EU EDF8-SOPAC Project Report 75
Reducing Vulnerability of Pacific ACP States

TUVALU TECHNICAL REPORT

ASSESSMENT OF SALINITY OF GROUNDWATER IN SWAMP TARO (*CYRTOSPERMA CHAMISSONIS*) *"PULAKA"* PITS IN TUVALU

March 2007

Swamp taro (pulaka) growing on Funafara Islet, Funafuti, Tuvalu.

Prepared by:

Dr Arthur Webb
SOPAC Secretariat

March 2007

PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
c/o SOPAC Secretariat
Private Mail Bag
GPO, Suva
FIJI ISLANDS
http://www.sopac.org
Phone: +679 338 1377
Fax: +679 337 0040
director@sopac.org

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author is indebted to the help and assistance of the Government of Tuvalu, particularly Mr Faatasi Malolonga (Director of Lands) and Mr Itaia Lausaveve (Director of Agriculture) whose assistance and willingness to share ideas add much to this report. The fieldwork by the SOPAC/EU Project Intern Ms Loia Tausi in travelling to the outer islands and collecting much of the raw data is also gratefully acknowledged. Sincere thanks must also be given for the invaluable assistance of various individuals and outer island councils during the field surveys.

EXECUTIVE SUMMARY

The Government and broader Tuvaluan community have raised concerns over increased salinity of groundwaters in pits used to cultivate swamp taro or "*pulaka*". As such, the SOPAC EU-funded Reducing Vulnerability of Pacific ACP States Project, was requested to investigate this issue. The request was initially outlined in the 2003 Tuvalu Work Plan as Task TV 2.3.5 (Investigate saline incursion problems of *Pulaka* pits on Niutao and Nui). As a result of additional requests, this task was subsequently incorporated into the revised EU Project work plan within Result Area 1 (Coastal Processes), as Task TV 1.3.2. The attachment of the Tuvalu SOPAC/EU Project Intern (Ms Loia Tausi) allowed a broader approach to the issue and all nine atolls were visited.

Despite this issue having been discussed in Tuvalu for a number of years, no known previous or systematic assessment or monitoring has been undertaken. This study attempts to determine, through accurate conductivity measurement, the present condition of groundwater quality (salinity) within the pits throughout Tuvalu. Additionally, this data will now act as a baseline from which repeated sampling can be made and future results compared. It is stressed that in order for this data to become more useful, continued monitoring must be undertaken.

Pits on all islands of Tuvalu (except Niulakita) were surveyed between January and April 2006. At the time of study, only three islands (Nukulaelae, Niutao and Funafuti) had pits which showed salinity concentrations thought to be too high for successful swamp taro growth, (≥ 3 000, 4 000 and 5 000 µS cm^{-1}, respectively). In the case of both Nukulaelae and Niutao these high readings were restricted to one pit area. Otherwise, conductivity readings in the remaining pits on these islands were generally low (≤1 000 µS cm^{-1}) and adequate for swamp taro growth. There is anecdotal evidence to suggest that causeway engineering activities in Niutao's central lagoon may have contributed to higher salinity in localised areas. Alternatively, sampling in Funafuti (*Fongafale*) showed that all pits were either too saline or very marginal and swamp taro production is unlikely to succeed anywhere on *Fongafale* islet.

Average conductivity (salinity) readings from the remaining islands ranged between 1 321 ± 363 and 161 ± 90 µS cm^{-1} (Vaitupu and Nukufetau, respectively). There was a large degree of variability in all samples from each island during the survey and this is likely an intrinsic characteristic of the water conditions in these fragile and dynamic lens systems. Analysis of the variability showed Niutao, Nukulaelae and possibly Vaitupu to depart from the "normal" range with exceptionally high variability in Niutao (%CV 188) and lower variability in Vaitupu (%CV 27). The average %CV (coefficient of variability) across all the islands was approximately 75.

Conductivity sampling undertaken during this survey indicated that only the island of Funafuti (*Fongafale*) had consistent groundwater salinity conditions which were too high for successful swamp taro growth. Niutao and Nukulaelae had isolated pit areas where conditions were too saline but conditions elsewhere on these islands were adequate for Swamp taro growth. Otherwise, at the time of this study all other pits sampled on all other islands, showed adequate groundwater salinity conditions to allow successful swamp taro growth. It is however stressed that ongoing monitoring must be continued to better develop these preliminary findings.

INTRODUCTION / BACKGROUND

Swamp taro (C*yrtosperma chamissonis*) locally known as *pulaka* is grown in Tuvalu and throughout the Central Pacific atolls as a starch crop. In past times, it had an important role as a daily food crop and although today it is fast being replaced by imported starch products (e.g. rice and flour), swamp taro still has a significant place in the diet and culture of the Central Pacific atoll peoples.

Atoll soils are extremely poor and crop cultivation of any sort in these environments presents great challenges. Since soils are predominantly derived from carbonate reef-borne material and are relatively young, they are poorly developed, lack structure and texture and are very porous with poor water holding capacity (Barr 1992). Additionally, atoll soils are naturally deficient in nutrients required for successful crop growth and due to their high pH, important micro-nutrients such as, iron and zinc (already present in very low concentrations) are made less available for plant uptake (Barr 1992; Webb 1994). The natural depressions and excavated pits used to grow swamp taro present one of the best opportunities to circumvent these agronomic limitations.

Figure 1. A typical healthy swamp taro pit. This pit is actually located on Tarawa Atoll, Kiribati however, Tuvaluan cultivation practices and varieties are very similar. Note the free standing water indicating the base of this pit is roughly equivalent to the upper surface of the fresh groundwater lens. The two commonly grown varieties are also evident in this picture; to the left is the smaller (Ikamava or Kasusu) variety; and to the right is the slower-growing much larger (Teikalaoi) variety. Note the careful attention to traditional composting techniques on the larger plants (woven pandanus leaf baskets), these may be cultivated for between 5 and 10 years before harvest. Alternatively, the smaller variety may be harvested within 12 months.

Swamp taro pits tend to have comparatively deep, dark, organic rich soils in comparison to surrounding soils. This occurs both due to the natural propensity for organic materials (leaves, husks, etc.) to collect in such depressions but also (and importantly) through the efforts of the farmers who over the years have laboured intensively and applied systematic traditional cultivation practices. These methods include the importation (from surrounding vegetation) of large volumes of organic material to improve and stimulate crop production (see Figure 1). Not only does this maintain the supply of nutrients to the crop but soil quality and chemistry in such humus rich environments is subtly changed to improve plant nutrient availability and uptake (Barr 1992; Webb 1994). Additionally, the proximity of the pit floor to the upper layer of the groundwater lens also ensures a constant level of moisture.

Swamp taro, as it's name suggests, prefers these constantly wet soil conditions. Early indigenous settlers to the atolls have variously taken advantage of natural depressions (where easy access to the fresh groundwater lens can be gained) or excavated depressions (often to a depth of 1.5 m and sometimes 100's of square meters in area), to allow the reliable cultivation of their crops. It follows that since the crop is dependent on groundwater to maintain soil moisture it is also susceptible to any natural or human induced perturbation of groundwater quality in these fragile lens systems.

Natural perturbations such as wave wash over and/or extreme high water and storm events can contaminate the fresh groundwater lens with saline marine water. Periods of extended low rainfall can also cause the freshwater lens to contract and saline transition zones to move inland. Similarly, over pumping or extraction of groundwater resources to supply human needs also act in a similar fashion to drought, where removal of freshwater is greater than recharge, causing the lens to contract. In extreme cases, deeper saltwater can even be drawn to the surface by over pumping of the freshwater lens, causing localised saline contamination (White *et al.* 2006).

Swamp taro is locally understood throughout the Central Pacific atolls to be intolerant of saline groundwater conditions and Mourits (1996) who worked on Makin and Butaritari atolls in Kiribati, indicated that a conductivity range of 3 300 to 5 000 μS cm^{-1} was too high for successful swamp taro growth. An upper salinity limit for potable atoll groundwater is suggested by Falkland (1999) as ≤ 2 500 μS cm^{-1}.

Table 1. Comparative conductivity value guidelines developed by Falkland (1999) for coral atoll groundwater lenses (μS cm^{-1} – microsiemens per cm; ppt – parts per thousand).

Type of Water	Typical conductivity range (μS cm^{-1})	Approximate salinity equivalent (ppt)
Rainwater	40 – 120	< 1
Very fresh groundwater	250 – 500	< 1
Fresh groundwater	500 – 1 500	< 1
Limit of freshwater	*1 500 – 2 500*	*< 1*
Mildly brackish water	3 000 – 5 000	2 – 3*
Brackish water	5 000 –10 000	3 – 5*
Very brackish water	10 000 – 25 000	5 – 15
Highly brackish water	25 000 – 50 000	15 – 33
Seawater	50 000 – 55 000	33 – 37

*An approximate, intuitive guide to salinity concentrations is human ability to detect (taste) salt in water.
This usually this starts around 3.0 to 4.0 ppt, however there is considerable variation in ability between individuals.

The Government of Tuvalu has received a number of complaints with respect to increasing salinity of groundwater in the swamp taro pits in Tuvalu. Farmers have indicated that pits have been abandoned due to increasing salinity issues and ultimately this phenomena has been linked with rising sea level in the Central Pacific region.

A recent publication specifically assessing sea level in Funafuti, Tuvalu (Church *et al*. 2006) indicates that the "best estimate" of sea-level rise in Funafuti is 2 ± 1 mm $year^{-1}$ over the period

1950 to 2001 (10 cm ± 5 cm over the last 50 years). Additionally, the 2006, Summary Statement by the World Climate Research Programme (WCRP, Sea-level Rise and Variability Workshop, 2006), arrived at a consensus that global sea levels have risen at an approximate rate of 3 mm $year^{-1}$ since the early 1990's in comparison to rates derived from tide gauges over the past century of approximately 2 mm $year^{-1}$.

As mentioned, swamp taro was once intensively cultivated however today it has been at least partially replaced by imported food products. As relics from past subsistence lifestyles pits can at least be hundreds of years old and early aerial photographs (1941) of Fongafale (the main settlement on the capital island, Funafuti), show clear evidence of well established and cultivated swamp taro pits (Webb, 2006). Many of these older pits were dug and maintained by hand and overall they represent huge establishment and maintenance efforts and it is presumed this would not have been expended if cropping was not usually reliable.

It is likely this locally well-understood premise, which has lead people in Tuvalu to ask "why is it that such pits were known to have produced reliable crops in the past, yet now they are unsuitable?" Within the bounds of this study it was not possible to investigate the complex hydrological factors, which may or may not lead to increased salinity in atoll groundwater. Rather, the project has undertaken to sample a number of pits in Funafuti and throughout all the islands of Tuvalu (except Niulakita which was visited but does not have any pits [L. Tausi, *pers comm.* 2006]). Presently this data represents a "snapshot" of salinity conditions throughout Tuvalu's pits during the early part of 2006 and as a snapshot, the data has restricted analytical value. However, it is the first systematic attempt to produce baseline data from which future monitoring of salinity can be continued and it is stressed that to better understand this issue continuous monitoring should be undertaken.

PRE-SURVEY DISCUSSIONS WITH THE DIRECTOR OF AGRICULTURE MR ITAIA LAUSAVEVE, FUNAFUTI

During an earlier visit to Funafuti by the author in May 2005, the issue of swamp taro pit salinity was discussed at some length with the Director of Agriculture, Mr Itaia Lausaveve. It is useful here to record some of the main (albeit anecdotal) points from these discussions as they provide some interesting background insights to this issue.

Within the context of Tuvaluan atolls, the islands of Nui, Nanumea and Nukufetau have a history of comparatively reliable groundwater and the use of wells is better established on these islands than elsewhere in the country. Nui, in particular is thought to have reliable groundwater supplies. In Mr Lausaveve's experience, there is no unusual saline incursion problem with swamp taro cultivation on these islands.

Niutao has natural pools (groundwater windows – *tepela* area) which are used for swamp taro cultivation. Swamp taro health has declined in some of these pits in more recent times and farmers perceive that increasing salinity is the cause of this decline. Mr Lausaveve also indicated that the decline is perceived to have corresponded with the building of a dyke (in 1996) across the inner pool area. This dyke was built to stop water in the larger western pool moving into the eastern swamp and swamp taro pit areas, presumably because the main lake is more prone to saline conditions (the darker green vegetation surrounding the western pool is mostly mangrove, supporting this argument). A similar situation was reported by Mourits (1996) on the atoll of Makin, in Kiribati. On this island a similar natural saline pool introduced salty water into swamp taro growing areas every time there was heavy rainfall and the pool's water level rose. Like the Niutao situation, the local people built a small bund to prevent the flooding, but this appeared to have had limited success. Certainly in Niutao the dyke appears not to have had the desired effect and it is suggested by Mr Lausaveve to have possibly worsened the salinity issue.

On Nanumanga and Nukulaelae and sometimes Nanumea, Mr Lausaveve indicated that the main issue with saline incursion occurs during westerly gales when sea level is naturally increased on the eastern shores of the islands due to wave set-up. At such times wave over topping (and presumably increased hydrostatic pressure) can deliver marine waters into pits near these shore lines.

Vaitupu had saltwater intrusion in some swamp taro pits following the construction of a seawall along the western shore of Vaitupu Lagoon (similar comments were made to the author by the Vaitupu *Kaupule* [Council] in September 2004). Again it appears that disturbance of the natural hydrology may have worsened saline intrusion problems.

Nanumanga has natural depressions and pits near its northern and southern points. The northern point in particular has an ongoing history of saline incursion and Mr Lausaveve indicated that good quality groundwater on this island has always been a problem.

Funafuti has ongoing chronic problems with saline incursion in its *Fongafale* pits. This situation appears aggravated during natural high water events but continues as a background problem year round. As such, serious cultivation of swamp taro on *Fongafale* is no longer really practised. During the author's 2005 visit a similar, but likely more salt tolerant species of taro (*Colocasia esculenta*) was being grown in *Fongafale* (see Figure 2).

*Figure 2. "Dalo" (taro – Colocasia esculenta) is currently being grown in this Fongafale swamp taro (*Cyrtosperma chamissonis*) pit – it would appear that dalo (*C. esculenta*) has a better tolerance of saline conditions than the swamp taro (e.g. Nyman et al. 1983 and Onwueme 1999). However, dalo is not generally as tolerant of continual water logging and the better health of the plants in the background may be due to the greater elevation of the mounded soil. Average conductivity in this pit, measured in early 2006, was 4 493 ± 1 203 µS cm^{-1}.*

A previous study which investigated groundwater conductivity and hydrology on Funafuti (Falkland 1999) found consistently saline groundwater conditions on Fongafale and indicated that generally Fongafale's groundwater is too saline for potable use (or presumably, reliable swamp taro cultivation). Falkland (1999) found average conductivity values ranged between 5 000 to 40 000 µS cm^{-1} (mean value 16 552 µS cm^{-1}) from a variety of locations and also provided evidence of strong hydraulic connectivity between the ocean and Fongafale's brackish groundwater lens. In essence, Falkland (1999) indicated that the course rubble from which much of *Fongafale* is composed, allows comparatively free movement of marine waters into and out of the island, preventing the sustained formation of a reliable freshwater lens.

