important. In this study, Mucuna growth was terminated by chopping the plants with a knife at 16 WAP and the remains were allowed to decompose on the soil surface providing a mulching effect. At this period Mucuna crop was in the flowering stage. During peak Mucuna growth period, vines were removed from taro plants to reduce competition for light and space.

Unlike with corm yield, the use of 280 kg N, 120 kg P and 200kg K/ha with and without Mucuna produced significantly ($P < 0.05$) more suckers than Mucuna treatment with 120 kg N and 120 kg P/ha treatment. This confirms previous findings, that for optimum sucker production, 280 kg N/ha with or without Mucuna treatment is recommended.

Mucuna cover crop with higher rate of P application (120 kg/ha P) showed significantly ($P < 0.05$) higher total N content indicating that uptake of N by Mucuna cover is dependent on uptake of P. Mucuna cover crop, consolidated with 120 kg N, 120 kg P and 200 kg K/ha accumulated 228 kg N, 20 kg P and 73 kg K/ha. Other studies of N accumulation by Mucuna have shown that it can accumulate between 145- 412 kg N/ha (Buckles *et al*., 1998; Steinmaier and Ngoliya, 2001; Martini, 2004; Lal, 2013). Furthermore, Martini (2004) quantified N accumulation in Mucuna biomass at 9, 13 and 17 WAP to be 170.8, 303.1 and 421 kg N/ha, respectively. They suggested that planting date had an influence on biomass production and nutrient accumulation. The longer the crop duration, more dry matter production and nutrient accumulation occurred. Mucuna crops that are planted at least 16-20 weeks before the flowering period, accumulates maximum N (Martini, 2004). Lal (2013) in a study in Fiji measured N accumulation by Mucuna cover crop of 145 kg N/ha at 26 WAP. In Fiji, Mucuna flowers in the months of May and November. In this experiment, Mucuna growth was terminated at 16 WAP and the crop had started to flower, indicating maximum N uptake and recycled in its biomass. It has been estimated that between 70-96% of total N accumulated by Mucuna is fixed from atmospheric N and the remainder coming from available soil N (Sanginga *et al.,* 2001; Chikowo *et al.*, 2004; Goh and Chin, 2007; Ngome *et al.*, 2011). Mucuna is an herbaceous annual legume which decomposes quickly, mineralizing N faster than cereals because of lower C: N ratios. Throughout the Mucuna growth cycle, it is shedding old leaves, which are continuously decomposing below the actively growing cover crop (Buckles et al., 1998) providing nutrients for taro growth.

The treatments with Mucuna cover crop had significantly lower weed biomass at 12, 16, 20 and 24 WAP as compared to non-cover crop treatment across all sites (Figure 6.22, 6.23 and 6.24). Low weed numbers will reduce paraquat use in Fiji and will provide savings to the farmer. On an average at 12 WAP, across the three sites, Mucuna cover crop treatment had 151 kg/ha weeds dry matter and this was 336% less than non-cover crop treatments. All three Mucuna cover crop treatments established well and by 12 WAP had fully covered the soil surface between taro plants. Lower weed numbers in taro production lead to savings on herbicide and labour requirements, thus reducing farmer's cost of production and increasing profit margin. A study by Coyne and Mubiru (2009) concluded that natural cover crop had significantly more weed infestation than lablab fallow, but there were no significant differences between Mucuna (*Mucuna pruriens)*, crotalaria (*Crotalaria juncea*) and canavalia (*Canavalia ensiformis*) cover crop systems. In addition, Boateng (2005) stated that weeds were suppressed significantly under Mucuna cover crop as compared with grass system. The results of this study confirm the findings of Boateng (2005). Sakala *et al.* (2003) proved that Mucuna cover crops produced huge quantities of leaf biomass, which protected the soil from direct penetration of sunlight, thus reducing weed infestation. Living cover crops can reduce light and moisture availability to germinating weed seeds. Weeds attempting to germinate often compete with cover crops for resources and fast-growing cover crops are able to supresses them. However, Mucuna has a climbing habit and requires regular pruning to prevent it smothering neighbouring crops.

The weed population also decreased under non cover crop system throughout the growing season. Taro plants had reached maximum vegetative growth at 16 WAP. The weeds under non cover crop may have been suppressed by shading effect of the taro plants from 16 WAP. The extent of weed suppression was associated with the coverage (percentage of vegetation covering area to unit soil surface area) by the main crop plus cover crop.

All liming treatments and 280 kg N, 120 kg P and 200 kg K/ha treatment had significantly ($P < 0.05$) lower corm rots as compared to non-liming treatment across all sites. Calcium content of the liming materials or optimum nutrient supply may have contributed to lower corm rots. Calcium is important in stabilizing cell membranes and cell walls. It activates enzymes and is required as an intermediary between environmental signals and plant responses. Application of lime significantly ($P<0.05$) increased soil pH but there was no significant difference between 1 and 2 ton/ha lime treatments on soil pH. In addition, local and imported lime had significantly ($P < 0.05$) similar effect on soil pH. Both the imported and local lime is sold in Taveuni and costs $639 and $444/ton respectively. The Fijian government, through its Ministry of Agriculture, has further subsidised local lime and growers can buy them at 1/3 of the actual price. Since lime was broadcasted in the plots, the soil pH remains same across different sampling locations

6.9 Conclusion

This study concludes that fresh taro corm yields of 15 t/ha can be achieved when N, P, K and S fertilisers are added up to 200 kg N, 120 kg P, 200 kg K and 82 kg S/ha. Similar yields could also be achieved by using Mucuna cover crop incorporated and 80 kg N/ha less N fertiliser. However, when the demand for taro suckers is high, especially after natural disasters, increasing the N fertiliser rate to 280 kg N/ha will produce the maximum number of suckers and near optimum taro corm yield. Intercropping taro with Mucuna will also reduce weed population by 336% at 12 WAP, which will help reduce herbicide use. Phosphorus fertiliser placement may cause non-uniform nutrient distribution in the soil, making it difficult to determine whole-field fertility by traditional sampling methods.

Chapter 7 : Predicting taro plant N content and corm yields using a remote sensing method to assess plant chlorophyll status

7.1 Introduction

The appropriate rate and timing of nitrogen (N) fertiliser applications are critical factors in optimising taro yield and quality, and minimising environmental pollution. Taro growth is characterised by three distinct growth phases, namely the establishment phase, the vegetative phase (grand growth phase) and the maturity phase. Root formation and rapid root growth take place immediately after planting, followed by rapid growth of the shoot up until 6-8 weeks after planting (WAP). This initial phase is known as the crop establishment period. This is followed by a grand growth phase (vegetative growth) in which taro plants accumulates biomass very rapidly reaching a peak at 20 to 22 WAP. Most fertiliser should be applied during the vegetative phase (i.e. between 8 between 22 WAP). Nitrogen application also prolongs the vegetative stage, which influences the partitioning of growth between the above and below portions of taro plants (Fa'amatuainu, 2016; Goenaga and Chardon, 1995; Lebot, 2009). Field studies have shown that taro plants require large quantities of N to produce key plant compounds, such as protein, adenosine triphosphate, and nucleic acid (Miyasaka et al., 2002). Jacobs (1990) state that higher levels of N earlier in the taro growth cycle, increases leaf area and the number of leaves. Leaf area determines light interception, plant CO_2 fixation and photosynthesis (Liu & Stutzel, 2002), which influence dry matter (DM) production of plants. Shoot growth and total shoot dry weight show a rapid decline after about 24 WAP. At this time, there is a reduction in the number of active leaves, a decrease in the mean petiole length, a decrease in the total leaf area per plant, and a decrease in the mean plant height. By 24 WAP, when shoot growth declines, the corm becomes the main sink and grows rapidly (FAO, 2006). Corm growth continues until harvest, which is typically at 28-32 WAP.

Nitrogen deficiency can substantially reduce corm yield, whereas, excessive N application can delay corm maturity, lower corm quality, and increase the chance of nitrate contamination of surface and ground water. Early detection of N stress and timely and appropriate N application are important field management practices for optimising plant growth and minimising N losses. Conventional tissue testing involves leaf sampling and testing for plant nitrogen (N) concentration under laboratory conditions (Miyasaka, 1994). It provides a relatively accurate assessment of plant N status, but the time lag between sample collection, chemical analysis and N supplementation, as well as the labour and cost required in each step, represent significant drawbacks, particularly for farmers in many Pacific Islands countries.

An alternative to directly measuring plant N concentration is the use of leaf chlorophyll meters (CM). Leaf CMs have been used for various crops as indirect indicators of plant N status (Wu et al., 2006), because there is a strong relationship between chlorophyll content and the leaf N concentration. Different portable systems (Hydro-N-Tester [Yara] or Soil Plant Analysis Development - SPAD [Minolta]) are able to estimate leaf chlorophyll content based on leaf transmittance in specific wave bands (403 and 750 nm) of the tested tissues. Therefore, indirect estimations of leaf N concentration using CM readings could be an effective way to estimate N concentration in taro plants. The SPAD-502 meter (hereafter referred to as SPAD) is a hand-held device widely used for rapid, accurate and non-destructive estimates of leaf chlorophyll concentrations (Ling *et al*., 2011). It is a device that uses two light-emitting diodes and a silicon photodiode receptor, that measures leaf transmittance in the red (650 nm; the measuring wavelength) and infrared (940 nm; a reference wavelength used to adjust for non-specific differences between samples) regions of the electromagnetic spectrum. These transmittance values are used by the device to derive relative SPAD meter values that are proportional to the amount of chlorophyll in the sample (Uddling et al. 2007).

Successful use of CMs varies with crop type and has been affected by many factors including varietal differences (Hoel, 2003), growth stages (Ramesh et al., 2002), nutrient deficiencies other than N (Turner and Jund, 1991), environmental conditions (Schepers et al., 1992), and the measurement positions on leaves (Chapman and Barreto, 1997). It has also been reported that irradiance might affect SPAD readings, especially for shaded plants (Hoel and Solhaug, 1998). To help minimise the impact of these factors, CM readings are usually normalised to an adequately N fertilised reference crop (Denuit et al., 2002).

Wu *et al*. (2007) compared potato petiole nitrate (NO_3^-) concentrations and SPAD chlorophyll readings, for assessing the N status of potato crop canopies. They used three fertiliser N rates (134, 202 and 270 kg N/ha) applied in three split applications, while another two rates of N (202 and 270 kg N/ha) were applied in five split applications. These treatments were compared with a single application treatment of 34 kg N/ha applied at planting. This study found that overall treatment variations in SPAD readings were consistent with changes in petiole NO_3^- concentrations. However, the ability of the SPAD meter to detect treatment differences varied with growth stage and growing season. Severe N deficiency was detected about 1 month after emergence with SPAD readings, but this deficiency was detected earlier, at 2 weeks after emergence, using measurement of petiole NO_3^- concentrations. Petiole NO_3^- concentrations tended to differentiate more treatment variations than SPAD readings at all growth stages except at hilling. They concluded that SPAD meters could be used as an indirect method for detecting N deficiency at the hilling stage, when making supplemental N fertiliser applications, but this method was not as sensitive as the petiole sampling method.

