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– ARTICLE –

Experimental Kūmara Gardens at Whatarangi, Palliser Bay and Robin Hood Bay, Marlborough, New Zealand: Results after 23 years

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ABSTRACT

Two experimental gardens of kūmara (*Ipomoea batatas*), one on each side of Cook Strait, New Zealand, were planted and harvested without fertiliser for a period of 14 and 23 years respectively. The mean annual yield for the garden on the north side of Cook Strait was 10.2 tonne/ha and 7.5 tonne/ha for the southern garden. More than 90% of tubers harvested weighed less than 100 g. Yields fluctuated considerably, but did not decline over time. We monitored rainfall, sunshine hours, air and soil temperatures, and several soil chemical characteristics. Some correlations with yield were found, but do not account for the high degree of variation in annual yield. Between plant variation in yield was a similar order of magnitude as annual variation. Attention to individual plants during the growing season may contribute to yield variation. No correlation was found between seed size and individual plant yield. Several soil nutrients declined significantly over time. Conversely, phosphorus consistently rises over time in both gardens, starting about 10mg/L and rising to *c.*50 mg/L after 12 years. This is attributed to vesicular-arbuscular mycorrhizae (VAM) around the root system of kūmara. A minor sub-project with taro, *Colocasia esculenta*, shows success on both sides of Cook Strait. Results from the research were modelled to estimate pre-European population size in Palliser Bay.

Keywords: experimental archaeology, kūmara, population estimates

INTRODUCTION

This long term research project began 9 September 1999 when we established the first of two experimental kūmara gardens, one on either side of Cook Strait. The first was at Robin Hood Bay on the east coast of the South Island near Blenheim, and the second at Whatarangi in Palliser Bay in the North Island. Both were in close vicinity of gardens outlined by stone rows associated with pre-European Māori kūmara gardens. The project was under the joint auspices of the Museum of New Zealand Te Papa Tongarewa and the Open Polytechnic of New Zealand.

Work on the Robin Hood Bay garden terminated after the 2014 harvest, partly because of limitation of funds to continue crossing Cook Strait five times a year. We also suspect that the accidental use of herbicide by a person in the area may have affected the growth of the plants and the consequent 2014 yield.

The Palliser Bay experiment continues to this day, 23 years so far. This project began with several objectives, and results have already been reported in four publications (Harris *et al.*, 2000, Burtenshaw *et al.*, 2003, Burtenshaw and Harris, 2007, and Davidson *et al.*, 2007). All details regarding the method of planting, cultivation and harvesting are provided in these publications. In brief, four different cultivars were initially tested for suitability for long term study: *taputini*, *hutihut*i and *rekamaoroa*, and the former was chosen for detailed attention. Tubers were planted in small mounds in a quincunx pattern. The ground was not cultivated between harvests, and each mound was formed from surface soil. Another researcher has recently contributed significant new information about kūmara horticulture in New Zealand (Gumbley, 2003, 2021), although this was in an area more favourable for kūmara than Palliser Bay.

The main remaining objective, so far unrealised, is to find the point at which soil exhaustion would make the continued planting and harvesting of this plant sufficiently unrewarding so that the land would need to be placed in fallow for eventual rejuvenation. This has an important bearing on the human carrying capacity of these narrow coastal strips along the east coast of the North Island. On this issue Helen Leach devised a simple, but useful, algorithm for estimating pre-European population size in Palliser Bay based on the kūmara gardening activities of these coastal communities (H. Leach, 1976:Appendix 4).