METHODS AND APPROACH

Taking advantage of regular shipping services to the outer islands of Tuvalu, the in-country SOPAC/EU Project Intern (Ms Loia Tausi, based in the Division of Lands) travelled to all islands in the group between the months of January to April 2006.

Limited time was available on each island so complete coverage of all pits, on each island, was not possible. However, a representative number of pits were surveyed and the names and locations of these pits are recorded to allow future monitoring and follow up.

The following observations were carried out at each location:

- Date and time of sampling.
- Location and name of pit.
- Local weather at time of sampling.
- General health of plants and overall condition of pit.
- Where possible, anecdotal information from local landowners / cultivators.
- A conductivity meter (Hanna Instruments – HI 9033, Multi-range Conductivity Meter) was used to record conductivity (salinity) of the freestanding water within each pit at the approximate centre or deeper basins. Measurements were taken at the surface (~5 cm) bottom (~30 cm) and midway (~15 cm) through the water column and recorded as $\mu S\ cm^{-1}$ (microsiemens per cm). (For more details see Attachment 1).

Strictly speaking a depth profile was measured at each point in each site, rather than a triplicate sample (see Attachment 1). This profile was however treated as a triplicate for data analysis purposes and this is justified since swamp taro plants grow and presumably absorb; and are influenced by water quality from the muddy substrate through to the surface of the pit waters.

Rainfall

Rainfall is extremely important with respect to groundwater recharge and salinity conditions of the groundwater lens and could also greatly influence the results gained at the time of sampling (see White *et al.* 2006). Wetter than normal weather could reasonably be expected to result in data which suggests the conductivity (or salinity) is lower than true average conditions and alternatively, dryer than normal weather may result in data which shows higher than the true average conductivity conditions.

Accurate daily rainfall data could only be obtained for Funafuti and other than the visual observations taken during the fieldwork it is assumed that Funafuti weather conditions are representative of the rest of the group. Generally, the Funafuti rainfall data during the months of January to May 2006 were close to the 78-year averages for these months with the exception of April, which was unusually dry. However, conditions appear to return to the normal range in May (see Table 2). Overall, rainfall conditions during the survey are thought to reflect average conditions in the group for this time of the year and as such the conductivity data collected should be a representative of ambient groundwater conditions.

Table 2. Average rainfall conditions (Funafuti) during the sample period January – April 2006, compared to the 78-year monthly averages. April 2006 is significantly dryer than normal otherwise the remainder of the 2006 averages fit well with prevailing patterns.

o t	o t er e r –	o t r 7 er er e S –
January	382.8	389.9 ± 170
February	392.7	364.1 ± 189
March	407.3	340.9 ± 196
April	58.8	261.7 ± 133
May	230.5	232.1 ± 124

RESULTS

On the following pages the results section is presented as tabulated raw data collected from each island including: sample time, date, location, conductivity readings and sampler's relevant comments*. Conductivity means and standard deviations for each island and each pit area are also included. The data is arranged on an island-by-island basis from the most Northern (Nanumea) to the most Southern (Nukulaelae). (Note that simple regression analysis of relationships between groundwater salinity and island location was also undertaken but no trends were apparent).

Facing each table, is a location map of each island within the Tuvalu group (source – Smith & Sandwell, 1997). Additionally, for the larger atolls a location map is included showing the position of each island's swamp taro growing areas (in most cases these areas represent the main, current swamp taro growing location/s for each community – local guides were sought on each island to assist in identifying these areas).

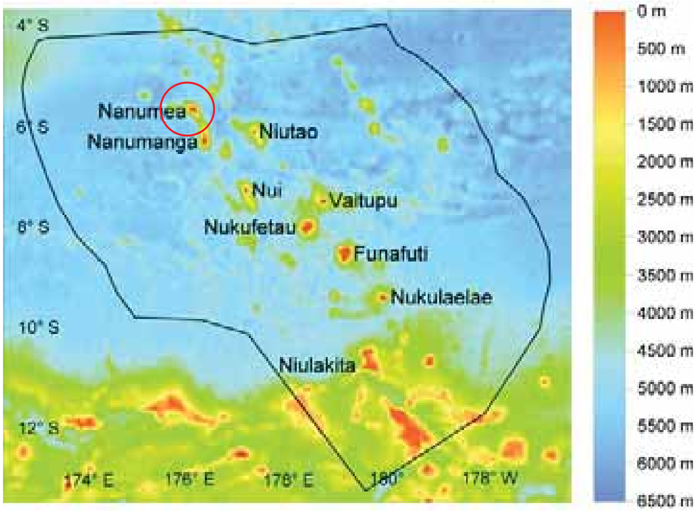
Finally, a large-scale map showing the location of each sample profile is given. Yellow points indicate the sample position and where possible, red outlines approximate pit area boundaries. Note that the area names match (with some unnamed exceptions) the pit names in the data tables. It is hoped that these clear maps will assist local authorities to continue sampling efforts.

---

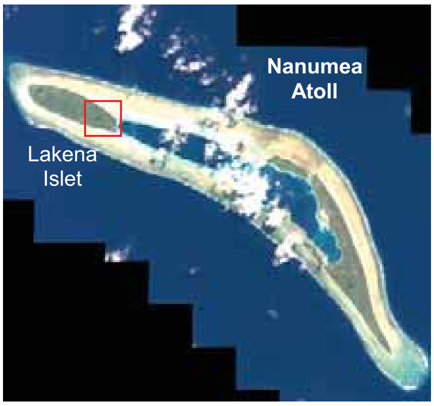
*Note: "*dalo*" = taro (*Colocasia esculenta*) as opposed to "*pulaka*" or swamp taro (C*yrtosperma chamissonis*).

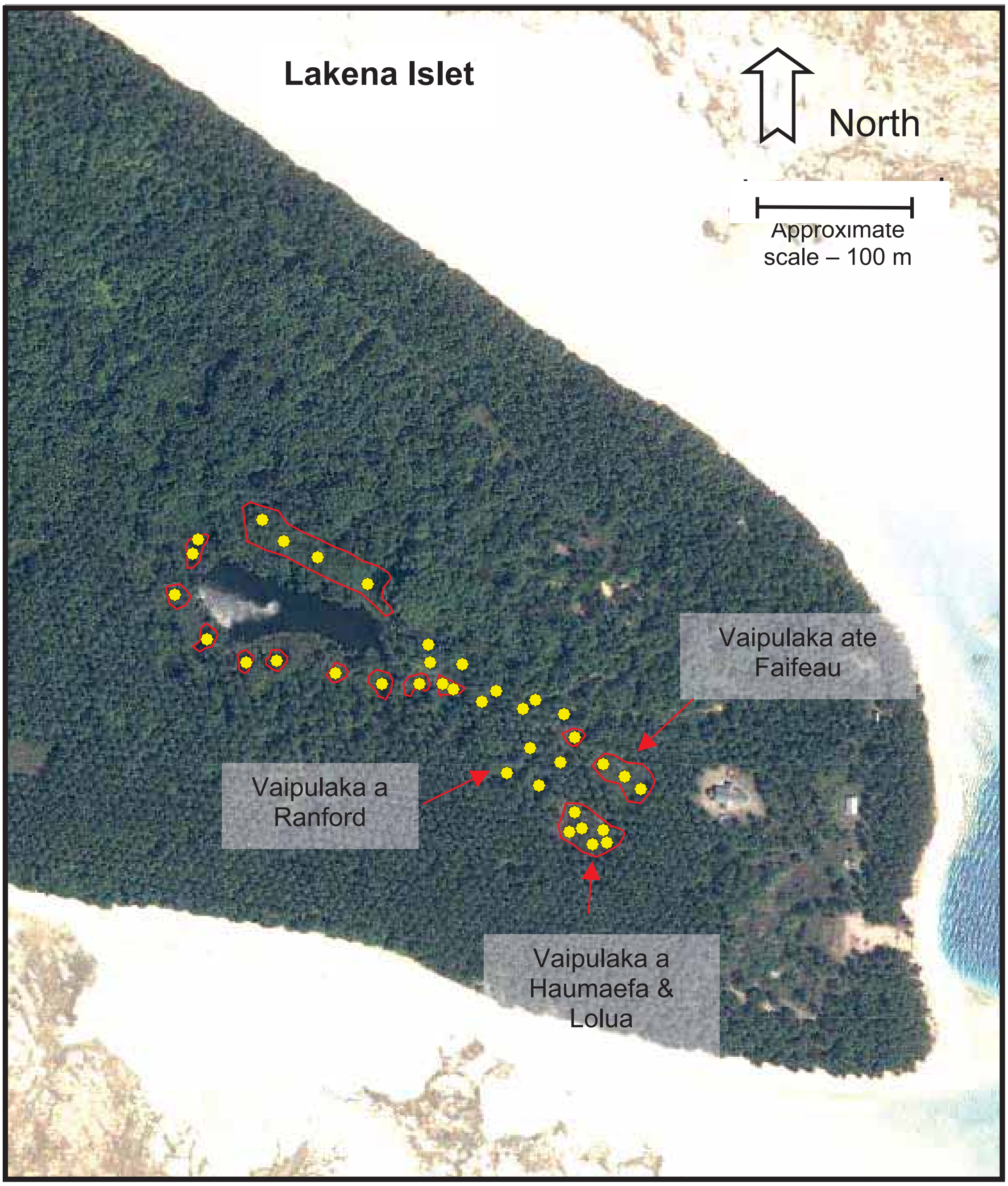
Nanumea – conductivity profiles 1/03/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm					Pit Area Mean		Notes / Observations
				Surface	Mid.	Bottom	**Mean**	Std. Dev.	Mean	Std. Dev.	
16/03/06 11.45 am	Fine	Nanumea- Lakena	Vaipulaka ate Faifeau	260	730	750	**580**	277			Pit grown with pulaka, in good health
"	Fine	"	"	800	900	1000	**900**	100			Pit grown with pulaka, in reasonable health
"	Fine	"	"	100	700	800	**533**	379	671	296	Pits well manage by the kaupule (Is. Council)
16/03/05 12.00 pm	Fine	"	Vaipulaka a Haumaefa & Lolua	590	740	800	**710**	108			Pit grown with pulaka, in good health
"	Fine	"	"	480	510	600	**530**	62			Pit partially grown with pulaka - overgrown with weeds
"	Fine	"	"	1250	2040	2450	**1913**	610			
"	Fine	"	"	240	660	780	**560**	284			
"	Fine	"	"	540	730	860	**710**	161			
"	Fine	"	"	740	900	1040	**893**	150	886	547	
16/03/06 12.15 pm	Fine	"	Vaipulaka a Haulagi/Ranford	200	530	630	**453**	225			Small pit grown with pulaka - plants in good health
16/03/06 12.17 pm	Fine	"	Unknown	620	780	850	**750**	118			Small pit grown with dalo and pulaka - all healthy
16/03/06 12.20pm	Fine	"	Unknown	130	610	670	**470**	296			Small pit grown with pulaka - plants in good health
16/03/06 12.25 pm	Fine	"	Unknown	200	650	760	**537**	297			Small pit grown with pulaka - plants in good health
16/03/06 12.30 pm	Fine	"	Unknown	340	630	740	**570**	207			Small pit grown with pulaka - plants in good health
16/03/06 12.32 pm	Fine	"	Unknown	130	480	490	**367**	205			Small pit grown with pulaka - plants in good health
16/03/0612.35 pm	Fine	"	Unknown	420	670	430	**507**	142			Small pit grown with pulaka - plants in good health
16/03/05 12.36 pm	Fine	"	Unknown	480	600	700	**593**	110			Small pit grown with pulaka - plants in good health
16/03/05 2.00 pm	Fine	"	Unknown	530	610	680	**607**	75			Small pit grown with pulaka - plants in good health
16/03/05 2.05 pm	Fine	"	Unknown	350	560	610	**507**	138			Small pit grown with pulaka - plants in good health
16/03/05 2.10 pm	Fine	"	Unknown	540	640	750	**643**	105			Small pit grown with pulaka - plants in good health
16/03/05 2.15 pm	Fine	"	Unknown	680	710	820	**737**	74			Moderate size pit partially grown with pulaka - overgrown with weeds
"	Fine	"	Unknown	530	720	840	**697**	156	717	111	
16/03/05 2.20 pm	Fine	"	Unknown	130	760	880	**590**	403			Small pit partially grown with pulaka and some dalo - mostly overgrown with weeds
16/03/05 2.25 pm	Fine	"	Unknown	380	540	640	**520**	131			Small pit grown with dalo and pulaka - all healthy
16/03/05 2.30 pm	Fine	"	Unknown	310	760	890	**653**	304			Small pit grown with pulaka - weeds
16/03/05 2.35 pm	Fine	"	Unknown	780	940	1120	**947**	170			Well planted with pulaka and dalo
16/03/05 2.40 pm	Fine	"	Unknown	480	1630	1940	**1350**	769			Grown with pulaka - poorly cultivated
16/03/05 2.45 pm	Fine	"	Unknown	780	1000	1180	**987**	200			Well planted with pulaka and dalo
16/03/05 2.50 pm	Fine	"	Unknown	210	970	1030	**737**	457			Well planted with pulaka and dalo and banana - all healthy
16/03/05 2.55 pm	Fine	"	Unknown	780	107	1260	**716**	579			Pulaka , dalo and banana grows in the pit - poorly managed, overgrown with weeds
"	Fine	"	Unknown	780	1390	1480	**1217**	381			
"	Fine	"	Unknown	1320	1600	1890	**1603**	285	1179	538	
16/03/05 3.10 pm	Fine	"	Unknown	360	790	960	**703**	309			Pulaka , dalo and banana grows in the pits - poorly managed - weeds
"	Fine	"	Unknown	210	640	750	**533**	285			
"	Fine	"	Unknown	160	730	870	**587**	376			
"	Fine	"	Unknown	380	650	770	**600**	200			
"	Fine	"	Unknown	2100	480	620	**1067**	898	698	454	
			Overall - means	**522**	**786**	**928**	**745**				
			Standard deviation	394	358	414	421				
			%CV	76	45	45	57				


4° S
6° S
8° S
10° S
12° S
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
174° E
176° E
178° E
180°
178° W
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