Hgaza *et al.,* (2009) used the SPAD meter to identify the optimal leaf position on yam vines for predicting N fertiliser response. They concluded that leaf area and SPAD readings increased with plant age, while leaf N content decreased. There were no significant difference in SPAD reading between fertilised and non-fertilised plots at 10 weeks after planting (WAP), but significant differences were observed at 14, 18 and 22 WAP. The SPAD values were significantly higher under fertilised plots (160 kg N/ha, 180 kg K/ha, 10 kg P/ha) than non-fertilised plots. They identified that optimal leaf position for predicting N response using the SPAD meter, which was between the 4th and 7th leaf position.

Byju and Anand (2008) used a SPAD and leaf colour chart to estimate chlorophyll content and yield of cassava. These two methods were used to assess crop differences in leaf positions, growth stages, cultivars and N fertiliser rates. The study found that the SPAD reading of leaf 1 at 4 and 8WAP accounted for 83% and 81% of the variation in tuber yield of cassava, respectively. These relationships became insignificant at 12 WAP. The SPAD readings of leaves 2 and 3 were not significantly correlated to tuber yield, and it was concluded that SPAD readings of cassava were influenced by the leaf position. Howeler

(1996) reported that the youngest fully expanded leaf reflected the most recent history of N availability to cassava and an immediate reflection will be more noticeable in the green colour of leaf 1 than in in lower leaves.

There is no information on the use of the SPAD meter to predict N fertiliser requirements for taro production systems. Therefore, this study aimed to evaluate the relationship between SPAD chlorophyll meter measurements and N fertiliser application rates on taro yield at different growing stages of taro crops. A further comparative study was also conducted to evaluate the efficiency of the SPAD meter on predicting taro yield when N was optimum but soil P availability was limiting yield.

7.2 Materials and method

This study was part of field Experiment 2, which was conducted from August 2017 to March 2018 at three sites on Taveuni Island (refer to Chapter 3 for methods). The selected N fertiliser (urea) treatments used in this study were 0, 120, 200, 280 and 360 kg N/ha. All N fertiliser rates were applied in three equal applications at 5, 10 and 15 WAP. All these treatments also received 120 kg P, 200 kg K and 82 kg S/ha, which are sufficient rates of these nutrients to ensure they are not having a major influence on limiting yield potential.

Taro yields are not only limited by N but are also affected by soil P status. There are limited studies that have assessed the relationship between SPAD readings and yield when the supplies of key plant growth limiting nutrients, other than N, are inadequate. Therefore, this study also evaluated how well of SPAD reading predicted taro yield when soil P availability was more limiting than N availability for plant growth. In this evaluation, P fertiliser was applied at two rates of 60 and 120 kg P/ha, with both rates also receiving 120 kg N and 120 kg K/ha. All treatments were replicated 4 times and were arranged in a randomised complete block design.

Details of taro planting technique and fertiliser application methods and timing are described in Chapter 3. The SPAD meter was used to estimate the chlorophyll content in taro leaves at 8, 12, 16 and 24 weeks after planting (WAP) on selected treatment plots. Sampling dates were selected in order to have information on the different stages of the crop cycle, including: the establishment phase, vegetative growth, and from corm formation until physiological maturity. The SPAD readings of the second youngest open leaf were measured because they are the youngest leaf most exposed to the sunlight. The leaves most exposed to sunlight tend to have higher N contents than the lower leaves (Andrade, 2005). All SPAD readings were taken during sunny conditions between 10 am and 2 pm. Six plants were selected from each treatment plot (Figure 7.1) and SPAD readings were recorded from eight different positions per leaf, as shown in the Figure 7.2. All readings were taken in the middle between leaf veins, approximately 3 cm inside from the outer leaf edge. Necrotic areas that were damaged by pests and diseases were avoided. At each position, four repeated measurements were made to provide a single average reading. Therefore, a total of 48 of SPAD readings were recorded for each plot and the average for each plot was used for comparisons.

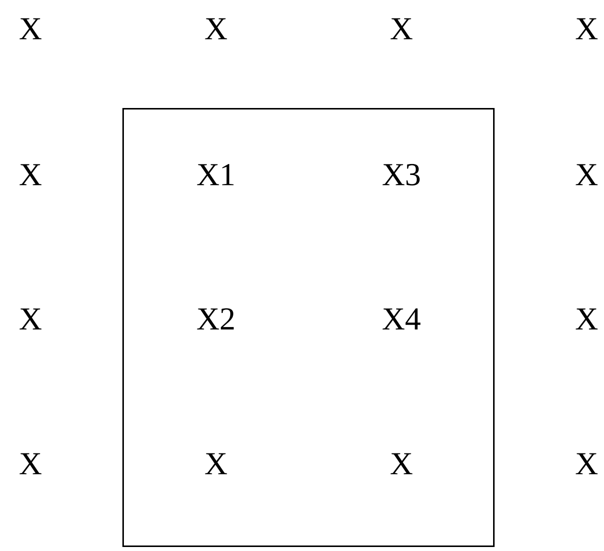


Figure 7.1 Data plants which were used for SPAD readings in each plot

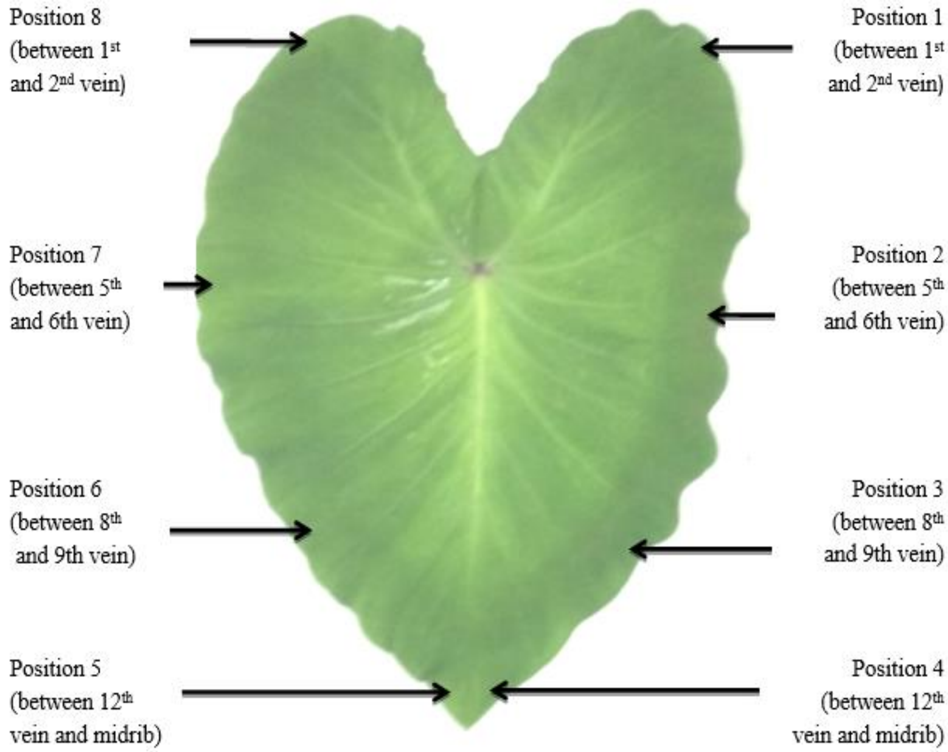


Figure 7.2. Positions on a leaf where SPAD readings were made.

At physiological maturity, the 4 (X1-X4, Figure 7.1) plants from each plots, that were also used for the SPAD readings, were harvested to determine the corm yields and plant total N content. All 4 plants were harvested, and roots and soil were removed from the plant components. Plant components, such as taro leaves, petioles, suckers and corms, were separated, weighed, chopped into small pieces and packed separately in clearly marked bags. These plant components were oven dried (72 ºC for 48 hours) and their dried weights were recorded. Dried samples were ground to pass through a 1 mm mesh screen. Representative samples from each plant component were sent to the Massey University Soil Chemistry Laboratory, Palmerston North, New Zealand, for total N analysis. The relationship between corm yield, plant total N content and SPAD readings were then evaluated.

7.3 Statistics and data analysis

An Analysis of Variance was performed using Genstat (version 19) to test the effect of sampling date and fertilisation on all of the parameters measured. Means were compared with the least significant difference (LSD) test at P = 0.05. To determine the mean SPAD value for all leaf positions, all data were an average of multiple replicated measurements. Graphs were plotted using Microsoft Excel.

7.4 Results and discussion

7.4.1 Treatment effect on SPAD readings

The effect of different rates of N fertiliser on SPAD readings at the Qeleni, Lagiloa and Delaivuna trial sites on Taveuni Island are presented in Figures 7.3, 7.4 and 7.5, respectively. Similar trends were seen across the three sites; therefore, SPAD values at the three sites on average were used to explain the relationship between SPAD readings and N fertiliser rates at different taro growth stages (Figure 7.6). The N applications were applied in three even amounts at 5, 10 and 15 WAP.

At each sampling time, there was a trend of the SPAD readings increasing as N fertilisation levels increased at all sites. The lowest SPAD readings at all four different growth stages was recorded for the no N fertiliser treatment and the highest readings were from the treatment plots with the highest N fertiliser rate (360 kg N/ha). The SPAD readings for the no N fertiliser treatment remained relatively flat over the entire monitoring period, ranging from 32 to 35. At higher N application rates, SPAD readings increased up until 16 WAP and then decreased after this. The greatest separation between SPAD meter readings of the different N fertiliser rates occurred at 16 WAP. These readings were taken a week after the final N application, which may have influenced the elevated readings. At this sampling time, the SAP readings were 36, 60, 66, 73 and 86 for the 0, 120, 200, 280 and 360 kg N/ha, respectively. Smaller differences in average SPAD readings between the N fertiliser treatments at 8 WAP may have been due lower N requirements by the crop at this early stage of growth and canopy development.

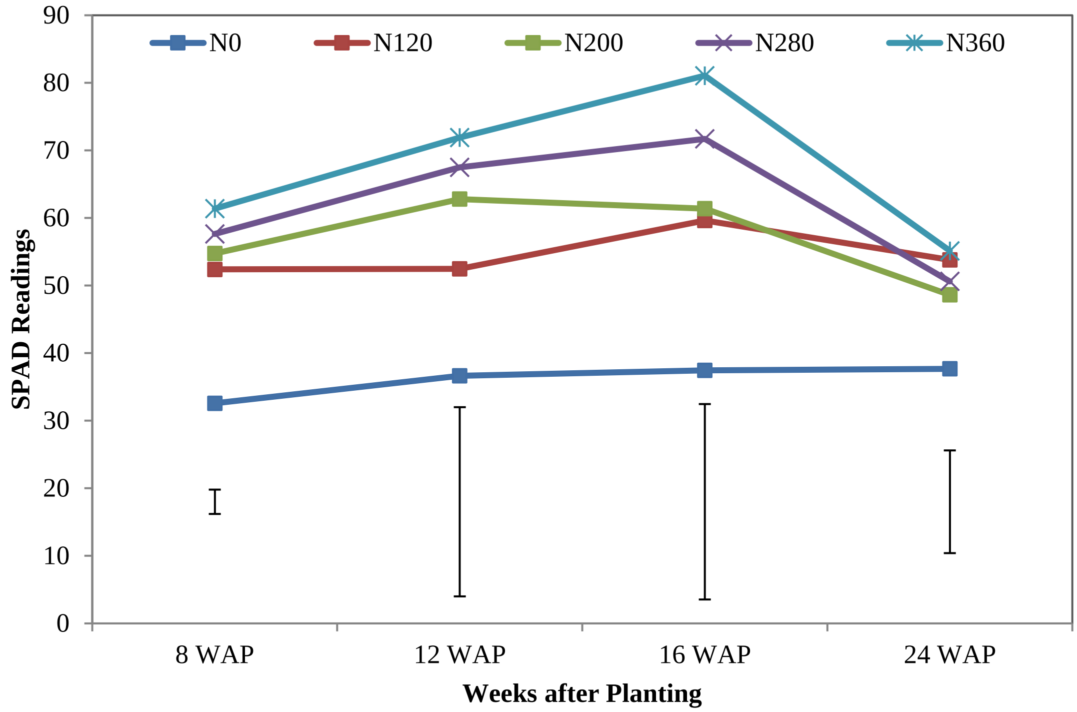


Figure 7.3. The effect of N fertiliser rate on SPAD readings at the Qeleni trial site (error bars indicate the LSD at different growth stages). All N treatments, except N0, also received both 120 kg P/ha and 200 kg K/ha. The N0 treatment received 0 kg P/ha and 200 kg K/ha.