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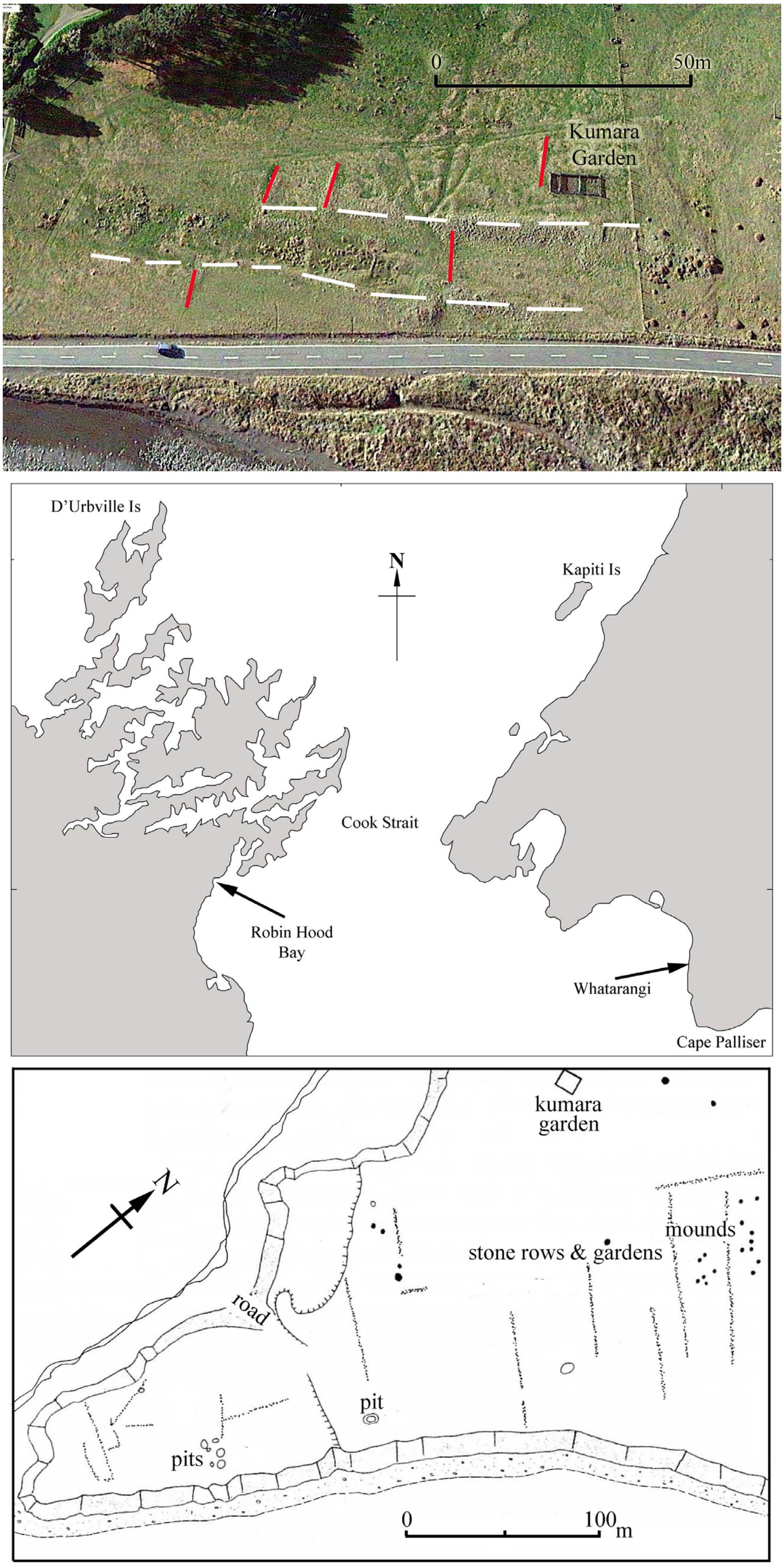

Figure 1. The two experimental kūmara gardens. Upper: Whatarangi (From Google Earth. White dashed lines are modified beach ridges. Black lines are stone rows added by pre-European Māori). Lower: Robin Hood Bay (adapted from Brailsford, 1981).

One limiting factor is the total area able to be gardened by any one community on a sustained basis (variable C in Appendix 1: the cropping period). Although not explored in this paper, pre-European Māori in this region would find it very difficult to survive on kūmara alone as the macronutrient ratio (MNR) of kūmara 8: 2: 90 is very low in both protein and fat. Finding a satisfactory balance of nutrients in this region is discussed elsewhere (Leach and Davidson, n.d., Leach *et al.*, n.d.).

As often happens with research projects, objectives defined at the outset, have a habit of generating secondary questions, and this project is no exception. Consequently, the main outstanding issue – variable C: the number of years one patch of garden could continue to be used profitably – has assumed less importance than first thought. The reason for this, as will be seen below, is that we have found little evidence over a 23 year period of sustained decline in yield per annum. In addition, we have found far greater annual variation in crop yield than expected, and this has generated new questions that demand attention.

YIELD OF KŪMARA FROM THE TWO GARDENS

The Robin Hood garden produced 14 annual harvests and the Whatarangi garden 23. The annual yield, scaled up to tonnes per hectare, for each year is provided in Table 1.