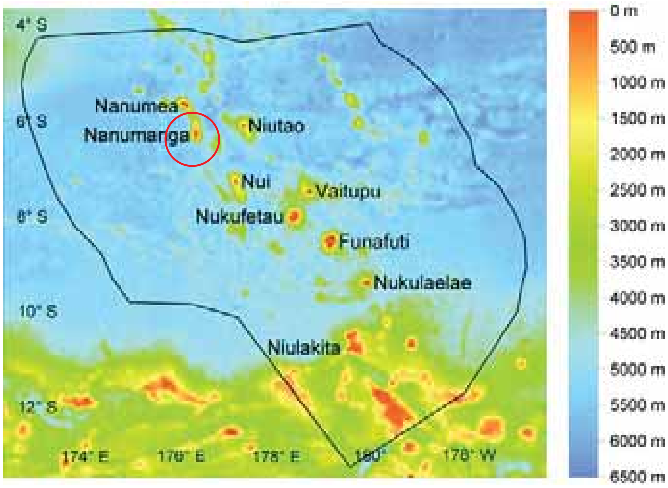
Nanumea


Nanumea Atoll
Lakena Islet

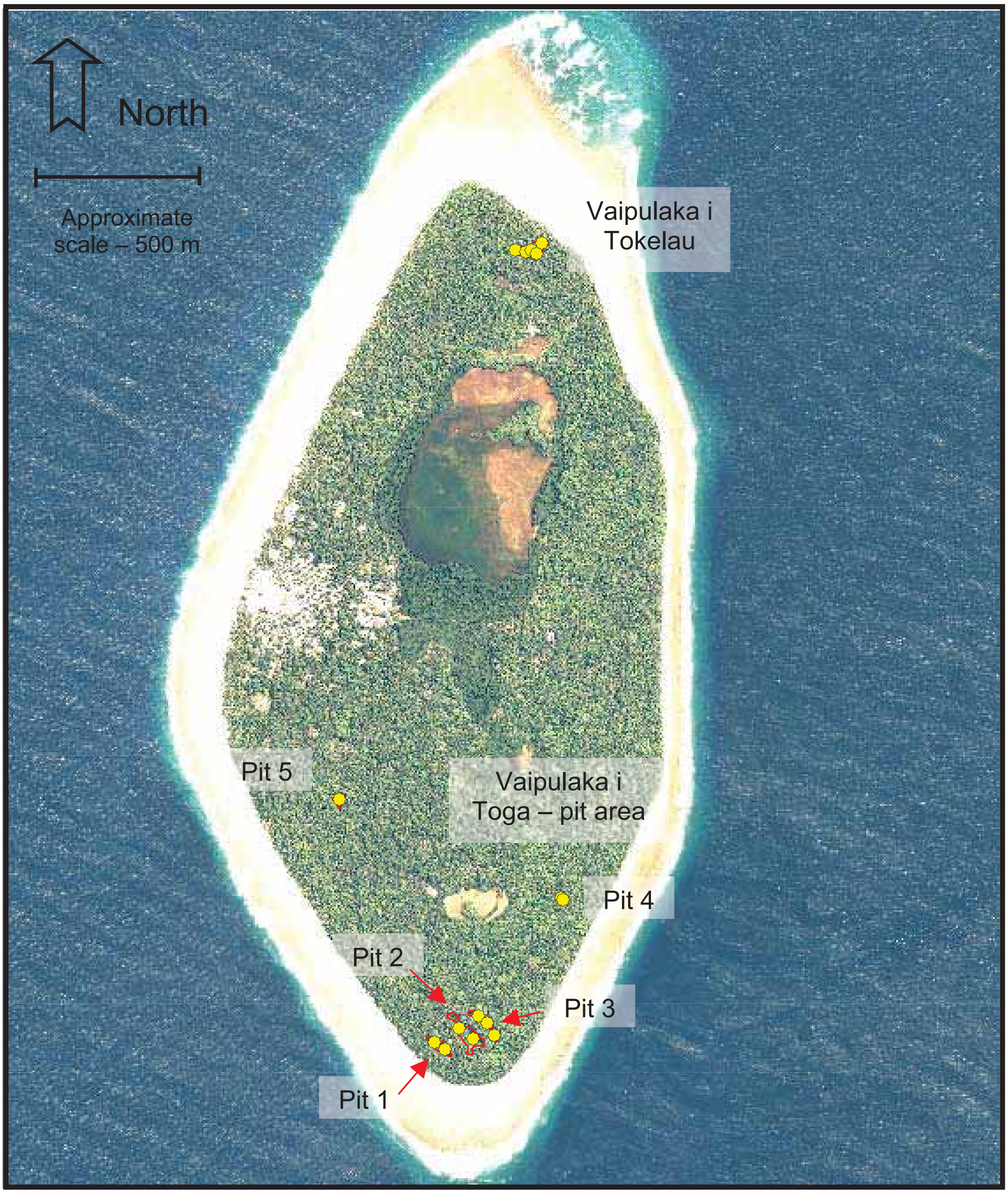

Lakena Islet
North
Approximate scale – 100 m
Vaipulaka ate Faifeau
Vaipulaka a Ranford
Vaipulaka a Haumaefa & Lolua

Nanumanga – conductivity profiles 15/03/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm					Pit Area Mean		Notes / Observations
				Surface	Mid.	Bottom	**Mean**	Std. Dev.	Mean	Std. Dev.	
15/03/06 10.00am	Fine	Nanumanga	Vaipulaka i Tokelau	1180	1200	1350	**1243**	93			Pit well planted with pulaka, dalo and banana
"	Fine	"	"	1370	1550	1600	**1507**	121			Overall growth of plants – average
"	Fine	"	"	140	680	810	**543**	355			
"	Fine	"	"	230	570	670	**490**	231			
"	Fine	"	"	150	460	560	**390**	214	835	504	
15/03/06 10.30am	Fine	"	Vaipulaka i Toga Pit 1	600	710	730	**680**	70			Pit planted with pulaka, dalo and bananas
"	Fine	"	"	450	470	550	**490**	53	585	118	Plants are in good health - pit appear well cultivated
15/03/06 10.45am	Fine	"	Vaipulaka i Toga Pit 2	1880	1980	2190	**2017**	158			Dalo, pulaka and bananas - all healthy
"	Fine	"	"	1450	1500	1670	**1540**	115	1778	289	Individual plots well cultivated
15/03/06 11.00am	Fine	"	Vaipulaka i Toga Pit 3	110	560	800	**490**	350			Pulaka in good health
"	Fine	"	"	300	490	570	**453**	139			
"	Fine	"	"	1050	1300	2060	**1470**	526	804	595	
15/03/06 11.20am	Fine	"	Vaipulaka i Toga Pit 4	1130	1730	1880	**1580**	397			Pulaka in good health
"	Fine	"	"	820	1190	1430	**1147**	307	1363	396	
15/03/06 11.45am	Fine	"	Vaipulaka i Toga Pit 5	200	450	540	**397**	176			Only pulaka grown in this pit - small but healthy
			mean	**737**	**989**	**1161**	**962**				
			Standard deviation	573	528	603	583				
			%CV	78	53	52	61				


4° S
6° S
8° S
10° S
12° S
174° E
176° E
178° E
180°
178° W
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

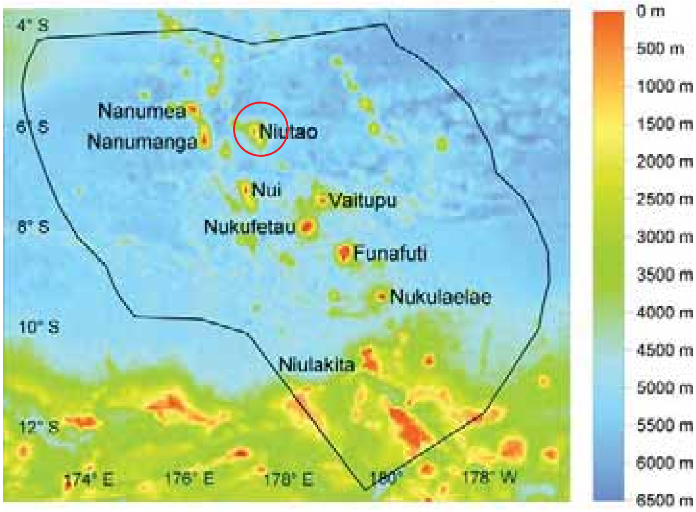
Nanumanga

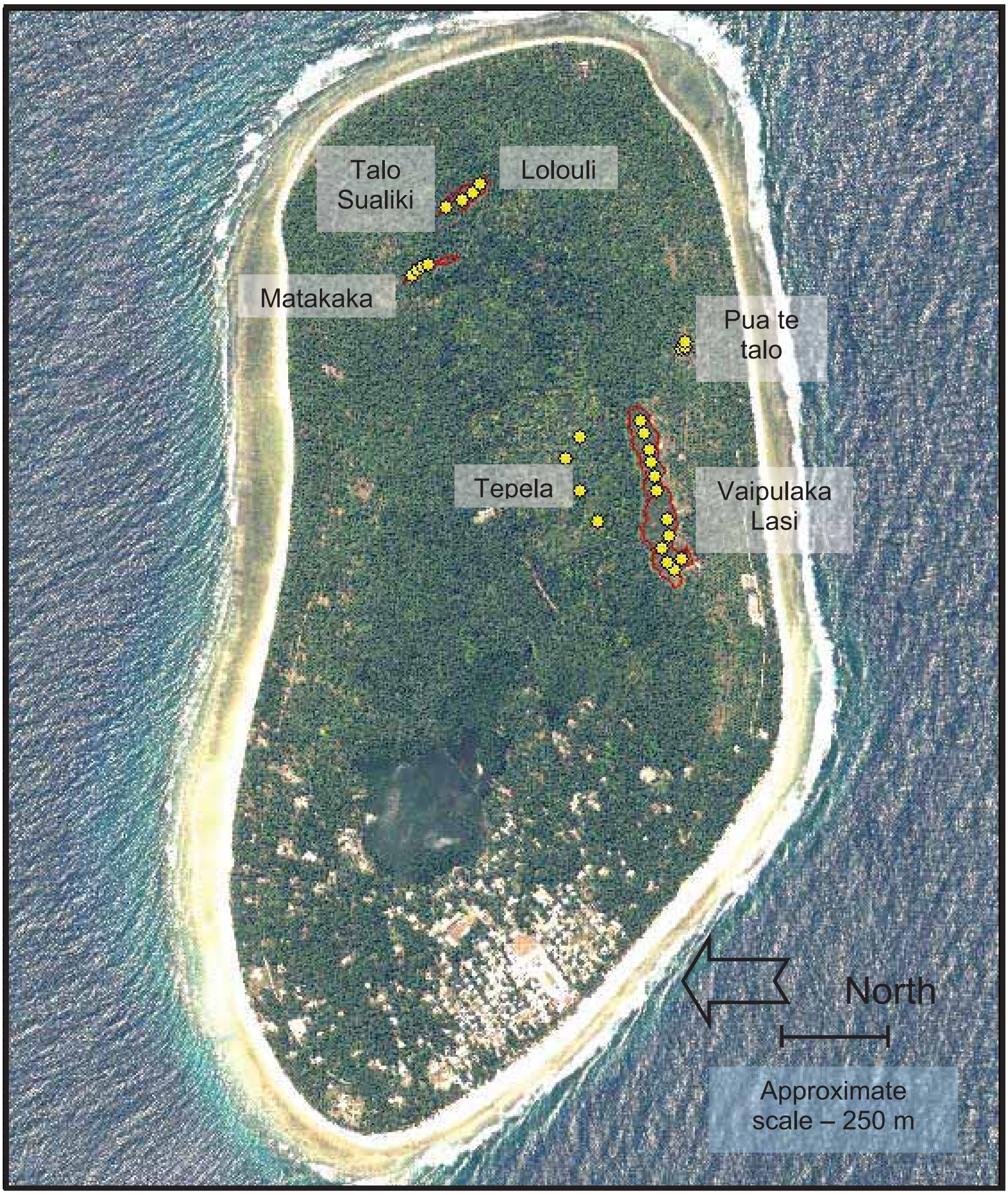

North
Approximate scale – 500 m
Vaipulaka i Tokelau
Pit 5
Vaipulaka i Toga – pit area
Pit 4
Pit 2
Pit 3
Pit 1

Niutao – conductivity profiles 17/03/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm Surface	Mid.	Bottom	**Mean**	Std. Dev.	Pit Area Mean Mean	Std. Dev.	Notes / Observations
17/03/06 10.00 am	Rainy	Niutao	Tepela	2150	331	3450	**1977**	1567			Partially in use - planted with dalo, pulaka - only a few surviving plants
"	Rainy	"	"	1390	1550	1900	**1613**	261			Pit is abandoned due to poor growing conditions
"	Rainy	"	"	2270	4170	4690	**3710**	1274			
"	Rainy	"	"	3990	4500	5280	**4590**	650	2973	1570	
17/03/06 10.10 am	Rainy	"	Vaipulaka Lasi (West)	130	170	180	**160**	26			Main village pulaka pit - divided in half with 2 many owners
"	Rainy	"	"	140	150	160	**150**	10			Pit grown with banana, pulaka,dalo and some sugarcane
"	Rainy	"	"	130	130	160	**140**	17			Pulaka and other plants are healthy and growing well
"	Rainy	"	"	160	1800	200	**720**	936			There are a few weeds between the pulaka and dalo but generally well cultivated
"	Rainy	"	"	21	235	250	**169**	128			
"	Rainy	"	"	110	140	170	**140**	30	246	391	
17/03/06 10.20 am	Rainy	"	Vaipulaka Lasi (Eastern)	120	220	250	**197**	68			People are cultivating these pulaka pits regularly
"	Rainy	"	"	180	210	270	**220**	46			
"	Rainy	"	"	150	180	200	**177**	25			
"	Rainy	"	"	110	130	170	**137**	31			
"	Rainy	"	"	180	210	240	**210**	30			
"	Rainy	"	"	200	240	270	**237**	35	196	48	
17/03/06 10.30 am	Rainy	"	Matakakasi	40	190	220	**150**	96			Part of this pit is well cultivated while the other part is overgrown with weeds
"	Rainy	"	"	40	140	390	**190**	180			Where dalo and Pulaka are grown they are healthy
"	Rainy	"	"	50	110	150	**103**	50			
"	Rainy	"	"	100	130	170	**133**	35	144	97	
17/03/06 10.55 am	Rainy	"	Pua te talo	90	110	150	**117**	31			Pulaka, dalo and sugarcane grown - all mostly healthy.
"	Rainy	"	"	40	140	170	**117**	68			People visit these pits daily
"	Rainy	"	"	70	110	140	**107**	35	113	42	
17/03/06 11.10 am	Rainy	"	Talo Sualiki	220	410	440	**357**	119			A small pit with healthy pulaka
17/03/06 10.25 am	Rainy	"	Lolouli	170	240	280	**230**	56			Pulaka , dalo are grown in this pit - healthy.
"	Rainy	"	"	260	320	360	**313**	50			
"	Rainy	"	"	260	390	420	**357**	85	300	80	Plants in this pit also healthy
			mean	**473**	**617**	**768**	**619**				
			Standard deviation	921	1145	1399	1163				
			%CV	195	186	182	188				