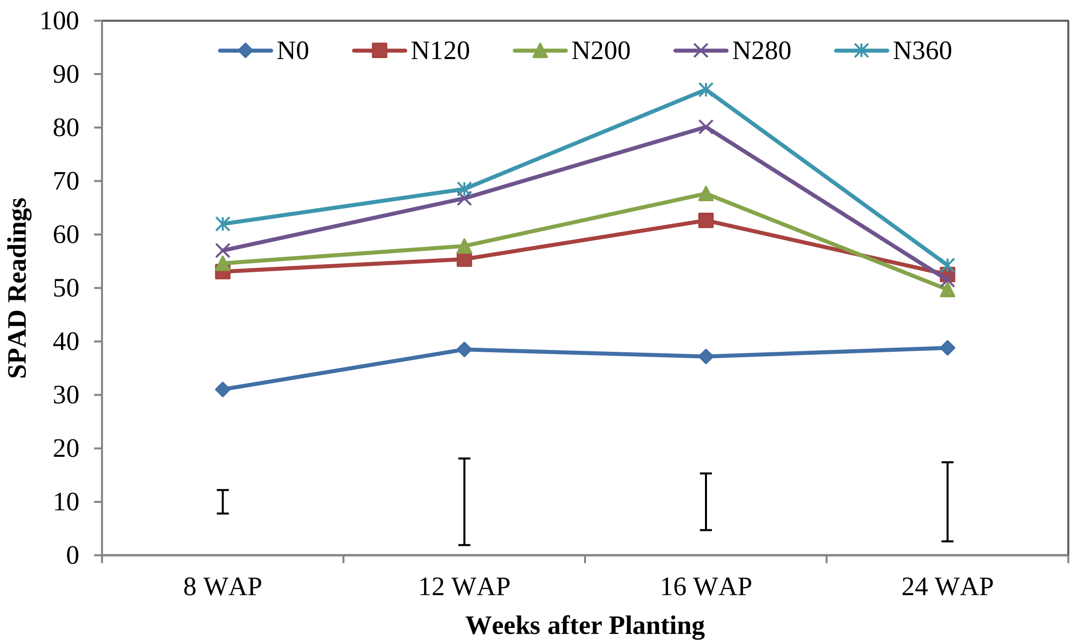


Figure 7.4. The effect of N fertiliser rate on SPAD readings at the Lagiloa trial site (error bars indicate the LSD at different growth stages). All N treatments, except N0, also received both 120 kg P and 200 kg K/ha. The N0 treatment received 0 kg P and 200 kg K/ha.

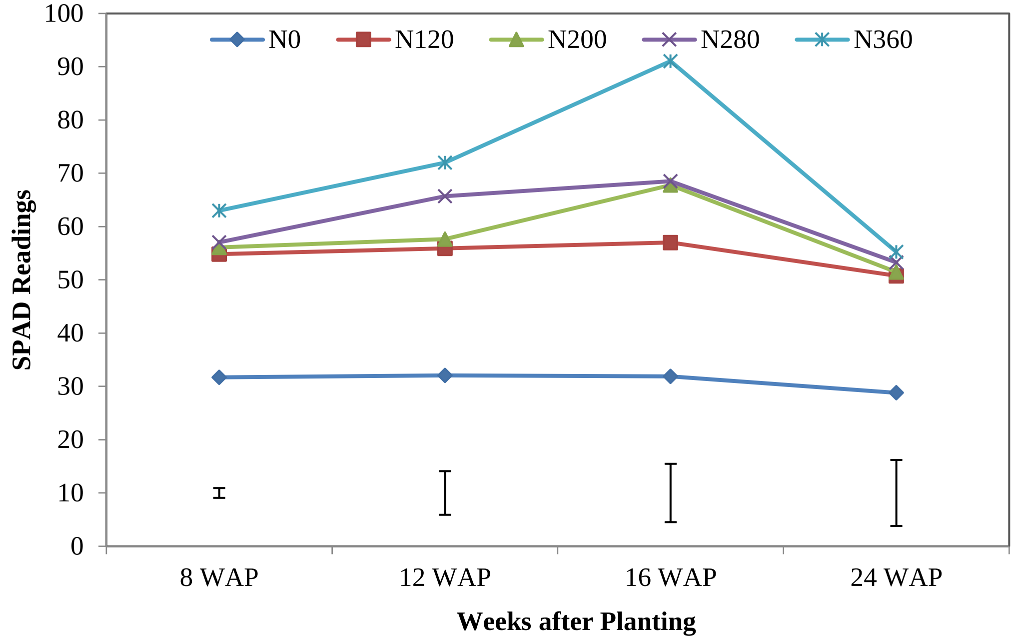


Figure 7.5. The effect of N fertiliser rate on SPAD readings at the Delaivuna trial site (error bars indicate the LSD at different growth stages). All N treatments, except N0, also received both 120 kg P and 200 kg K/ha. The N0 treatment received 0 kg P and 200 kg K/ha.

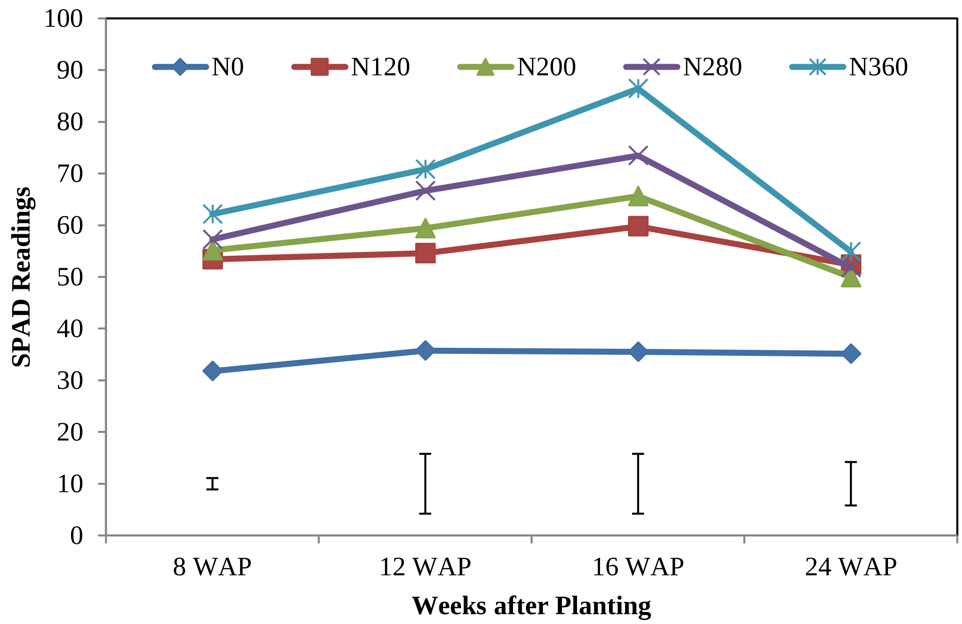


Figure 7.6. The effect of N fertiliser rate on SPAD readings across all the sites on average (error bars indicate the LSD at different growth stages). All N treatments, except N0, also received both 120 kg P and 200 kg K/ha. The N0 treatment received 0 kg P and 200 kg K/ha.

7.4.2 Relationship between N rates applied and SPAD readings

There were positive relationships between applied N fertiliser and SPAD readings with R^2 values of 0.68, 0.70 and 0.83 at 8, 12 and 16 WAP, respectively (Figure 7.7). The relationship becomes weaker and insignificant at 24 WAP. At all of the earlier sampling times, similar associations were observed between N fertiliser rates and SPAD readings. When no fertiliser was applied, SPAD readings were below a SPAD reading of 40 on average at all three sampling times. There was a greater increase in SPAD readings, with increasing quantities of N fertiliser applied, when reading were made at 12 and 16 WAP compared to 8 WAP. However, at each N rate there was a wide range of SPAD readings. For example, at 12 WAP the SPAD readings ranged from 50 to 60 when the N fertiliser rate was 120 kg N/ha. Whereas, when 200 kg N/ha was applied, SPAD readings were between 55-65. Due to the cross over in SPAD readings at different rates, it is difficult to use SPAD to clearly differentiate between N rates unless the difference is large. However, there is a clear separation in SPAD reading from plants that had not received N fertiliser and the lowest rate of N fertiliser used of 120 kg N/ha.

In terms of using SPAD readings to inform N fertiliser requirements of a taro crop, the readings at 8 and 12 WAP are more practical in terms of being early enough in the crop cycle to be able to be used for informing N fertiliser recommendations at 10 and 15 WAP, respectively. The Fijian Ministry of Agriculture recommends that the last application of N fertilisers to be at 15 WAP, as later applications can lead to excessive vegetative growth and can produce peanut shaped corms.

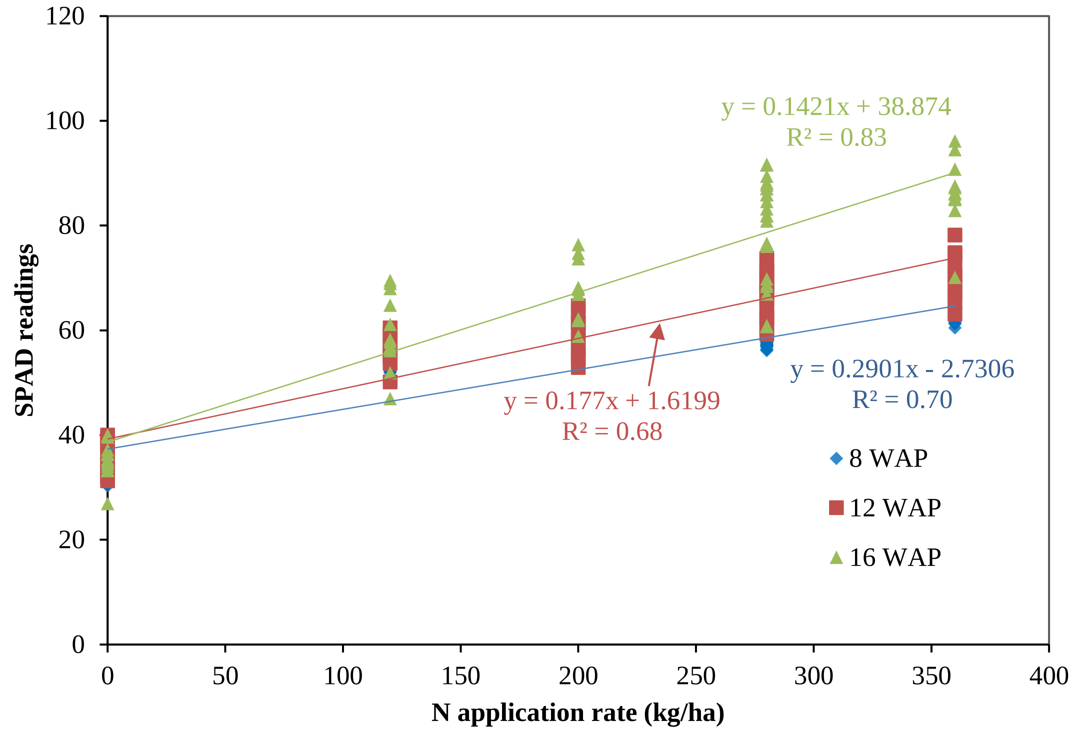


Figure 7.7. The relationship between total fertiliser N applied (at 5, 10 and 15 WAP combined) and SPAD readings and different taro plant growth stages.

7.4.3 Relationship between taro leaf N concentrations and SPAD readings

Nitrogen fertiliser use had a strong relationship with taro total leaf N content and SPAD readings at 12 and 16 WAP measurement times (Figure 7.8). At 12 WAP, plants that received no N fertiliser had N content in the range 2.0-2.6% and SPAD readings of 31-33. In comparison, plants that received N fertiliser had N content ranging from 3.0-4.2% and SPAD readings ranging from 54-74. Using the linear relationship for 12 WAP in Figure 8.8, plants with SPAD readings > 50 had consistently high total N contents of > 3.0%. These results show that SPAD measurement made early in the taro crop's development can be used to predict the crops final N status.

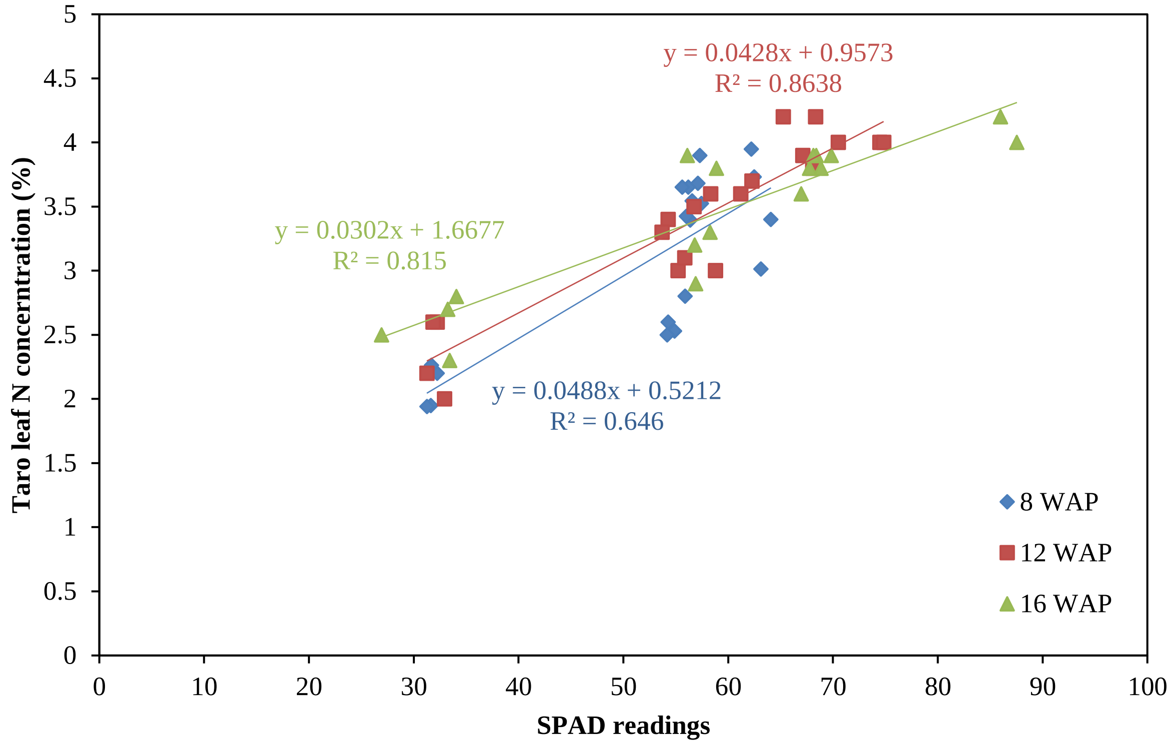


Figure 7.8. The relationship between SPAD readings made at different taro growth stages and plant N concentration at harvest.

Strong positive associations were also observed for taro total plant N uptake at harvest and SPAD readings at 8, 12 and 16 WAP, with the strongest relationship (R^2=0.95) being for readings at 12 WAP (Figure 7.9). At 12 WAP, when SPAD readings were >35, the total plant N uptake at harvest was very low at <25 kg N/ha. When SPAD readings were >50 then N uptakes were >50 kg N/ha, and when readings were > 65 N uptakes were >75 kg N/ha. Therefore, SPAD readings at 12 WAP were effective as a predictor for total plant N uptake at harvest. However, all rates of N involved 3 even split application of N fertilisers at 5, 10 and 15 WAP. Accordingly, if SPAD readings at 8 and 12 WAP are high, this is indicative that plant N status will be high at final harvest, as long as the subsequent recommended N applications are also made at 10 and 15 WAP. Therefore, high SPAD values at either 8 or 12 WAP does not mean that the N fertiliser programme can be terminated at that point in time.

A close relationship between leaf greenness or chlorophyll content and a plant's N status has been reported in other horticultural crops (Tremblay et al., 2011). Peng *et al*., (1993) found that better correlations between these parameters were found at earlier crop stages. SPAD meter readings and leaf chlorophyll concentrations are not reliable at low chlorophyll concentrations, such as those occurring at maturity or near senescence (Dwyer *et al*., 1991). Based on SPAD meter readings being correlated with leaf-blade N concentrations, the meter provides a tool for the early detection of N deficiency in crops and can be used as a valuable tool in N fertiliser management.

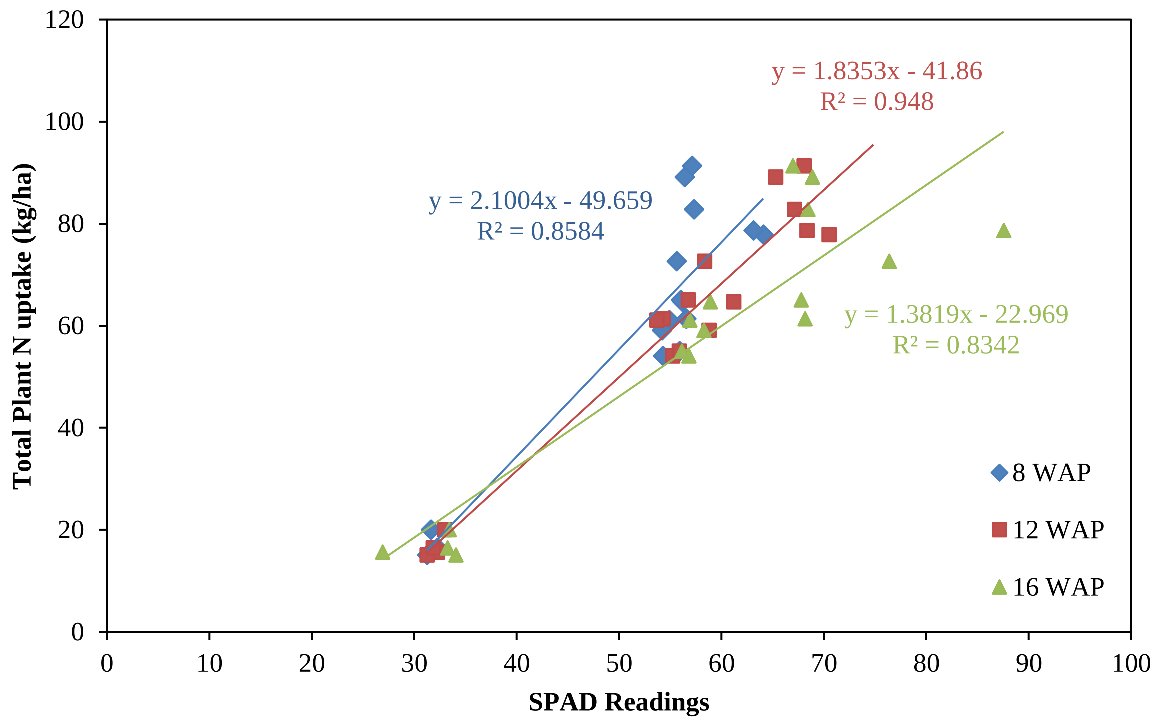


Figure 7.9. The relationship between SPAD readings, made at different taro growth stages, and total plant N uptake at harvest.

7.4.4 Relationship between SPAD reading and taro yield

The SPAD readings at 8, 12 and 16 WAP showed positive associations with yields taro yields at harvest (Figure 7.10). At all three SPAD reading times, their relationship with yield were confined to two main populations; treatment plots with no fertiliser N addition and those that received N fertiliser. At 12 WAP, for the N added treatment plots there was the was a general trend of yields being higher and less variable at higher SPAD readings. For example, all yields were > 12.5 t/ha when SPAD readings were > 60 and all yields where higher than 13.8 t/ha when readings were > 70. In contrast, SPAD readings of < 45, at all three sampling times, would indicate that plant N status is likely to limit taro yield to < 10 t/ha, and that a review of N fertiliser use is required. The use of SPAD has also been used successfully in other tuber crops. For example, Anand and Byju (2008) found that relationship SPAD and cassava tuber yield was significant at 4 and 8 WAP (P<0.05), but not significant. The SPAD readings at 4 and 8 WAP accounted for 83% and 81% of the variation in tuber yield, respectively.