Niutao

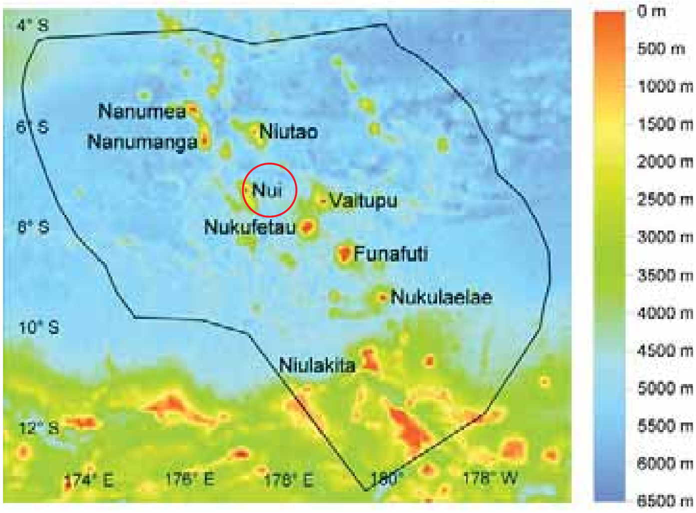

4° S
6° S
8° S
10° S
12° S
174° E
176° E
178° E
180°
178° W
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m


Talo Sualiki
Lolouli
Matakaka
Pua te talo
Tepela
Vaipulaka Lasi
North
Approximate scale – 250 m

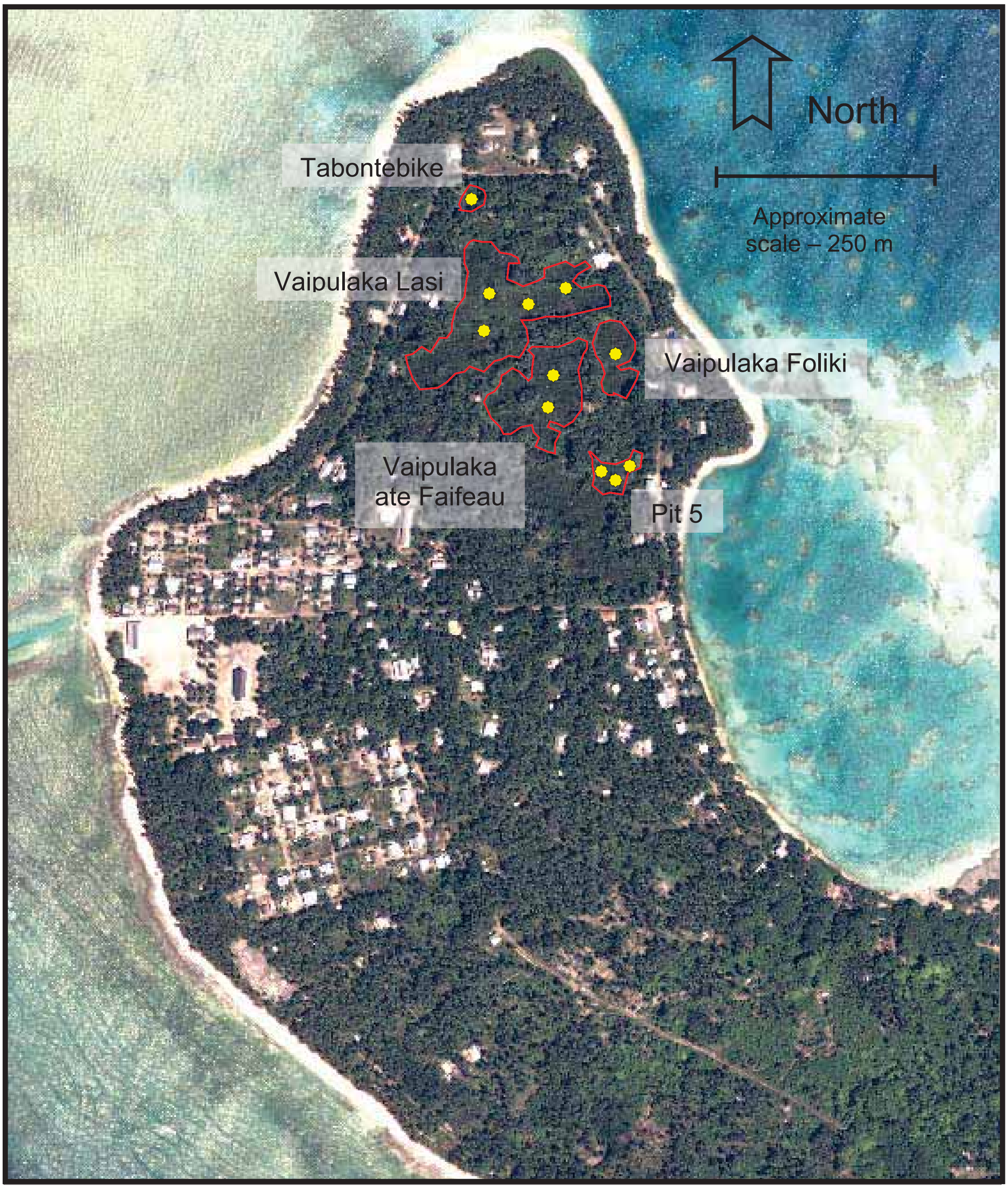
Nui – conductivity profiles 05/04/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm					Pit Area Mean		Notes / Observations
				Surface	Mid.	Bottom	**Mean**	Std. Dev.	Mean	Std. Dev.	
05/4/06 9.50 am	Fine	Nui	Tabontepike	80	140	195	**138**	58			Only pulaka are grown in pit - healthy
05/4/2006 10.00 am	Fine	"	Vaipulaka Lasi	170	203	379	**251**	112			Pulaka and dalo and few sugarcane - some weeds but cultivation OK
"	Fine	"	"	110	132	160	**134**	25			
"	Fine	"	"	120	140	160	**140**	20			Plants are in good health
"	Fine	"	"	116	148	182	**149**	33	168	72	
05/4/2006 11.00a.m	Fine	"	Vai ate Faifeau	134	202	433	**256**	157			Small pit pulaka healthy
"	Fine	"	"	168	210	252	**210**	42	233	106	
05/4/2006 11.20 am	Fine	"	Vai pulaka Foliki	180	242	427	**283**	129			Part of this pit are well grown while the other over grown with weeds
05/04/06 11.30 am	Fine	"	unknown	424	468	490	**461**	34			Pulaka , dalo and sugarcane - mostly healthy - people visit these pits daily
"	Fine	"	"	689	840	851	**793**	91			
"	Fine	"	"	405	430	473	**436**	34	563	180	
			mean	**236**	**287**	**364**	**296**				
			Standard deviation	190	216	208	205				
			%CV	80	75	57	69				

Nui


4° S
6° S
8° S
10° S
12° S
174° E
176° E
178° E
180°
178° W
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

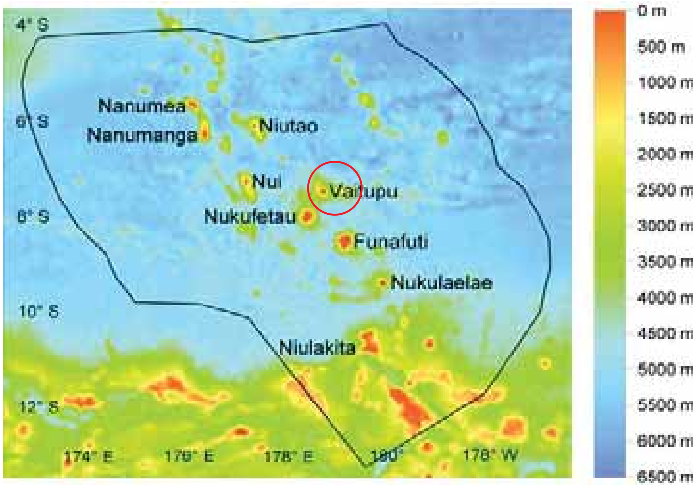

Nui
Atoll

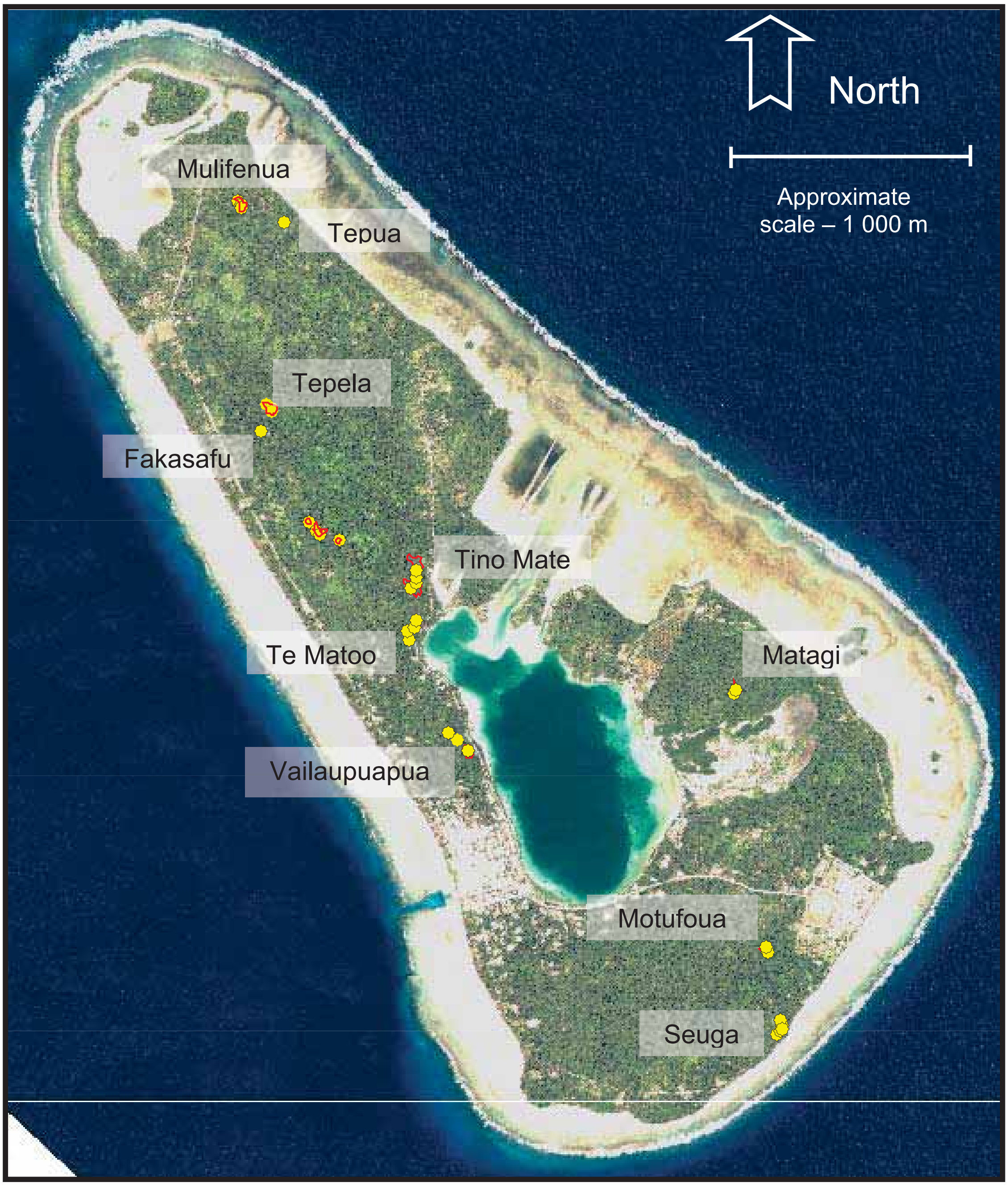

North
Approximate
scale – 250 m
Tabontebike
Vaipulaka Lasi
Vaipulaka Foliki
Vaipulaka
ate Faifeau
Pit 5

Vaitupu – conductivity profiles 25– 29/01/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm					Pit Area Mean		Notes / Observations
				Surface	Mid.	Bottom	**Mean**	Std. Dev.	Mean	Std. Dev.	
25/01/06 10.00 am	Fine	Vaitupu	Matagi	1625	1770	1924	**1773**	150			Seems to abandoned - a few surviving pulaka
"	Fine	"	"	1727	1800	1978	**1835**	129	1804	129	
25/01/06 10.30 am	Fine	"	Motufoua	709	787	839	**778**	65			Only pulaka are grown in this pit - in fair condition
"	Fine	"	"	624	861	1101	**862**	239	820	163	
25/01/06 11.00 am	Fine	"	Seuga	1123	1574	1973	**1557**	425			Pit grown with pulaka and dalo - used by a number of farmers - some plants here are in good health others just seem to be
"	Fine	"	"	1358	1617	1989	**1655**	317			surviving.
"	Fine	"	"	1245	1445	1605	**1432**	180			- weeds grow amongst the pulaka
"	Fine	"	"	984	1106	1423	**1171**	227			
"	Fine	"	"	1425	1558	1680	**1554**	128	1474	291	
26/01/06 10.20 am	Fine	"	Vailaupuapua	325	441	694	**487**	189			Pulaka seems to be in good health
"	Fine	"	"	550	612	785	**649**	122			
"	Fine	"	"	475	684	759	**639**	147	592	156	
26/01/06 11.00 am	Fine	"	Te Matoo	1310	1417	1569	**1432**	130			Series of small pits mostly connected to each other - pulaka mostly healthy
"	Fine	"	"	940	1140	1390	**1157**	225			
"	Fine	"	"	1540	1690	1874	**1701**	167			
"	Fine	"	"	1200	1430	1670	**1433**	235	1431	261	
26/01/06 12.00 pm	Fine	"	Tino Mate	1190	1350	1570	**1370**	191			Pulaka , dalo and sugarcane - all mostly healthy
"	Fine	"	"	1122	1290	1520	**1311**	200			- people appear to visit these pits regularly
"	Fine	"	"	1170	1250	1500	**1307**	172			
"	Fine	"	"	1220	1381	1512	**1371**	146	1340	156	
29/01/06 10.00am	Fine	"	Fakasafu	1200	1360	1440	**1333**	122			A small pit with healthy pulaka
29/01/06 10.30am	Fine	"	Te pela	1170	1240	1280	**1230**	56			Pulaka , dalo are grown in this pit - all in good condition.
"	Fine	"	"	1260	1320	1460	**1347**	103			
"	Fine	"	"	1260	1390	1420	**1357**	85	1311	95	
29/01/06 11.30am	Fine	"	Fusi	1270	1345	1780	**1465**	275			Pulaka , dalo are grown in this pit - health is poor
"	Fine	"	"	1260	1320	1817	**1466**	306			- pit is water logged - heavy rainfall recently
"	Fine	"	"	1117	1315	1550	**1327**	217	1419	243	
29/01/06 12.00pm	Fine	"	Tepua	1571	1650	1810	**1677**	122			Pulaka in good health
29/01/06 12.30pm	Fine	"	Mulifenua	1215	1400	1515	**1377**	151			Main pit grown with pulaka - abundant, good health
"	Fine	"	"	1545	1650	1800	**1665**	128			
"	Fine	"	"	1015	1250	1350	**1205**	172			People indicate some areas are poor for cultivation and avoid these
"	Fine	"	"	1245	1250	1600	**1365**	204	1403	224	Some areas with poor growth.
			mean	**1156**	**1303**	**1506**	**1321**				
			Standard deviation	328	327	354	363				
			%CV	28	25	23	27				