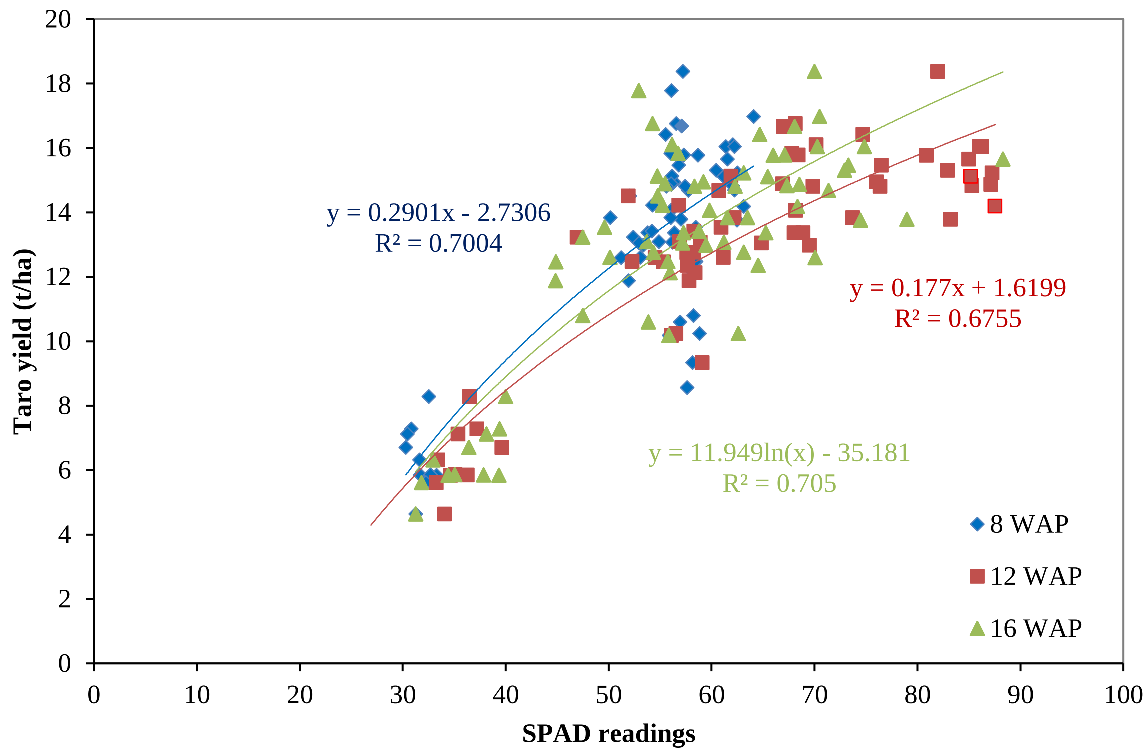


Figure 7.10. The relationship between SPAD readings, made at different taro growth stages, and taro corm fresh yield at harvest.

7.4.5 The effect of P fertiliser use on the relationship between taro yield and SPAD readings

The relationship between SPAD reading and taro yield can also be influenced by the P status of the crop. If P is the more limiting than N, then increases in N fertiliser use may increase SPAD readings, but yield will be lower compared to when P availability is adequate. At the lower rate of P fertiliser (60 kg P/ha), the range in SPAD readings is similar to the higher rate of P fertiliser (120 kg P/ha), but the yields are lower. Both the treatments received a single rate of nitrogen fertiliser at 120 kg N/ha. Thus, the ability to predict yield from SPAD readings rely, to a certain degree, on N being the main growth limiting nutrient. Therefore, reliance on SPAD to predict yield depends on the P, K and S soil status and or fertiliser inputs of being adequate for optimum yields.

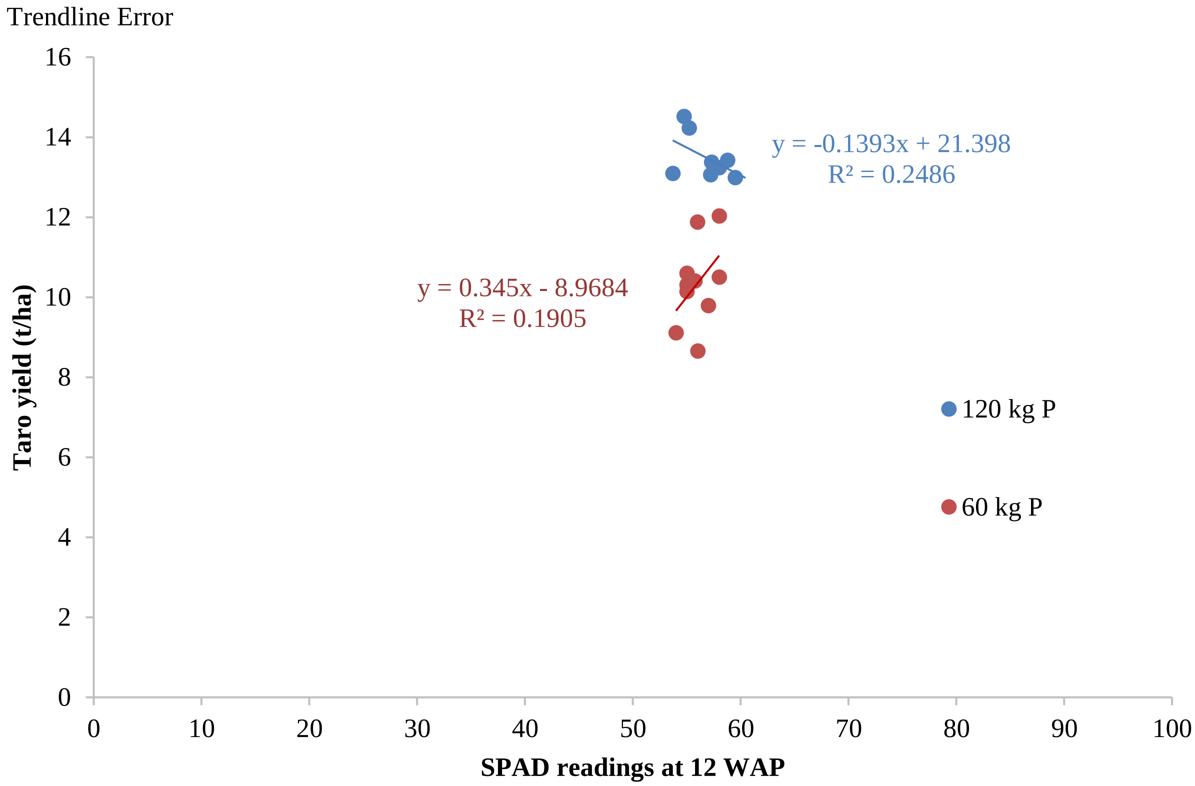


Figure 7.11. Relationship between SPAD readings (12 WAP) and fresh taro yields at 2 different P fertiliser rates

7.4.6 Relationship between SPAD readings and taro suckers

The production of high biomass in the taro leaves, petioles, roots, corms and suckers requires a sufficient supply of N (Manrique, 1994). The relationship between SPAD readings at 8 and 12 WAP and taro sucker numbers at harvest is shown in Figure 7.12. SPAD meter readings had a positive association with taro suckers at 8, 12 and 16 WAP. The highest association (R^2 = 0.84) existed at 8 WAP, however, the usefulness of the relationship may be limited by the steep slope of the trend line and the wide range in sucker numbers at similar SPAD meter readings. For example, sucker numbers ranged from 82,500 to 127,500/ha at a SPAD reading of 57. However, there was a large difference in SPAD readings and taro sucker numbers between the no N fertiliser treatment and the treatments that received N fertiliser, which was also observed for taro corm yield. At the 8 WAP sampling time, the taro plants from the no N fertiliser treatment had SPAD readings of < 34 and sucker numbers < 34,000/ha. Whereas, the taro plants from plots that had N fertiliser applied, had SPAD readings of > 50 or greater and sucker numbers of greater than 63,000/ha. In addition, the majority of the very high sucker numbers (i.e. > 100,000/ha) at harvest occurred when the 8 WAP SPAD readings were > 55. When SPAD readings were made at 12 WAP, there was also a clear separation between in SPAD readings for taro plants from treatment plots that had not received N fertiliser, compared to those that had received N fertiliser. At 12 WAP when no N fertiliser was applied, the SPAD readings were < 45 and taro sucker numbers were < 34,000/ha. All N applied treatment plots had taro plants with average SPAD readings of > 50 and taro sucker numbers > 68,000/ha. Overall, SPAD readings at either 8 or 12 WAP have potential to be used to identify taro plants with very low N status and with low potential to produce suckers. This could be used to identify crops with inadequate N status early in the crop development, which may provide an opportunity to improve crop sucker numbers if corrected early enough. Therefore, SPAD readings taken 2-3 weeks after each N fertiliser application time, has the potential to guide the need for further additions of N to improve crop status.

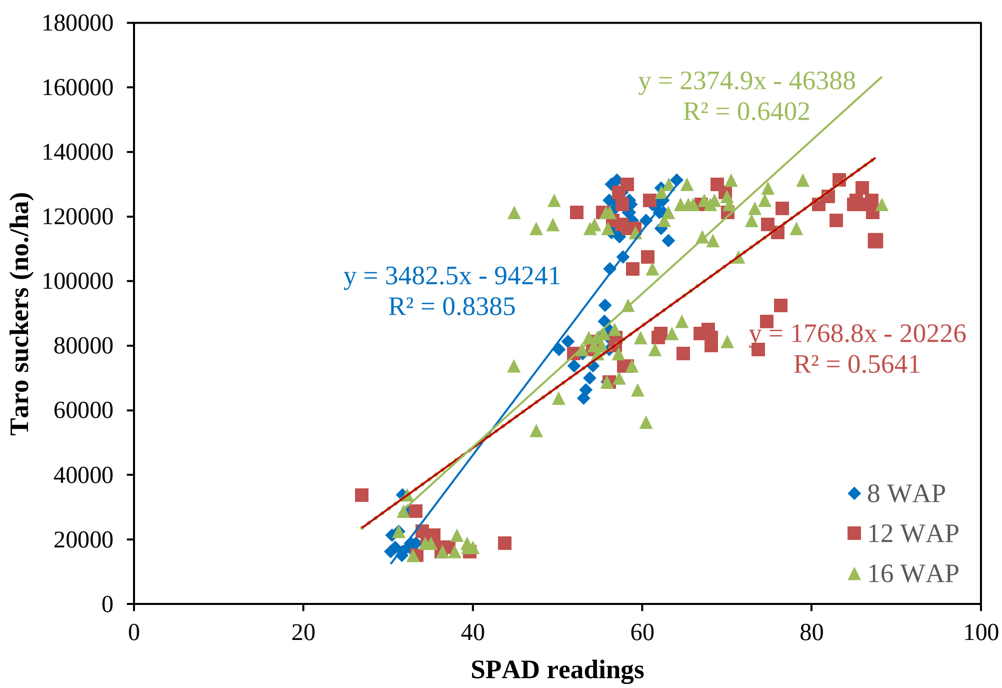


Figure 7.12. Relationship between SPAD readings and taro suckers

7.4.7 Relationship between taro suckers and SPAD readings with two variable P application rates

The results in Figure 7.13 show that the relationship between SPAD readings (12 WAP) and taro sucker numbers at harvest is not strongly influenced by P fertiliser rate. Therefore, unlike with taro corm yield, the relationship between SPAD readings and sucker numbers is not dependant on the P status of the crop. At two different P rates (60 and 120 kg/ha) there was no difference in taro sucker numbers when plots also received 120kg N/ha fertiliser. Therefore, SPAD readings can be a more reliable predictor of sucker numbers irrespective of P status.