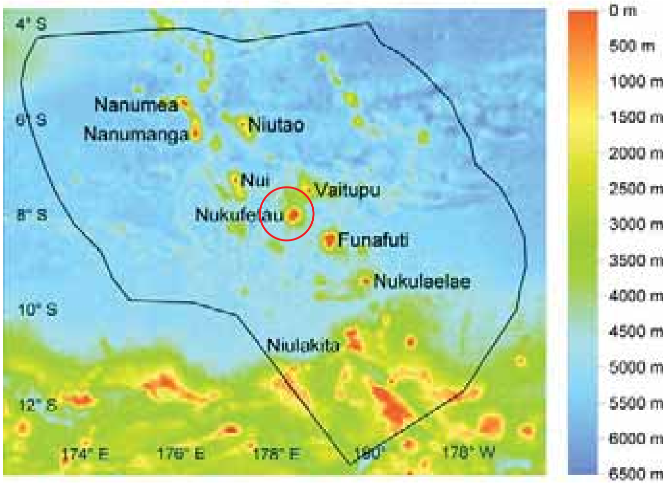
Vaitupu


4° S
6° S
8° S
10° S
12° S
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
174° E
176° E
178° E
180°
178° W
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

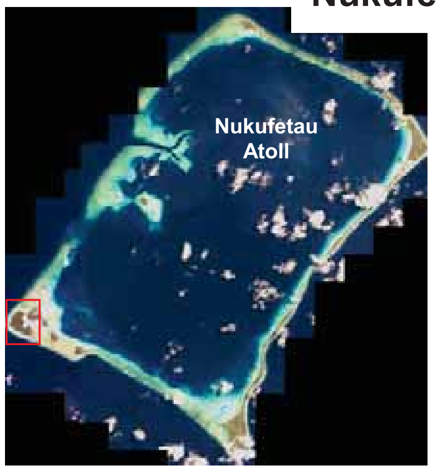

North
Approximate scale – 1 000 m
Mulifenua
Tepua
Tepela
Fakasafu
Tino Mate
Te Matoo
Matagi
Vailaupuapua
Motufoua
Seuga

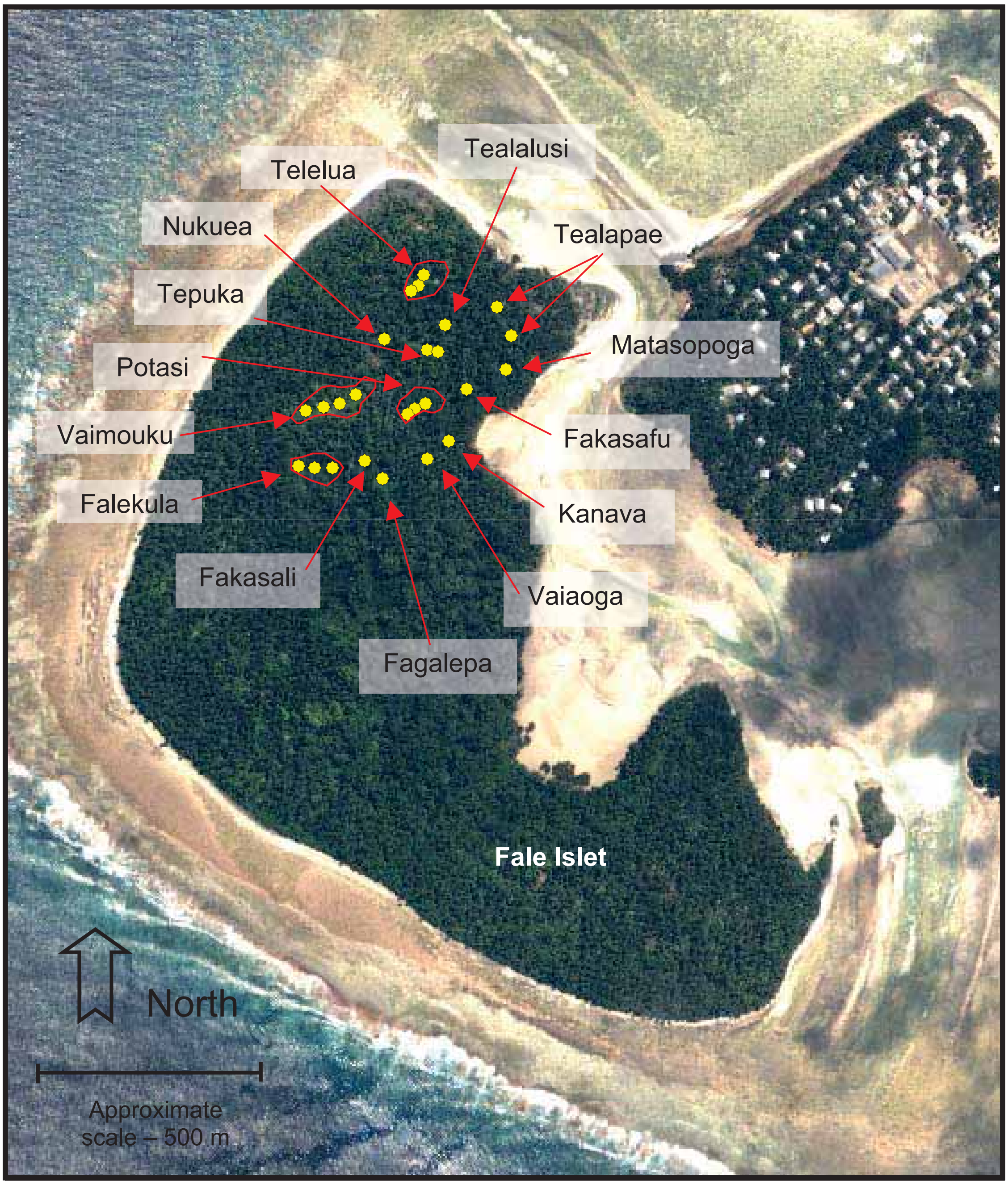
Nukufetau – conductivity profiles 04/04/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm: Surface	Mid.	Bottom	**Mean**	Std. Dev.	Pit Area Mean: Mean	Std. Dev.	Notes / Observations
04/04/06 11.30 am	Fine	Nukufetau / Fale islet	Fakasafu	21	47	160	**76**	74			Healthy pulaka and dalo in this pit
04/04/06 11.40 am	Fine	"	Tepuka	225	265	272	**254**	25			Healthy pulaka and dalo in this pit
"	Fine	"	"	487	488	495	**490**	4	372	130	
04/04/06 11.45 am	Fine	"	Potasi	145	156	185	**162**	21			Only pulaka grown in this pit - healthy
"	Fine	"	"	180	200	211	**197**	16			
"	Fine	"	"	87	105	140	**111**	27	157	42	
04/04/06 12.00 pm	Fine	"	Falekula	78	115	150	**114**	36			Healthy pulaka are grown in this pit - some weeds
"	Fine	"	"	110	125	138	**124**	14			
"	Fine	"	"	132	151	165	**149**	17	129	26	
04/04/2006 12.30 pm	Fine	"	Vaimouku	140	160	178	**159**	19			Parts of this pit are well cultivated with healthy pulaka other areas over grown with weeds
"	Fine	"	"	140	151	164	**152**	12			Dalo and Pulaka are grown in this pit - some areas better looked after than others.
"	Fine	"	"	150	176	188	**171**	19			- some areas overgrown with weeds
"	Fine	"	"	110	130	163	**134**	27	154	22	
04/04/06 12.55 pm	Fine	"	Telelua	90	116	138	**115**	24			Pulaka , dalo and sugarcane - all look healthy
"	Fine	"	"	140	151	170	**154**	15			- pit visited regularly, well cultivated
"	Fine	"	"	112	126	140	**126**	14	131	24	
04/04/2006 1.10 pm	Fine	"	Nukuea								No standing water at time of sampling - small with healthy pulaka
04/04/2006 1.15 pm	Fine	"	Vaiaoga								No standing water at time of sampling - small with healthy pulaka
04/04/2006 1.20 pm	Fine	"	Fagalepa								No standing water at time of sampling - small with healthy pulaka
04/04/2006 1.25 pm	Fine	"	Fakasali								No standing water at time of sampling - small with healthy pulaka
04/04/06 1.30 pm	Fine	"	Matasopoga	78	90	103	**90**	13			Pulaka ,dalo and sugarcane - all in good condition.
04/04/06 1.35 pm	Fine	"	Tealapae	135	151	170	**152**	18			- pit visited regularly
04/04/06 1.40 pm	Fine	"	"	112	126	140	**126**	14			
04/04/2006 1.45 pm	Fine	"	Kanava								No standing water at time of sampling - small with healthy pulaka
04/04/2006 1.50 pm	Fine	"	Tealalusi								No standing water at time of sampling - small with healthy pulaka
			mean	**141**	**159**	**183**	**161**				
			Standard deviation	94	91	83	90				
			%CV	67	57	46	56				


4° S
6° S
8° S
10° S
12° S
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
174° E
176° E
178° E
180°
178° W
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

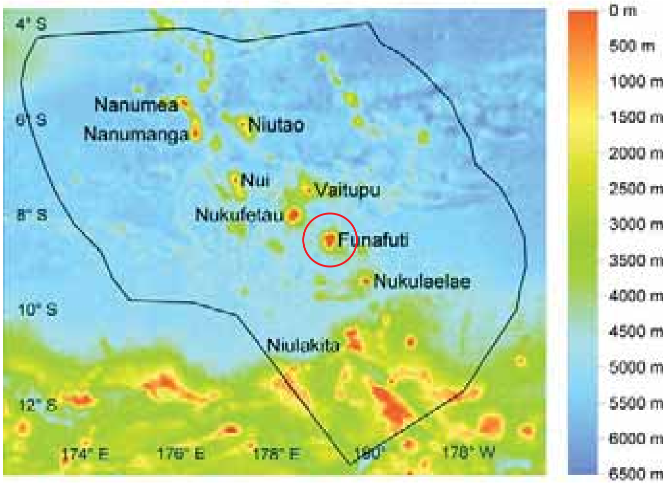
Nukufetau

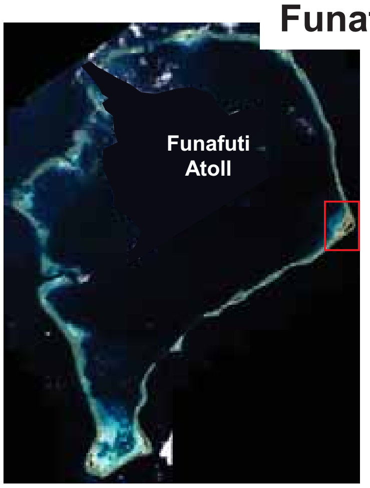

Nukufetau
Atoll

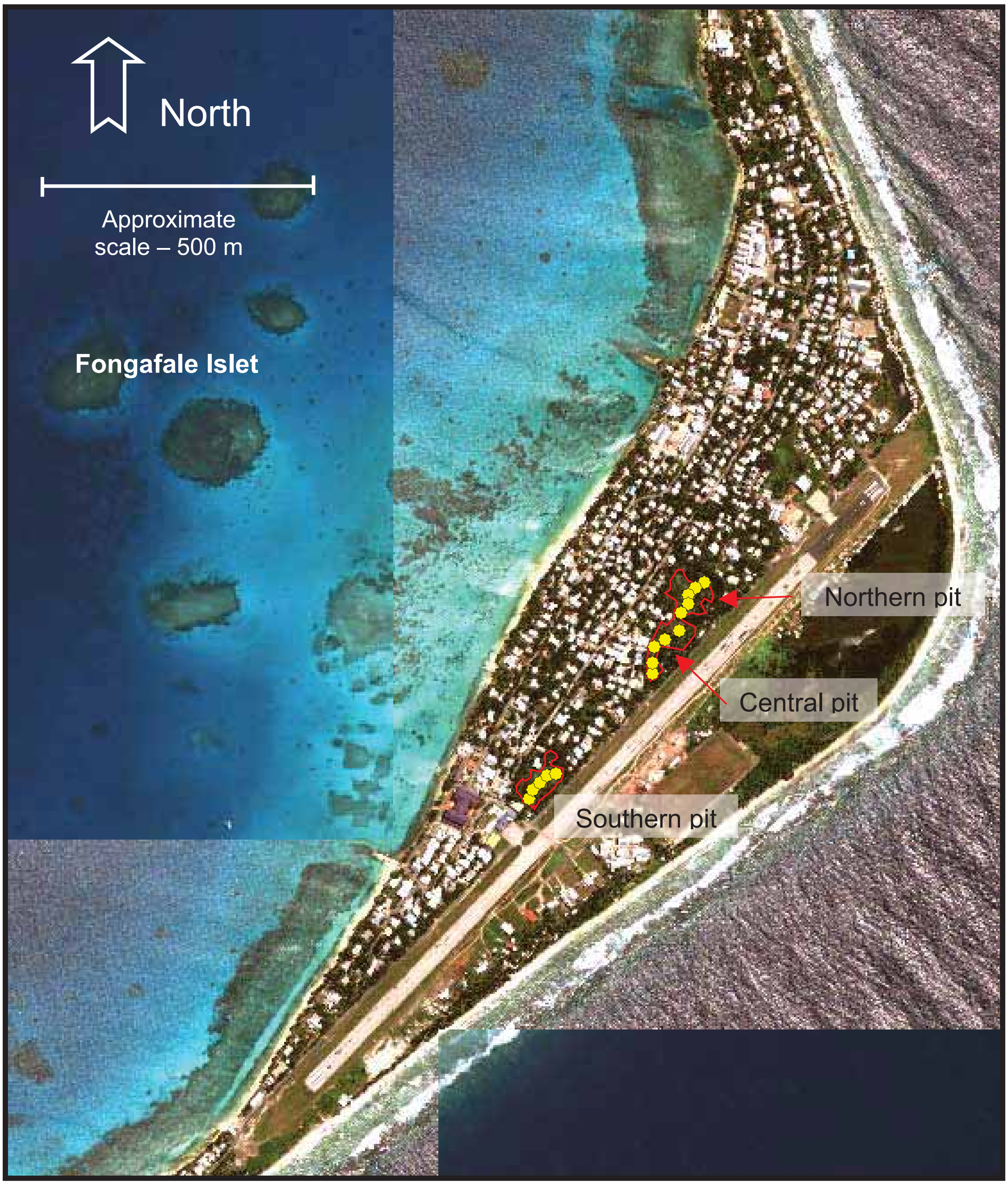

Telelua
Tealalusi
Nukuea
Tealapae
Tepuka
Matasopoga
Potasi
Vaimouku
Fakasafu
Falekula
Kanava
Fakasali
Vaiaoga
Fagalepa
Fale Islet
North
Approximate
scale – 500 m

Funafuti – conductivity profiles 20/03/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm Surface	Mid.	Bottom	Mean	Std. Dev.	Pit Area Mean: Mean	Std. Dev.	Notes / Observations
20/3/06 3.30pm	Fine	Funafuti-Fongafale	Pulaka pit Vaiaku (Southern)	4650	5200	5640	**5163**	496			Pit partially in use, planted with dalo, pulaka and bananas - banana look poor
"	Fine	"	"	4800	5020	6120	**5313**	707			- many areas overgrown with weeds only small patches near shallow edges well cultivated.
"	Fine	"	"	2270	2270	4690	**3077**	1397			- growers indicated that plants died off during recent very high tides and heavy rainfall to the bank of the pit
"	Fine	"	"	3990	3990	5280	**4420**	745	4493	1203	Planted dalo and pulaka are of average health
20/03/06 3.55 pm	Fine	"	Central Pulaka pit	5290	5290	6320	**5633**	595			Partially in use, planted with dalo, pulaka, bananas, sugar cane & breadfruit
"	Fine	"	"	4200	4670	4960	**4610**	384			- most area overgrown with weeds and unused, only a few patches of cultivated pulaka
"	Fine	"	"	6570	6570	7760	**6967**	687			Planted dalo and pulaka are of average health - some with yellowish leaves
"	Fine	"	"	4910	5510	5700	**5373**	412	5646	998	
20/03/06 4.10 pm	Fine	"	Northern Pulaka Pit (Fakaifou)	2330	2470	2500	**2433**	91			Overall, this pit seems better than the above two pits with pulaka in ok health
"	Fine	"	"	1450	2680	2800	**2310**	747			- not all of the pit area is properly cultivated and pulaka is growing wild
"	Fine	"	"	1050	1300	2060	**1470**	526	2071	646	Pulaka, dalo, banana and some sugarcane are growing in this pit
			mean	**3774**	**4088**	**4894**	**4252**				
			Standard deviation	1750	1666	1769	1741				
			%CV	46	41	36	41				

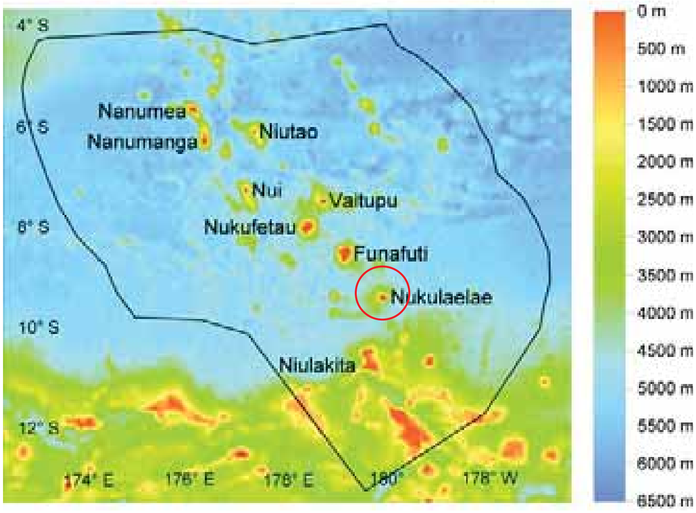

4° S
6° S
8° S
10° S
12° S
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
174° E
176° E
178° E
180°
178° W
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m


Funafuti
Funafuti Atoll


North
Approximate scale – 500 m
Fongafale Islet
Northern pit
Central pit
Southern pit

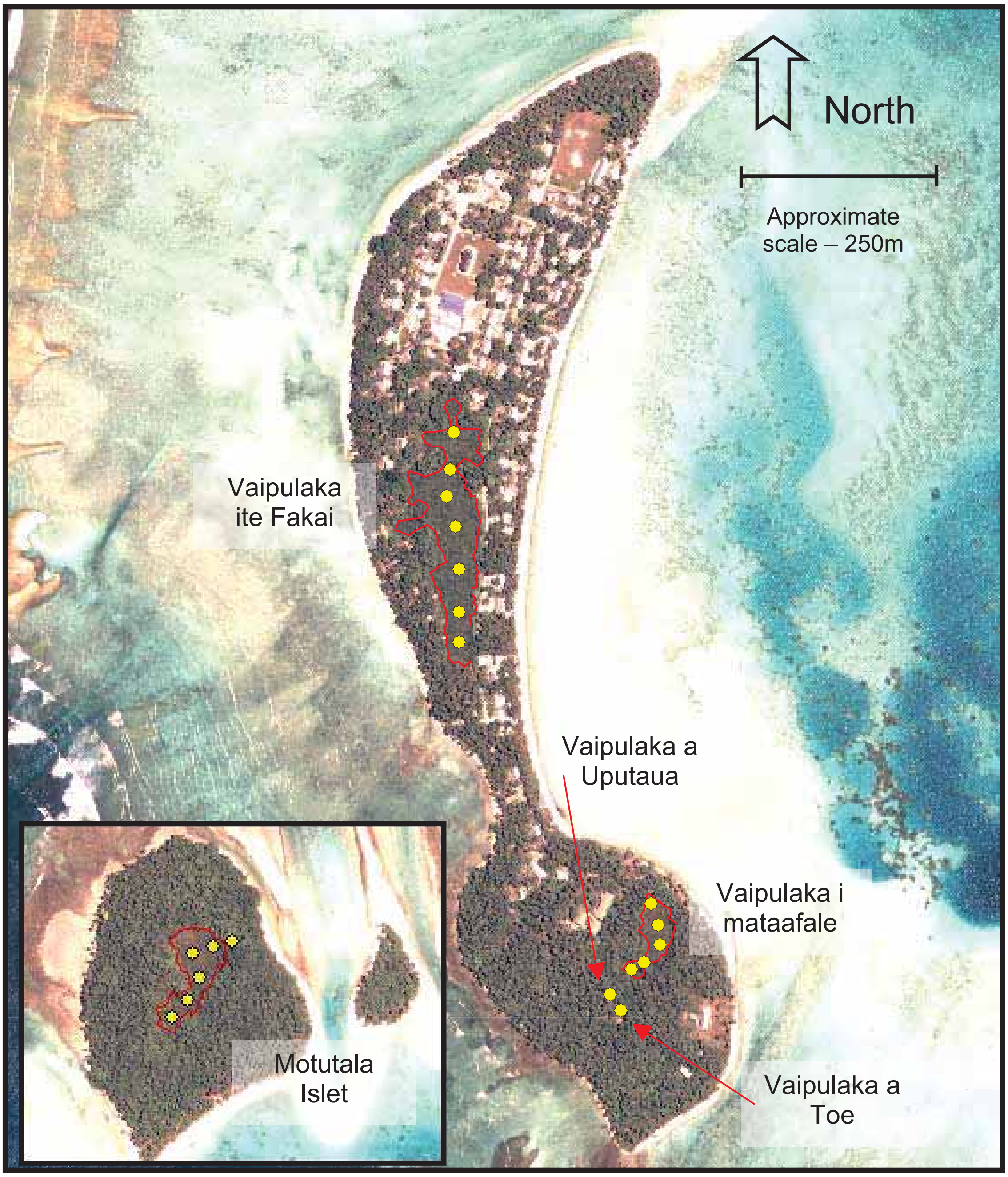
Nukulaelae – conductivity profiles 20/03/06

Date / Time	Weather	Island / islet	Pit name (if known)	Conductivity µS / cm					Pit Area Mean		Notes / Observations
		Nukulaelae-Fagaua		Surface	Mid.	Bottom	**Mean**	Std. Dev.	Mean	Std. Dev.	
11/03/06 8.55 am	Rainy	"	Vaipulaka a Toe	1000	1263	1282	**1182**	158			One small pit planted with pulaka – in ok health.
11/03/06 9.00 am	Rainy	"	Vaipulaka i Mataafale	3300	3800	4400	**3833**	551			Pits used for pulaka, sugarcane and banana.
		"	"	1780	2030	3600	**2470**	987			- plants in these pits are unhealthy with yellowish leaves.
		"	"	3730	4470	5870	**4690**	1087			- farmers say these pits are too salty to grow good pulaka.
		"	"	1120	1800	2750	**1890**	819			
		"	"	2300	3300	4800	**3467**	1258	2922	1437	
11/03/06 9.30 am	Rainy	"	Vaipulaka a Uputaua	1500	1600	1700	**1600**	100			Pit in use, grown with pulaka only - health is good
11/03/06 9.50 am	Rainy		Vaipulaka ite Fakai	480	520	530	**510**	26			The whole pit is in use planted with mostly pulaka - also some sugarcane & banana
"	Rainy	"	"	1200	1300	1400	**1300**	100			- there are several pit owners and pulaka are in good health
"	Rainy	"	"	300	400	520	**407**	110			
"	Rainy	"	"	200	220	230	**217**	15			
"	Rainy	"	"	210	225	260	**232**	26			
"	Rainy	"	"	150	170	200	**173**	25			
"	Rainy	"	"	250	275	290	**272**	20	444	378	
11/03/06 11.30 am	Rainy	Motutala	Vaipulaka i Motutala	470	490	520	**493**	25			This pit is located on the islet called Motutala and is used for pulaka and banana
"	Rainy	"	"	1050	1120	1140	**1103**	47			Pulaka that grows toward the inner part of the islet are doing well and look healthy
"	Rainy	"	"	1300	1500	1700	**1500**	200			- those that are located towards the ocean side are more yellowish - less healthy
"	Rainy	"	"	1050	1100	1250	**1133**	104			- farmers indicate that the pulaka in these poorer areas are dying out.
"	Rainy	"	"	640	675	690	**668**	26			
"	Rainy	"	"	490	520	645	**552**	82	908	384	
			mean	**1126**	**1339**	**1748**	**1385**				
			Standard deviation	1003	1235	1694	1339				
			%CV	89	92	100	97				


4° S
6° S
8° S
10° S
12° S
174° E
176° E
178° E
180°
178° W
Nanumea
Nanumanga
Niutao
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Niulakita
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m

Nukulaelae


Nukulaelae Atoll


North
Approximate scale – 250m
Vaipulaka ite Fakai
Vaipulaka a Uputaua
Vaipulaka i mataafale
Vaipulaka a Toe
Motutala Islet

ANALYSIS AND DISCUSSION

Whilst every attempt has been made to analyse and interpret the data so far gathered, it is very important to understand that this study represents a “snapshot” only and does not incorporate temporal variability, i.e. change over time related to tidal, seasonal or climatic factors, all of which are known to influence groundwater lens dynamics in atoll environments. However, the dataset does incorporate excellent spatial variability, that is, it covers both inter-island and within island relationships. It cannot be over emphasised how important it will be to continue monitoring along similar lines to the system established here and that ultimately with the incorporation of temporal variability (continued monitoring), this data set will become invaluable in terms of understanding and managing the swamp taro pit salinity issue in Tuvalu.

1. Development of tolerance guideline

A well-defined guideline indicating the salt tolerance range of swamp taro in Tuvalu or the Central Pacific atolls could not be found, however Mourits (1996) study indicated that conductivity of approximately 3 300 to 5 000 µS cm^{-1} resulted in swamp taro crop failure and pit abandonment in Kiribati. This study also found that where conductivity was above 3 000 µS cm^{-1} swamp taro was either in poor health or such pits had been abandoned. Continued monitoring will improve accuracy and understanding of tolerance ranges but based on this and past works the following guide is provisionally proposed (Table 3).

Table 3. Salinity tolerance range of swamp taro (Cyrtosperma chamissonis) in Tuvalu (Central Pacific Atolls).

R e µS c	E pecte Re t
≤ 1000	Ideal growing conditions
≤ 2000	Tolerable growing conditions
≥ 3000	Crop decline and failure

Whilst the provision and continued development of guidelines are important for ongoing monitoring and management, it must be understood that swamp taro is expected to have a complex response to stress. It is likely that both intensity and duration of any particular salinity event will be important; i.e. a plant may tolerate very short-term “pulses” of high salinity (above 3 000 µS cm^{-1}) so long as conditions rapidly return to acceptable salinity concentrations. Alternatively, plants may suffer and become unproductive if conductivity values remain at the upper limits thought to be acceptable (approximately 3 000 µS cm^{-1}) for long periods. It is also likely that other environmental conditions such as weather, soil conditions, shading, planting depth, etc. may also interact to reduce or enhance a crop’s ability to endure adverse groundwater conditions.

Basic guidelines such as those being suggested here are not very useful when considering these differences and also do not take into account natural variability within particular populations of swamp taro, i.e. swamp taro in some locations or islands may be more salt tolerant than others.

Only long-term monitoring will assist our understanding of such complexities and again it is stressed that the Tuvalu Government should seek to continue simple monitoring along the lines established here. In turn, SOPAC could be approached again to assist in documenting and analysing such additional data.