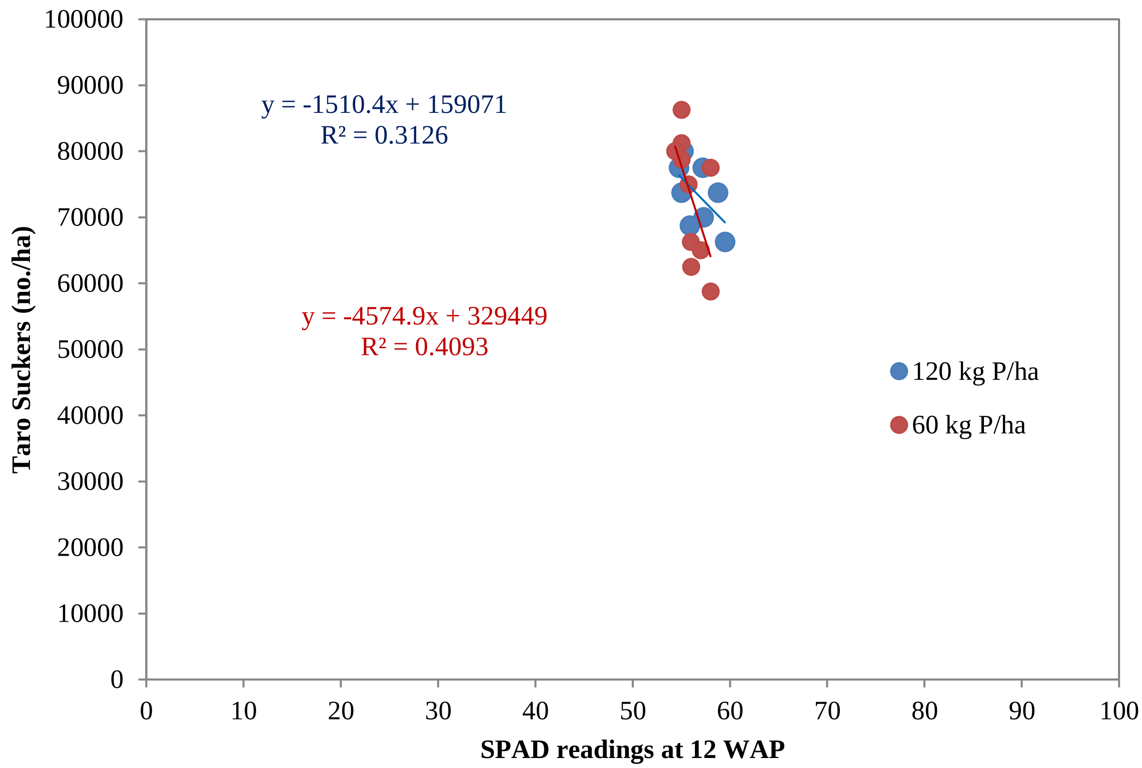


Figure 7.13. Relationship between SPAD readings (12 WAP) and taro suckers at 2 different P fertiliser rates

7.5 Conclusion

This experiment confirms that SPAD meter can be used as a tool to predict N status and potential yield of taro crops, when other key nutrients, such as P, are non-limiting. A strong positive association exists between total plant N uptake at harvest and SPAD readings at 8, 12 and 16 WAP. At all measurement times, when SPAD readings was below a value of about 40, taro total plant N uptake and taro corm yields at harvest were low, being < 30 kg N/ha and < 8.5 t/ha, respectively. When SPAD readings were above a value of about 65, taro total plant N uptake and corm yields were high, being > 60 kg N/ha and 12 t/ha, respectively.

SPAD readings at either 8 or 12 WAP also have potential to be used to identify taro plants with very low N status and with low potential to produce suckers. This could be used to allow N fertiliser application to be targeted to plants with the greatest potential to respond to N inputs. At 8 WAP sampling time, the taro plants from treatment plots that had not received N fertiliser had SPAD readings of less than 40 and sucker numbers of less than 34,000/ha. Whereas, the taro plants from plots that had N fertiliser applied, had SPAD readings of 50 or greater and sucker numbers greater than 63,000/ha. In addition, when SPAD readings were greater than 65, taro suckers numbers tend to be very high (80,000-130,000 suckers) as long as subsequent N applications are also made. When SPAD readings were measured at 12 WAP, there was also a clear separation between in SPAD readings for taro plants from treatment plots that had not received N fertiliser, compared to those that did receive N fertiliser. Similarly at 12 WAP, when no N fertiliser was applied, the SPAD readings were less than 45 and taro sucker numbers were low (< 35,000/ha). All N applied treatment plots had taro plants with average SPAD readings greater than 50 and taro sucker numbers greater than 68,000/ha.

In order for SPAD readings to be effective in predicting corm yields, it is important for P is not limiting and for subsequent N applications to be adequate. However, taro sucker population can still be predicted with SPAD readings when low levels of P fertilisers, due to sucker growth not being strongly influenced by P availability.

Chapter 8 : Summary

8.1 Introduction

Taro is a major contributor to the well-being and livelihoods of farmers in Pacific Island countries. In Fiji, taro is the third most important economic crop after sugar cane and coconuts, Annual total taro exports reached a peak in 2007, and then declined by about 50% over subsequent years. As much as two-thirds of Fiji's taro export crop was grown on the island of Taveuni, where production has declined by about three-quarters in recent years. This decline in productivity has, in part, been influenced by a decline in yields. In addition, recent extreme climate events, a Category 5 (Winston) in 2016 and a drought in 2018, have reduced the availability and increased the price of the taro suckers needed for establishing crops, which has increased farmers' costs for growing taro. The combination of lower yields and increased costs have reduced famer's returns on existing farmland. This has caused some farmers to move farming activity into new areas, often involving deforestation of forest reserves, which has impacts on the wider environment, including the loss of biodiversity. This is of particular concern for Taveuni Island because it has some of the last remaining indigenous forests in Fiji. The overall aim of this study was to develop sustainable nutrient management strategies on existing farmland to support growers achieve sustainable taro yields and financial returns on Taveuni Island.

8.2 Taro grower and soil fertility survey (Chapter 4)

This study used a survey of 73 taro growers and their farm's soil fertility to document growing practices and identify taro yield limiting factors on Taveuni Island. The results of the survey confirmed that fresh taro corm yields were very low, being on average 6.9 t/ha, compared to yields of up to 15-20 t/ha previously achieved. The majority of taro growers surveyed had farms with soil Olsen P levels of below 10 mg P/kg, which is a very low level of plant available soil P, implicating soil fertility as a key limiting factor affecting taro yields for most farms surveyed. Soil Olsen P levels of > 20 mg P/kg are recommended to achieve taro yields of > 10 t/ha. The survey found that all growers with soil Olsen P levels < 9 mg/kg, had taro yields < 9 t/ha. Therefore, it would be expected that yield gains could be achieved by increasing Olsen P levels above 10 mg P/kg, but ideally closer to 20 mg P/kg and above. However, the highest yields achieved by the farmers surveyed were 10 t/ha, even for farms with soil Olen P levels > 20 mg P/kg. Therefore, this indicated that other key plant growth limiting nutrients, such as N and K, were likely to be limiting further yield increases above 10 t/ha for the sites with optimum soil P status. About two-thirds of growers' farms had low soil exchangeable K levels of < 0.4 me/100g. However, the relationship between soil exchangeable K and taro yields was not strong, which is likely to be due to available soil P being the most limiting factor at most the sites surveyed.

Fertiliser nutrient inputs provided to taro crops on the farms surveyed were low on average. Semi-commercial growers used an average of 31 kg N, 17 kg P and 27 kg K/ha, while commercial growers used 41 kg N, 26 kg P and 40 kg K/ha. Based on a number of other studies (Anand, 2015; Hartemink and Johnston, 1998; Blamey, 1996), the amounts of nutrients removed in a high yielding (> 15 t/ha) taro crop can be more than 100 kg N, 10 kg P and 50 kg K/ha. This highlights that nutrient returns are not well matched with the amounts of nutrients removed in harvested crop, especially for N. However, nutrient inputs also need to account for all losses of nutrients in order to maintain soil fertility. Other losses include nutrients in crop residues removed from the cropped area during harvest, leaching and gaseous losses for nutrients, and the immobilisation of nutrients in the soil due to soil processes. For example, previous studies on phosphate adsorption on Fijian soils have shown that significant quantities of added P are strongly adsorbed by soils, especially soils with high levels of by the Al and Fe oxyhydroxide minerals (i.e. high P retention soils), and only limited quantities (i.e. < 30%) of fertiliser P are utilised by plants (Chee *et al*., 1978; Morrison, 1978; Dandy and Morrison, 1980; Morrison *et al*., 2005). In addition, for farms with below optimum soil fertility, then nutrient inputs also need to take into account the requirement to increase soil fertility status. For soils with medium to high P retention characteristic, like southern and central parts of Taveuni Island, very high rates of P are required (i.e. up to approximately 150-200 kg P/ha) to raise soil Olsen P level to > 15 mg P/kg (0-20 cm soil depth) from the average levels measured in the survey. Therefore, when all potential sources of nutrient losses, associated with growing and harvesting taro crops, are considered then it is likely that most taro growers are applying insufficient rates of nutrients. Because the majority of the taro growers surveyed don't use soil tests, then nutrient inputs also don't account for the low soil fertility status that has developed on these farms over time.

The survey also identified that fertiliser placement and timing of application may also have an influence on the plant availability of the fertiliser nutrients used. About half of the growers surveyed placed fertiliser at the bottom/base of their planting hole (i.e. about 20 cm below soil surface). This practice is likely to increase the leaching of more mobile nutrients, particularly N and K, and reduce the ability of crop roots to access less mobile nutrients, like P. Fertiliser application timing also influences nutrient availability and nutrient use efficiency. Root formation and rapid root growth take place immediately after planting, followed by rapid growth of the shoot until 6-8 weeks after planting (WAP). However, majority of the growers apply all fertiliser inputs as a basal application at planting only. This practice is likely to increase the leaching of N and K from the soil root zone, which increases losses and decreases the availability of these nutrients at later stages of plant growth.

The survey identified that the soil fertility and nutrient use were major and wide-spread constraints to taro production on Taveuni Island. Therefore, results for the survey support the need for further investigations to provide farmers with guidance on nutrient management practices, specific to their climate and soil context, to achieve sustainable production of taro.

8.3 Taro Field Experiment 1 (Chapter 5)

The three field sites used for this experiment on Taveuni Island had low initial soil fertility as a result of continuous long-term cropping. This field experiment showed consistent results of the influence that N and P fertiliser addition had on both fresh taro corm yield and taro sucker numbers across all sites. Fresh taro corm yields increased significantly with increasing rates of N and P up to 200 kg N/ha and 120 kg P/ha. These rates of N and P achieved an average yield 13.2 t/ha, which is 129% higher than the yield for the control treatment, without N and P added. Since all of the treatments used 200 kg K/ha and 82 kg S/ha, the optimum rates of these two nutrients was not assessed in this experiment. The taro yield response to added fertiliser K was assessed in the second field experiment.

There was a strong linear relationship between N fertiliser use and taro sucker population up to the maximum rate of N used, which was 300 kg N/ha. The maximum number of suckers achieved was ~110,500 suckers/ha (i.e. 11.1 suckers per plant) on average across the three sites, compared to only ~26,700 suckers/ha with the treatment without N added. There was an average increase of ~27,600 suckers/ha per 100 kg N applied. In addition, the sucker number response to N was not influenced by P fertiliser use. Therefore, following natural disasters, when sucker numbers are limited then the use of higher rates of N fertiliser may be an effective short-term strategy to help re-establish the taro industry and minimise inflation in sucker prices. For example, a hectare of taro receiving an N fertiliser rate of 300 kg N/ha will produce enough suckers to plant about 11 hectares after 7 months, which in turn, using the same rate of N fertiliser, will produce enough suckers to plant 121 hectares. In comparison, when no N fertiliser is used then the equivalent sucker protection would only be enough to plant about 7 hectares after two crop cycles (i.e. 14 months).

While high rates of N fertiliser were required to obtain higher taro yields and sucker numbers, the use of Mucuna, as a green manure crop intercropped with taro, reduced N fertiliser requirements. Mucuna provided a benefit, for both taro yield and sucker numbers, equivalent to approximately 100 kg N/ha as fertiliser. Some of the benefit provided by the Mucuna may also have been due to improved weed suppression and a mulching effect of Mucuna crop. The effect of Mucuna on weed control was investigated further in the second field experiment.