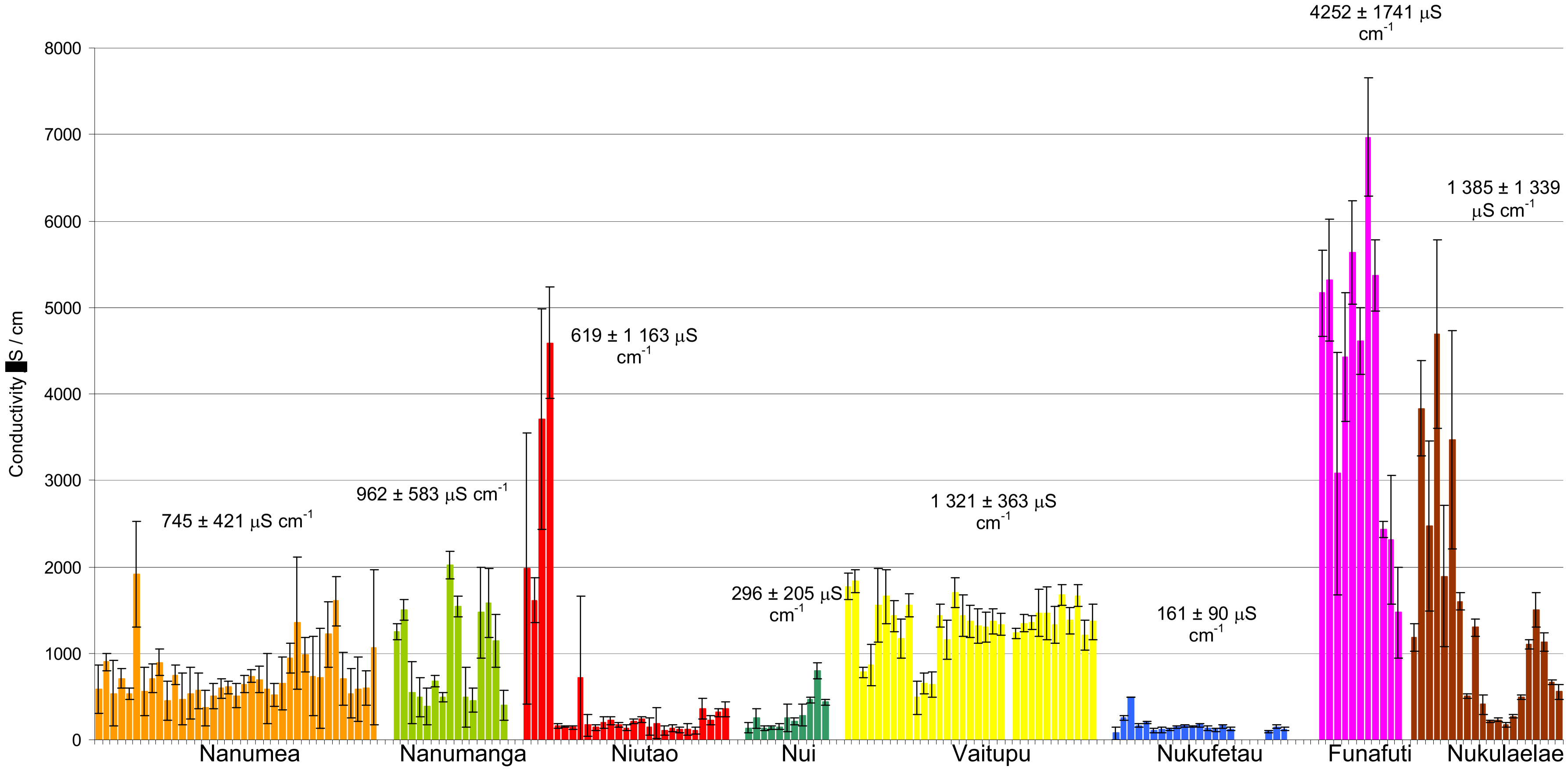


Figure 3. This histogram shows the comparative mean conductivity of each site sampled on each island (the mean value is derived from the triplicate samples taken at each sample point and the error bars indicate the standard deviation from the triplicate means). Additionally, the overall island mean and standard deviation value is shown above each island. A known cut-off conductivity value for swamp taro cultivation could not be found in existing literature but in light of Mourits (1996) work in Kiribati and analysis of the data collected here – it is suggested that values ≤ 1 000 µS cm^{-1} are ideal for swamp taro cultivation; ≤ 2 000 µS cm^{-1} are tolerable; and values consistently over 3 000 µS cm^{-1} result in crop failure. As can be seen, at the time of sampling certain areas on Niutao and Nukulaelae showed high conductivity readings and these corresponded to poor swamp taro health. Otherwise, Funafuti (Fongafale) was consistently higher in comparison to the other islands. Note the northern Fongafale pit of Fakaifou (last 3 bars) was mostly below 3 000 µS cm^{-1} and these values corresponded to the healthiest pit on Fongafale. It is also interesting to note Mr Lausaveve's earlier comments regarding groundwater on the islands of Nanumea, Nui and Nukufetau (he indicated that it was generally thought that these 3 islands had the best groundwater in the country). Note that this information corresponds to the lowest mean island conductivity readings taken during this survey with the exception of Niutao. Whilst Niutao's mean value was low the very large degree of variability (1 163 µS cm^{-1}) suggests groundwater is spatially less reliable than Nanumea, Nui and Nukufetau.

2. Inter-island and Within-island Conductivity Values and Variability

Figure 3 shows that only Funafuti (*Fongafale*) has an overall island mean conductivity value greater than 3 000 µS cm^{-1} (4 252 ± 1 741 µS cm^{-1}) and this is reflected in the generally poor quality and performance of crops in *Fongafale's* pits. Otherwise, Vaitupu and Nukulaelae had mean values above 1 000 µS cm^{-1} (1 321 and 1 385 µS cm^{-1}, respectively).

In the case of Vaitupu some pits are thought to have become more saline following engineering works on the western shore of Vaitupu Lagoon (see earlier comments from Mr Lausaveve – Director of Agriculture, 2005). This does not however correspond well with the findings of this study, which found that the area of the *Vailaupuapua* pits (western shore of the lagoon) had the lowest conductivity on the island (592 ± 152 µS cm^{-1}) and that the highest conductivity readings were at *Matagi* on the eastern side of the lagoon (1 804 ± 129 µS cm^{-1}).

Nukulaelae's higher mean conductivity value resulted from a single pit area *Vaipulaka i Mataafale*. Otherwise, the remaining pits on Nukulaelae had acceptably low mean salinity values (between 444 ± 378 and 908 ± 384 µS cm^{-1}) with generally healthy swamp taro. During the survey, landowners commented that the *Vaipulaka i Mataafale* pits are closer to the lagoon shore and are known to be more susceptible to saline incursion than others on the island. Furthermore, elders from Nukulaelae indicate that in living memory mangroves grew in the southern *Vaipulaka i Mataafale* pits (S. Manoa, pers comm. 2006). This suggests that this area has only recently been isolated from the lagoon (presumably by an accreting shoreline) and it is therefore not surprising that it remains susceptible to saline incursion.

The *Tepela* pit area on the island of Niutao also recorded a number of conductivity values considered too high for successful swamp taro cultivation (2 973 ± 1 570 µS cm^{-1}) and again, the issue of high salinity in some areas of Niutao has previously been highlighted by Mr Lausaveve (Director of Agriculture, 2005). The Director commented that Niutao has experienced problems of salinity in the *Tepela* pit area following the 1996 causeway engineering in Niutao's interior lake. It is possible that these works did disturb natural hydrological processes on this island which in turn resulted in more persistent salinity incursion in some areas, however more comprehensive study is needed to confirm these assumptions. Like Nukulaelae, high salinity was isolated to one area in Niutao and all the remaining pits sampled showed low mean conductivity values between 113 ± 42 and 300 ± 80 µS cm^{-1} with generally healthy swamp taro where planted.

Otherwise, at the time of sampling, mean conductivity values on all islands except Funafuti were consistently below 1 500 µS cm^{-1} and with the exception of those isolated locations on both Niutao and Nukulaelae, all sites sampled were adequate (in terms of groundwater conductivity / salinity) for swamp taro cultivation (Table 4).

The localised nature of the salinity issue in Niutao and Nukulaelae is reflected in analysis of the variability in conductivity conditions within and between islands (Figure 4), note the unusually high variability in Nukulaelae and especially Niutao (%CV 97 and 188, respectively). Put another way, if the *Tepela* pit is ignored on Niutao this island would otherwise have a very low mean conductivity value (210 ± 215 µS cm^{-1}) and likewise if the *Vaipulaka i Mataafale* area is ignored on Nukulaelae it too would also have a comparatively low mean conductivity of 726 ± 493 µS cm^{-1}, suggesting these are localised problems not island wide.

*Table 4. Table showing the overall mean conductivity values derived from each island ± the standard deviation (the range of the readings). Last the variability is shown as %CV (% coefficient of variation [Mean /SD)*100] – see also Figure 3).*

	e S µS c -	C
Nanumea	745 ± 421	57
Nanumanga	962 ± 583	61
Niutao	619 ± 1 163	188
Nui	296 ± 205	69
Vaitupu	1 321 ± 363	27
Nukufetau	161 ± 90	56
Funafuti	4 252 ± 1 741	41
Nukulaelae	1 385 ± 1 339	97

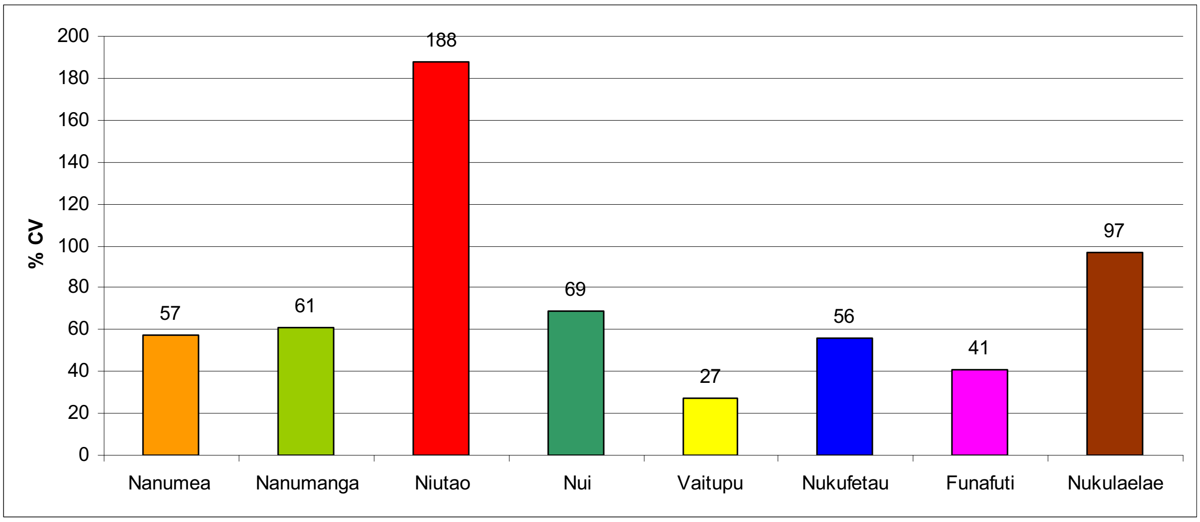


Figure 4. This analysis of variability between and within each island is useful to show that sampling results across the islands showed reasonably similar variability. In a more general sense, this is an indication that nothing unusual with respect to conductivity was occurring on any one island at the time of sampling. The obvious exception was Niutao, Nukulaelae (and possibly Vaitupu). These departures from the "normal" range suggest that the sampling picked up an unusual pattern in conductivity values on these islands. On Niutao, it seems that the single Tepela pit is unusually different from other areas and on Nukulaelae the Vaipulaka i Mataafale area. On Vaitupu there is generally lower variability or better correspondence between all the samples and this may be a reflection of this island's larger land mass (the largest in the country).

It is interesting to note that Funafuti (*Fongafale*) despite having a high mean conductivity value, showed similar consistency between all of the sample points (%CV 41). This indicates that groundwater conditions throughout *Fongafale* are uniformly poor and too saline for swamp taro cultivation and that this was not an isolated problem in one area alone. This finding corresponds well with a previous study by Falkland (1999) who found consistently poor groundwater conditions throughout *Fongafale* and provided evidence of the strong hydraulic connectivity between the ocean and the brackish groundwater lens in *Fongafale*.

Despite the evidence that *Fongafale* has uniformly poor groundwater and that this has been the case for some years, there is photographic evidence that swamp taro did grow successfully some 60 years earlier (see Figure 5). This suggests that swamp taro growing conditions on *Fongafale* have changed in the interim 65 years (since the early 1940's).

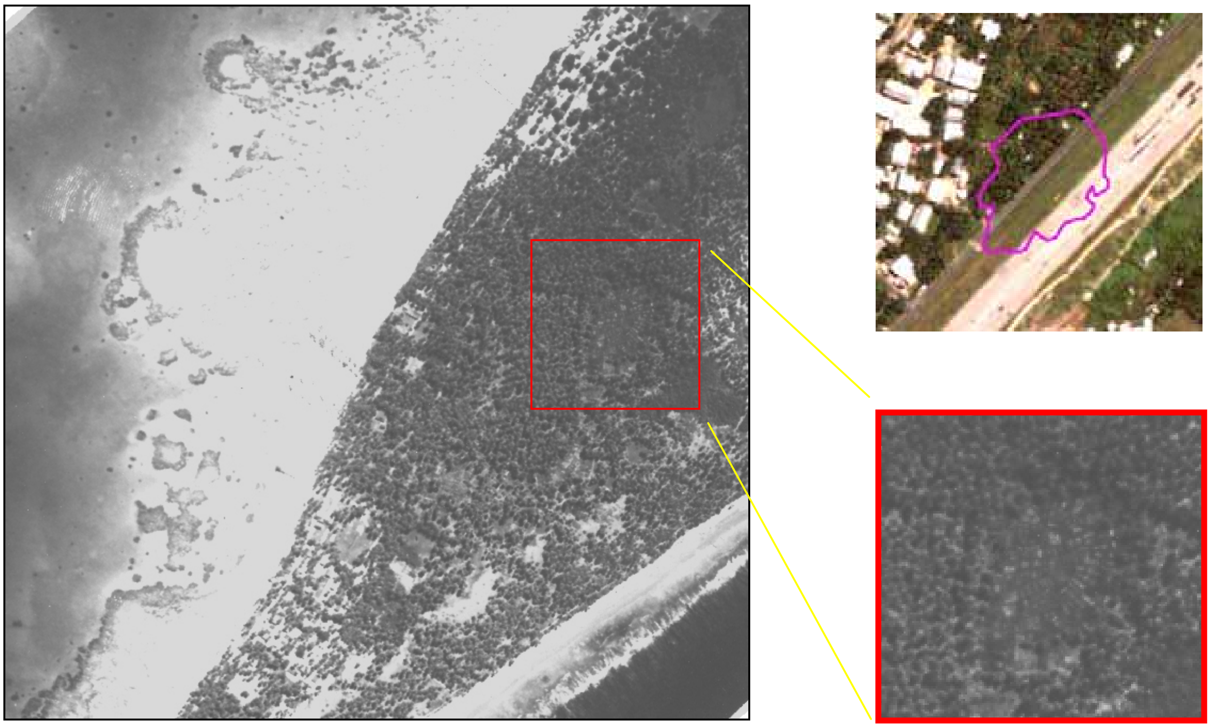


Figure 5. This 1941 aerial photograph of Fongafale Islet, Funafuti, shows the environment in a comparatively pristine condition before the US military build-up during 1942-1943 (see Figure 6). Note most of the islet is coconut woodland with small villages on the lagoon shore. The magnified highlighted area shows what appears to be the main swamp taro pit (approximately 75 m x 100 m and covering an area of about 5 800 m^2), which was divided into numerous plots and presumably supplied this former subsistence community with its taro needs (image taken from Webb, 2006). The top right hand colour picture shows the comparative current land use of the former pit.