8.4 Taro Field Experiment 2 (Chapter 6)

The response of taro corm yields to N, P and K fertiliser inputs was similar across all three site, and the response N and P addition was similar and consistent with the first field experiment. When no N and P fertiliser was applied, average fresh taro corm yields were very low at 6.2 t/ha, even when K and S fertiliser inputs were high. The addition of up to 200 kg N and 120 kg P/ha, resulted in substantial yield increase of 240% to about 15 t/ha. Taro yield was also responsive to K fertiliser use, with significant increases in yield up to 200 kg K/ha, which was the highest rate of K used. There was strong linear increase in yield with K addition up to 200 kg K/ha, when high rates of N, P and S were also applied.

Therefore, further yield responses from higher rates of K are possible and, therefore, warrant further investigation.

The response of taro sucker numbers to N fertiliser addition was also similar to the first field experiment. Sucker numbers increased with increasing N fertiliser rate up to 280 kg N/ha. Further increasing N rates up to 360 kg N/ha did not further increase sucker population. When no fertiliser was applied, average taro sucker numbers across the three sites was about 20,500 suckers/ha, which increased to about 122,500/ha when to 280 kg N/ha was applied. This equates to an average increase in sucker numbers of about 36,500/ha per 100 kg N applied. In the first experiment, sucker numbers increased significantly with N fertiliser rates up to 300 kg N/ha, which was the highest rated of N used in that experiment. Therefore, this current experiment supports that there is unlikely to be a further significant benefit from apply more than 300 kg N/ha, and that a rate of 280 kg N/ha is sufficient for maximising sucker numbers. Increasing K fertiliser rate from 100 to 200 kg K/ha had a small influence on increasing sucker numbers. Therefore, adequate soil K status is also required to optimise sucker numbers.

In this experiment, Mucuna cover crop also reduced the amount of N fertiliser required to achieve the highest yields. When Mucuna was grown with the 120 kg N/ha and 120 kg P/ha the fresh taro corm yield was similar to when 200 kg N/ha was applied without Mucuna, which represents N fertiliser saving of 80 kg N/ha. When Mucuna was grown with the 120 kg N and 120 kg P/ha fertiliser treatment, the average sucker population across all three sites was about 100,000 suckers/ha, which was about 30,000 suckers/ha greater than for the same fertiliser treatment without Mucuna. Based on a sucker response of 36,500 suckers per 100 kg N/ha, mentioned above, the Mucuna benefit would be equivalent to about 82 kg N/ha. Therefore, for both taro yield and sucker numbers the use of a Mucuna green manure crop gave a response that was equivalent to similar rate of N fertiliser, which was also close to N fertiliser benefit of 100 kg N/ha observed in the first experiment. Intercropping Mucuna also reduced weed population by 336% at 12 WAP, which has potential to reduce the amount of weeding or herbicide required.

On average, mixing P fertilisers in the planting hole increased taro yield compared to placing the fertiliser at the bottom of the planting hole. Mixing P fertiliser in the planting hole increased corm yield by 38%, compared to the when P fertiliser was placed at the bottom of the whole. Therefore, while the common practice that farmers use of placing P fertiliser at the bottom of the planting hole reducing the time involved with crop establishment, it is a less efficient use of P fertiliser, which can result in lower yields.

Despite the high rates of P fertiliser used in the first experiment, there was no significant P carry over effect on taro yields in the second experiment. Fertiliser P was confined to the places where it was applied in the planting holes, which were spaced 1 m apart. Therefore, there would was limited ability for taro plants in the second crop cycle, planted about 0.5 m from the precious planting holes, to access fertiliser P applied to the previous crop. However, in subsequent crop plantings there may be more opportunity for P recovery, as the area of soil with higher P status increases. Therefore, further research is required to assess how many crop cycles are required before P fertiliser rates can be reduced to more of a maintenance rate.

When basal P fertiliser application of 120 kg P/ha was applied to planting holes, the average Olsen P (0-20 cm soil depth) at about 15 cm out from the centre of the planting hole was 23 mg P/kg, which is within the optimum range of taro production. However, this area represents about 5% of the field area, with the remaining area of the field having low Olsen P levels. Because fertiliser placement in planting holes causes non-uniform spatial distribution of nutrient in the soil, assessments of whole-field fertility need to take this variability into account when assessing the soil nutrient status for the current crop's growth.

8.5 Evaluating of the Nitrogen Status of Taro using SPAD Remote Sensing (Chapter 7)

The use of the SPAD meter, in the second field experiment, demonstrated that it can be used as a tool to predict N status of taro crops and yield potential, when other key nutrients, such as P, are non-limiting. At both the 8 and 12 WAP, the yield and SPAD readings were confined to two populations, treatment plots with no fertiliser N addition and those that received N fertiliser. When the SPAD readings were < 40, then the taro yields were mostly low (< 8.5

t/ha). When SPAD readings were greater than 65 at both sampling times, then the taro yields were mostly high (i.e. > 12 t/ha). Therefore, SPAD readings < 40, at 8 and 12 WAP, would indicate that plant N status is likely to limit taro yield and that a review of N fertiliser use is required. If SPAD readings at 8 and 12 WAP are high (> 65), this is indicative that plant N status is high enough at that point in time for N not to be being limiting yield, as long as the subsequent recommended N applications are also made at 10 and 15 WAP. However, a high SPAD value at either 8 or 12 WAP does not mean that the N fertiliser programme should be terminated at that point in time.

SPAD readings at either 8 or 12 WAP have potential to be used to identify taro plants with a low potential to produce suckers. This could be used to allow N fertiliser application to be targeted to plants with the greatest potential to respond to N inputs. At 8 WAP sampling time, the taro plants from treatment plots that had not received N fertiliser, had SPAD readings of < 40 and sucker numbers of < 34,000/ha. Whereas, taro plants from plots that were applied with N fertiliser had SPAD readings of 50 or greater and sucker numbers > 63,000/ha. In addition, when SPAD readings were > 65, then suckers numbers tend to be very high (80,000-130,000 suckers) as long as subsequent N applications are also made. When SPAD readings were measured at 12 WAP, there was also a clear separation between in SPAD readings for taro plants from treatment plots that had not received N fertiliser, compared to those that did receive N fertiliser. While SPAD readings were only useful for predicting fresh taro corm yields when P was not limiting and subsequent N applications are adequate, taro sucker population can be predicted with SPAD readings even when soil P status is low, as long as subsequent N applications are adequate.

Nitrogen fertiliser use had a strong relationship with taro total leaf N content and SPAD readings at 12 and 16 WAP measurement times. At 12 WAP, SPAD readings > 50 consistently had high total N contents of > 3.0%. These results show that SPAD measurement made early in the taro crop's development can be used to predict the crops final N status. There was strong positive relationship between total plant N uptake at harvest and SPAD readings at 8,12 and 16 WAP, with the strongest relationship ($R^2 = 0.95$) being for readings at 12 WAP. At 12 WAP, when SPAD readings were > 50 then N uptakes were > 50 kg N/ha.

8.6 Economic Returns for Taro from Improved Nutrient Management

The income derived from the sale of taro corms has been the principle income for the growers on Taveuni Island until 2013. The fresh corms have been mainly exported to New Zealand, Australian and American markets over the last 24 years. The taro corm price that farmers receive has fluctuated from NZ$0.83 to 3.45/kg over the last 5 years, but prices of about NZ$1.38/kg has been more typical. On-going shortages of taro planting material over the last 5 years have created a market for taro suckers within the industry. The prices for suckers was typically NZ$0.07/sucker before Cyclone Winston (2016), however, post-cyclone the price increased three-fold to NZ$0.21/sucker and after a subsequent drought, the price further increased to NZ$0.35/sucker.

The current study demonstrated that the taro corm yields and suckers can be greatly influenced by fertiliser inputs and, consequently, farmers' financial returns. However, fertiliser use increases the cost of growing taro, so it is important to demonstrate to farmers the potential increase in income from fertiliser use. Because N fertiliser use strongly influences both corm yield and sucker numbers, the change in total gross income, from corm and sucker income, were determined at various rates of N. At all N rates the quantities of P, K and S applied were unchanged, being 120 kg P, 200 kg K and 84 kg S/ha (Figure 8.1). The analysis was conducted using the average price for taro corms and suckers over a two-year period (2017-2019) of NZ$1.38/kg corm and NZ$0.21/sucker.

The highest total gross income from the sale of taro corms and suckers combined is NZ$41,670/ha, which occurred at the highest rate of 300 kg N/ha. This income was made up of 44% from the sale of taro corms and 56% from suckers. The income from taro corms does not increase above a rate of 200 kg N/ha, because both field experiments in this study showed minimal further increase in taro yield above this rate of N. It was only the income from taro suckers that increased with N rate from 200 to 300 kg N /ha. The second field experiment confirmed that there was minimal increase in sucker numbers above about 280 kg N/ha. When no N fertiliser is applied, total gross income from the sale of taro corms and suckers combined is NZ$15,906/ha. This income was made up of 63% from taro corms and 37% from suckers. In comparison, when no fertiliser is applied the gross income decreases further to NZ$13,360/ha. Therefore, the use of fertiliser nutrient inputs at the optimum rates for both taro corm and sucker numbers (300 kg N, 120 kg P, 200 kg K and 84 kg S/ha) resulted in a NZ$28,310/ha (111%) increase in gross income, compared to when no fertiliser is used. This is achieved with a total fertiliser cost of NZ$2,354, or an increase of gross income NZ$12 per NZ$1 spent on fertiliser. However, if any one of the major nutrients is applied at a rate that is below optimum, then gross income can be substantially decreased, as shown for the N fertiliser example. Gross income increased by NZ$25,764/ha when N was increased from 0 to 300 kg N/ha, at the same rates of P, K and S. The cost of N fertiliser at a rate of 300 kg N/ha is only NZ$630/ha. This highlights the importance of ensuring that all nutrients are applied at optimum rates to optimise financial returns.

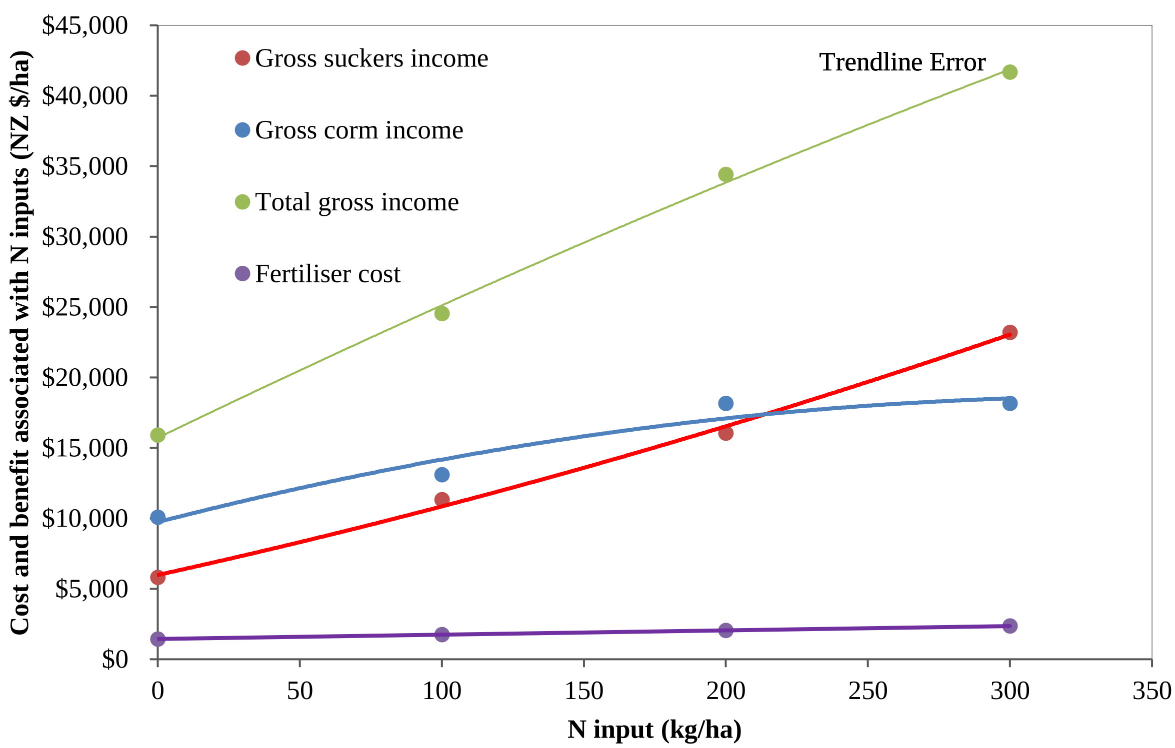


Figure 8.1. Effect of N fertiliser rate on individual incomes from taro corm and sucker production and on total gross income (P and K fertiliser rates were 120 kg P, 200 kg K/ha and 84 kg S/ha at all rates of N; Experiment 1. Average taro corm price of NZ$1.38/kg and sucker price of NZ$0.21 each sucker was used).

Comparative gross margin analyses are provided for three different nutrient management strategies for taro production; typical grower practice, recommended integrated nutrient management system and a suggested post natural disaster rehabilitation system (Table 8.1). With the grower practice of using 36 kg N, 22 kg P and 34 kg K/ha fertilisers, growers are earning a net income of NZ$10,320/ha, or NZ$5,411/ha when only corms are sold, which proves benefit cost rations (BCRs) of 3.23 and 2.32, respectively (Table 8.1). The recommended practice, based on the results of this study, is to use Mucuna integrated with 120 kg N, 120 kg P, 200 kg K and 82 kg S/ha as fertiliser. With this system, growers will earn a net income of NZ$35,835/ha, or NZ$16,906/ha when only corms are sold, which proves BCRs of 6.53 and 4.76, respectively. Therefore, the recommended practice achieves a gross margin up to 247% higher grower practice. While the Mucuna cover crop system requires additional costs for its establishment, its lower occurrence of weeds reduces the amount of herbicide spraying.

Table 8.1 Economic analysis of different fertiliser management practices on taro production system in Taveuni.

	Current farmer system (41 kg N, 22kg P and 34kg K/ha)	**Integrated nutrient management system** (Mucuna, 120 kg N, 120 kg P and 200 kg K/ha)	**Post natural disaster system** (280 kg N, 120 kg P and 200 kg K/ha)
Income			
Corm yield (t/ha)	6.9	15.5	15.2
Corm income (NZ$/ha) @ a price of $1.38/kg	9,522	21,390	20,976
Suckers yield (No./ha)	25,833	99,667	122,633
Sucker income (NZ$/ha) @ a price of $0.21/sucker	5,425	20,930	25,752
Total income (NZ$/ha)	14,947	42,320	46,728
Variable costs			
Land preparation (herbicide)	138	138	138
Planting material (NZ$/ha)	2,070	2,070	2,070
Labour planting Mucuna	0	150	0
Labour planting taro	1,035	1,035	1,035
Fertiliser - N (NZ$/ha)	86	252	588
Fertiliser - P (NZ$/ha)	87	476	476

Fertiliser - K (NZ$/ha)	127	749	749
Labour fertiliser application	69	129	172
Herbicide (NZ$/ha)	124	8	124
Labour weed control	414	103	414
Labour clearing Mucuna from taro plants	0	300	0
Harvesting corm (NZ$/ha)	476	1,070	1,046
Harvesting suckers (NZ$/ha)	516	1,993	2,452
Total costs (NZ$/ha)	4,627	6,482	6,814
Net income from corms only (NZ$/ha)	5,411	16,901	-
Net income from corms and suckers (NZ$/ha)	10,320	35,835	39,914
Benefit cost ratio from corms only (BCR)	2.32	4.76	-
Benefit cost ratio from corms and suckers (BCR)	3.23	6.53	6.86

Fiji is frequently affected by natural disasters, which have significant impacts on the taro industry and agriculture as whole. For example, there are on average 1.4 cyclones per year, with a Category 4 or 5 cyclone occurring once every 5 years on average. The occurrence and severity of cyclones, and other natural disasters like floods and droughts, are predicted to increase with Climate Change. Post disaster rehabilitation with crops grown from seeds are faster and easier because seeds can be sourced commercial seed companies, which store seeds for future planting. However, crops like taro, which are grown from vegetative material, natural disasters can destroy planting material. This reduced availability of planting material delays quick rehabilitation of the industry, which in turn affects food security and exports.

Rapid taro sucker multiplication strategies could be an advantage in quick recovery of the taro industry. This research has demonstrated that application of 280 kg N, 120 kg P, 200 kg K and 84 kg S/ha treatment after disasters will produces 23% more taro suckers than the recommended nutrient management system. The suckers produced through this system could be used to speed up post disaster rehabilitation. Growers can plant whatever they could and sell the remaining suckers to other growers. With this system, growers will earn a net income of NZ$39,914/ha from the sales of taro corms and suckers (Table 8.1). The high rates of N fertiliser used in this strategy could have negative implications on the environment, especially with the high leaching losses that may be associated with the high rainfall in Fiji. Therefore, this system is only recommended for short periods (i.e. two crops cycles) during the rehabilitation of the industry, post natural disasters.

The total cost from growing taro is estimated to be NZ$4,627/ha, using typical grower practice and NZ$6,814/ha for the recommended practice. The cost associated with the procurement of planting material is the biggest costs in taro production system (Figure 8.2). At NZ$0.21/sucker, the planting material costs are 45% and 32% of the total cost of production, respectively, for the grower practice and recommended practice. Therefore, increasing the supply of suckers is important for lowering the cost of growing taro and the savings from this cost could be invested in fertiliser and Mucuna green manure cropping. The fertiliser and Mucuna costs are a total of $1855/ha higher for the recommended practice, compared to the grower practice. However, this is well compensated for by a $25,515/ha increase in income when corms and sucker are sold or $11,490/ha when only corms are sold.

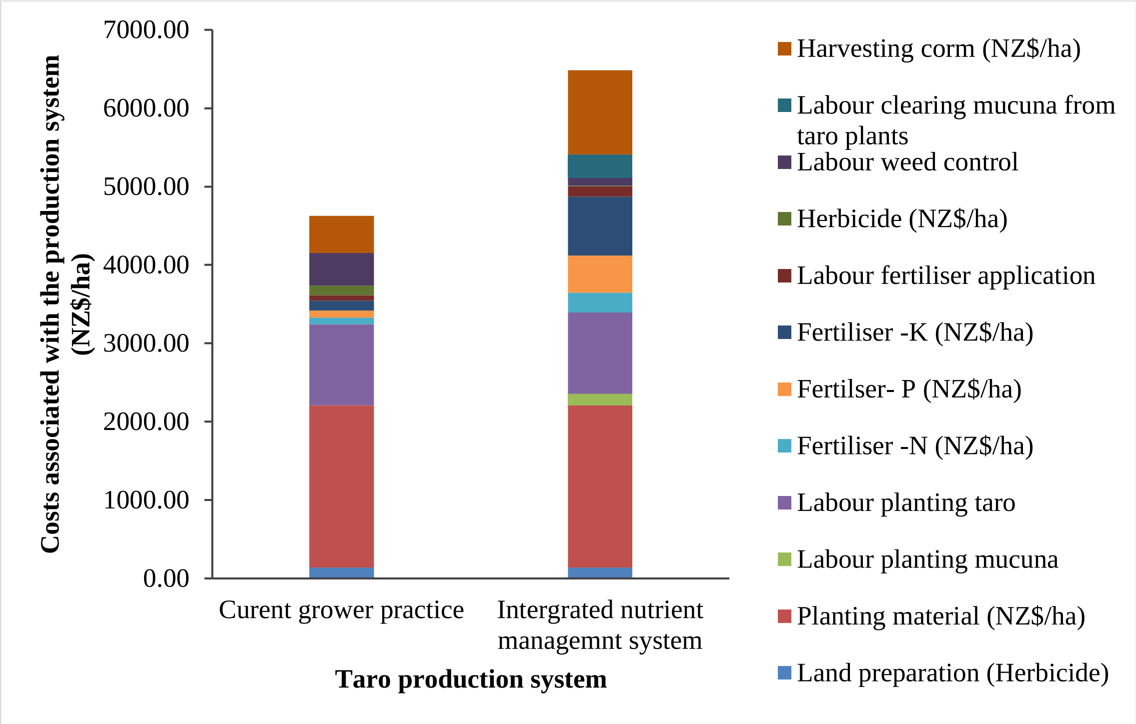


Figure 8.2. Costs associated with the current and recommended taro production systems

8.7 Conclusions and future research

The results of the study have shown that there is substantial potential to improve taro yields through improving soil fertility status and fertiliser application practices. Near optimum yields can be achieved by inter-cropping taro with a Mucuna green manure crop and using fertiliser applied at rates of 120 kg N, 120 kg P, 200 kg K and 82 kg S/ha. Inter-cropping taro with Mucuna also lowers weed populations, which reduces herbicide use. However, when the demand for taro suckers is high, especially after natural disasters than increasing N fertilise up to 280 kg N will produce the maximum number of suckers. It is recommended that P fertilisers are mixed in the planting hole to improve the availability for the added P and increase taro yield compared to placing the fertiliser at the bottom of the planting hole. The SPAD chlorophyll meter can be an effective tool at predicting N status of taro crop and potential yield when other key nutrients such as P are non-limiting.

The economic analysis suggests that adopting recommended nutrient management system, growers can earn a net income of NZ$35,835 from the sales of corm and suckers, which is a

247% higher gross margin than using typical grower practice. The cost associated with the procurement of planting material (suckers) is the largest costs in taro production system in Fiji. The recommended practice also produces 74% more taro suckers than the grower practice. Increasing sucker production is an important strategy to enable taro growers to increase production more rapidly following a natural disaster and minimise the effect of limited supply on inflating sucker prices. Therefore, improving nutrient management practices will help farmers be more resilient to the effects of Climate Change.

Recommendations for future research:

1. The high rates of P required in this study reflect the low soil P status. The addition of P to the localised area of the planting hole reduces P availability for subsequent crop. Further research is required to evaluate how many crop cycles are required before the P status has been increased over a sufficiently adequate area of the field to enable P rates to be reduced to maintenance levels.
2. The response taro corm yields to K fertiliser addition was shown to be linear up to 200 kg K/ha, thus future experiments should evaluate K rates above 200 kg/ha.
3. Further research is required to better understand the effect of lime and fertiliser inputs, and fellow periods on corm rots to help improve management of this disease.

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