Whilst comprehensive investigation has not been carried out, it would seem that increased salinity of some localised pit areas may be linked to hydrological changes brought about by earthworks and engineering (e.g. findings on Niutao Island and the Mourits [1996] study in Kiribati). It follows that if comparatively small engineering projects are possibly correlated to changed hydrology, then the comprehensive “landforming” which occurred on *Fongafale* in 1943 would, in all probability, have caused devastating hydrological changes.

There can be no doubts on the massive engineering changes wrought on the *Fongafale* environment by the US Corps of Engineers during 1942-1943 as part of the WWII Pacific Campaign (see comparative figures 5 and 6). The legacy of coastal instability, vast open borrow pits which line the island and the runway which covers a large portion of *Fongafale* are all testament to these unimaginably large changes on this small and extremely fragile atoll environment (McQuarrie 1994; Webb, 2006).

Figure 6. This 1943 aerial photograph shows the same area of Fongafale Islet as Figure 5 and the location of the former swamp taro pit visible in 1941 (purple line). By 1943 approximately 70% of the pit has been filled to allow the completion of the runway. Note also the large clearing and earthworks, north of the pit area and on the southeastern side of the runway. The exact volumes of material shifted, excavated and levelled is unknown however Gibb Australia (1985) estimated over half a million cubic meters of material was required just to fill the borrow pits left by these efforts. Considering Fongafale's meagre land area of 1.43 km^2 (the runway alone accounts for approximately 14% of this surface area) the changes wrought on this landscape cannot be ignored as a likely contributing factor to hydrological change.

It also must be understood that since 1943, environmental pressures on *Fongafale* have increased in the form of ongoing development and population expansion. As the site of the nation's capital, *Fongafale's* population density (approximately 3 150 km^{-2} – 2002 census) is over triple the national average; and infrastructure and other engineering and development pressures are far greater here, than on any other island in the group. To put this in context, estimation of Funafuti's early 1900 population was a mere 275 individuals (David, 1913). David (1913) also made direct mention of the former *Fongafale* pits and alludes to their conscientious management, indicating the former subsistence population regularly migrated between *Fongafale* and *Funafara* (a smaller islet on the southern rim of Funafuti atoll) and that this change of location provided, "*a distinct change of work, and the taro gardens on the main island (Fongafale) get a much-needed rest*".

In terms of population pressures, development, coastal engineering, etc. *Fongafale* represents the most disturbed environment in the country and in essence, these current management issues combined with the massive changes wrought on this environment by the US military in 1943, are all likely contributing causes of the perturbation to any former fresh groundwater lens.

Best estimates indicate that relative sea level has risen at Funafuti by approximately 10 cm over the last 50 years (Church *et al.* 2006), a period which approximately corresponds to the interim period from 1941 to the present. It is not known to what extent such a rise may contribute to changes in the salinity of Central Pacific atoll groundwater lenses. However, as a general observation, if changing sea level was the only contributing factor causing *Fongafale's* increased groundwater salinity issue; then at least some of the other islands in the group may be expected to have similarly uniform, high conductivity readings. At the time of this study there was no evidence to support this.

A further point of interest related more to the outer islands of Tuvalu, were observations of current cultivation practices and activity in swamp taro pits. The cultivation of swamp taro is a hugely laborious and time-consuming task and soil quality and nutritional conditions are only maintained if continual effort is expended carrying out traditional composting and cultivation techniques. A number of observations regarding pit use in various areas suggest that some pits were no longer intensively cultivated despite having acceptable conductivity ranges. Importantly, we need to understand that declining swamp taro production may also be related to life style changes (i.e. declining interest in swamp taro cultivation) and that production may also be negatively impacted by a reduction in cultivation effort; i.e. the improved soil conditions within swamp taro pits are to some degree dependent on continual cultivation efforts (composting) and it would follow that any long-term reduction in such effort will likely have a corresponding negative impact on overall soil fertility and production potential.

Figure 7. This large pit in Vaitupu is a good example of how habits of swamp taro cultivation are changing. Whilst certainly not representative of all pits, this photo does however make the point that some pits are adequate in terms of water quality but are no longer intensively cultivated (note dense weed infestation and the lack of evidence of traditional composting techniques, etc.).

CONCLUSIONS AND RECOMMENDATION

Only Funafuti (*Fongafale*) recorded an overall trend of high conductivity readings which were considered well above the optimum range for successful swamp taro cultivation. Two other isolated pits areas on Nukulaelae and Niutao (*Vaipulaka i Mataafale* and *Tepela*, respectively) also recorded salinity ranges thought to be too high for swamp taro cultivation. On Nukulaelae this pit area is locally known to have a history of saline contamination and on Niutao anecdotal evidence suggests engineering may have contributed to this salinity issue.

Otherwise, at the time of this study all other sample locations on Nukulaelae and Niutao and all other locations sampled throughout the islands of Tuvalu, had average groundwater salinity conditions which were acceptable and low enough, to allow successful swamp taro cultivation.

It is not known to what extent (if any) change in sea level may contribute to the significantly different and higher conductivity readings on Funafuti (*Fongafale*). In a more general sense, it would seem reasonable to expect that an overall failure of an atoll's groundwater lens in response to recent sea-level change would manifest as a more uniform sub-regional / regional phenomena. It is difficult in view of the results gained here to therefore link *Fongafale's* groundwater salinity issue to sea-level change alone. Rather, it is most likely that the groundwater salinity issue on *Fongafale* is not wholly related to any one particular factor but rather a range of possible causes, which act in synergy. These include natural hydrological features of the island; past engineering and land forming changes; and more recently ongoing population and development pressures. On the outer islands the issue of declining interest in swamp taro cultivation also deserves greater investigation.

Some enlightening information emerges from the analysis of the current dataset and in many ways these conclusions appear to correspond to anecdotal, historical and other scientific data. However, such conclusions will only become more reliable as additional data is collected. To this end it is again stressed and highly recommended that ongoing monitoring be established if the Government of Tuvalu wishes to continue to improve understanding of this issue.

REFERENCES

Barr, J.J.F. 1992. Coconut improvement in Kiribati. Ministry of Environment and Natural Resources Development. Tarawa, Kiribati.

Church J.A., White N.J., Hunter J.R. 2006. Sea-level Rise at tropical Pacific and Indian Ocean islands. Global and Planetary Change, 53, 155-168.

David, E. 1913. Funafuti, or three months on a coral island: An unscientific account of a scientific expedition. Sir Isaac Pitman & Sons, Ltd. London.

Falkland, T. 1999. Water management for Funafuti, Tuvalu. Australian Agency for International Development.

Gibb Australia. 1985. Tuvalu lagoon bed resources survey. Australian Development Assistance Bureau.

Lausaveve, I. 2005. Director of Agriculture, Government of Tuvalu – personal communications during an interview in 2005.

Manoa, S. 2006. Personal communications and observations – Tuvaluan national and former Nukulaelae resident, now working within the SOPAC Secretariat.

McQuarrie, P. 1994. Strategic atolls – Tuvalu and the second world war. Institute of Pacific Studies, University of the South Pacific.

Mourits, L. 1996. An assessment of saltwater intrusion in babai pits and some water supply projects on Makin, Butaritari and Abaiang, Republic of Kiribati. SOPAC Technical Report 229. SOPAC Secretariat, Suva, Fiji.

Nyman, L.P., Gozales, C.J., Arditti, J. 1983. In-vitro selection for salt tolerance of taro (*Colocasia esculenta var antiquorum*). Annals of Botany. 51, 229-236.

Onwueme, I. 1999. Taro cultivation in Asia & the Pacific. FAO. Bangkok, Thailand.

Smith, W.H.F., Sandwell D.T. 1997. Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, 1957-1962.

Tausi, L. 2006. Personal communications and observations undertaken during field survey. SOPAC EDF8 Tuvalu Reducing Vulnerability Project Intern.

WCRP. 2006. Understanding sealevel rise & variability workshop summary statement. Intergovernmental Oceanographic Commission, UNESCO. Paris, France.

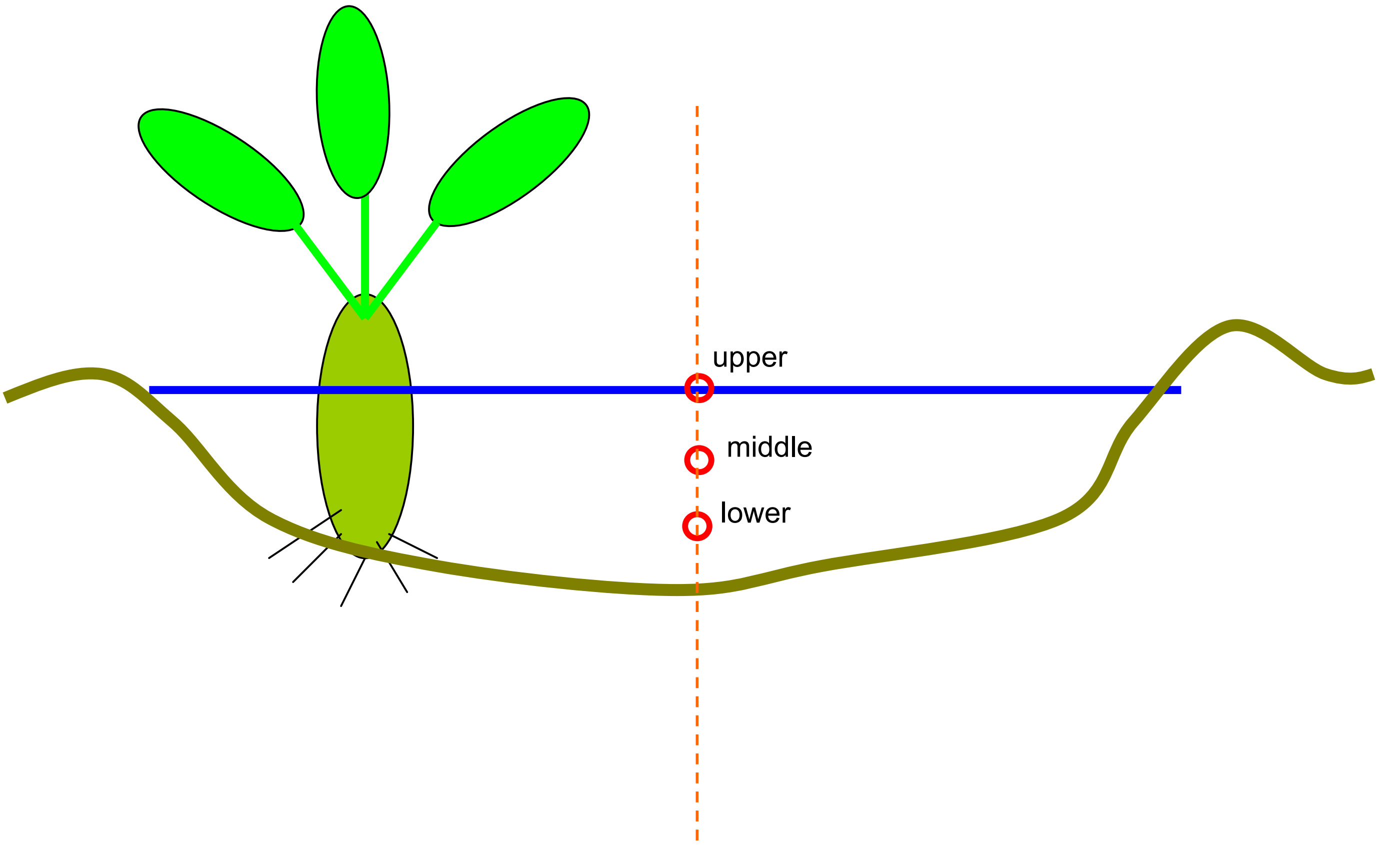
Webb, A.P. 2006. Coastal change analysis using multi-temporal image comparisons – Funafuti Atoll, Tuvalu. EU-SOPAC Project Report 54. SOPAC Secretariat, Suva, Fiji.

Webb, A.P. 1994. Tree and perennial crop introduction and extension in Kiribati, 1991-1994. Ministry of Environment and Natural Resources Development. Tarawa, Kiribati.

White, I., Falkland, T., Metutera, T., Metai, E., Perez, P., Dray, A., Overmars, M. 2006. Society-water cycle interactions in the Central Pacific: Impediments to meeting the UN millennium goals for freshwater. 1st International symposium on water and better human life in the future. Kyoto.

ATTACHMENT 1

In country sampling instructions



When sampling conductivity the following things are very important;

- Sample as many pits as possible.
- Do not select only poor pits for sampling or pits which people tell you are a problem.
- You should sample these pits, but it is just as important to sample "healthy" pits as well – try to do any and all the pits you can get to.
- Record the time, date and location every time you start on a new pit.
- Sample from the centre of the pit where it is deepest (see picture above).
    - When you are getting close to the sample point walk very slowly so as not to disturb and mix the water and mud.
- Take 3 readings – surface, middle, bottom (see picture above);
    - 1. Lower the probe (conductivity) to the bottom first wait a few seconds and take a reading.
    - 2. Pull it up half way, wait a few seconds, take another reading.
    - 3. Last take a reading from just below the surface.
- If the pit is very large (bigger than a house) take a couple of readings spaced evenly along the length of the pit.
- Take additional notes;
    - Is the pit in use – does it look like people plant and harvest regularly.
    - Is the pit full of weeds or other plants e.g. banana.
    - How is the health of the taro Good – average – poor.
    - What was the weather at the time of sampling.
    - What is the time and date of sampling.
    - Mark the location of the pit on your maps (you could use a numbering system so you can link the data with the pit easily).
    - Record any comments from local guides or farmers about the pit.