The annual kūmara yields are also plotted in Figure 2. This shows considerable variation from one year to the next. The Coefficient of variation is 35.0% for Whatarangi, and 61.5% for Robin Hood Bay. This reveals a degree of unreliability that would be potentially devastating for communities relying on kūmara crops for subsistence. It is notable that the crop failed once in 14 years at Robin Hood Bay (2005), when only four plants produced tubers; and there was a very low yield at Whatarangi in 2015. In addition, in some years many plants died without yield, while others produced more than normal. For example, of the 2003 Whatarangi crop only 20 plants survived, but the remainder produced 18.5 kg of tubers, equivalent to 7.41 tonne/ha (see Figure 2). Possible reasons for such high variation will be further examined later. It will be noticed

Table 1. *The kūmara yields for the two experimental gardens. Thirty–eight plants were planted in each 5 × 5 m plot, and as can be seen, some plants died each year. The total mass of tubers per annum is provided and scaled up to tones per hectare.*

	Whatarangi			**Robin Hood Bay**		
Year	**NPlants**	**Mass**	**Tonne/Ha**	**NPlants**	**Mass**	**Tonne/Ha**
2001	31	25731	10.29	38	19140	7.66
2002	36	23251	9.30	38	38832	15.53
2003	20	18525	7.41	38	16450	6.58
2004	30	51816	20.73	34	32359	12.94
2005	32	17207	6.88	4	6771	2.71
2006	38	30730	12.29	38	13841	5.54
2007	38	14476	5.79	37	19433	7.77
2008	36	26047	10.42	38	19339	7.74
2009	36	24799	9.92	38	21718	8.69
2010	37	19886	7.95	38	9808	3.92
2011	38	21188	8.48	38	40898	16.36
2012	38	27905	11.16	38	13063	5.23
2013	38	26580	10.63	33	10291	4.12
2014	38	27279	10.91	33	1432	0.57
2015	35	7831	3.13	–	–	–
2016	38	14314	5.73	–	–	–
2017	33	32821	13.13	–	–	–
2018	36	54454	21.78	–	–	–
2019	38	26389	10.56	–	–	–
2020	37	24694	9.88	–	–	–
2021	38	18558	7.42	–	–	–
2022	38	39172	15.67	–	–	–
2023	38	32294	12.92	–	–	–
Totals	–	**605,947**	–	–	**263,375**	–
Means	–	–	**10.15**	–	–	**7.53**
SE	–	–	**0.95**	–	–	**1.24**
SD	–	–	**3.55**	–	–	**4.63**

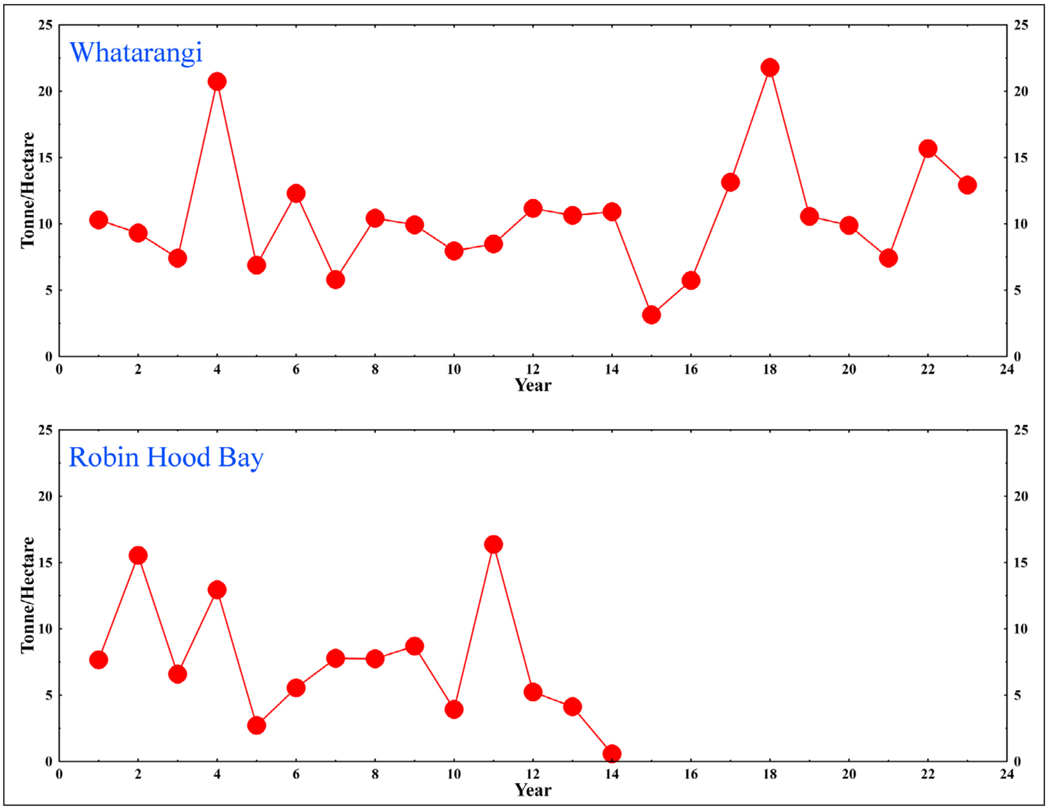

Figure 2. The annual kūmara yields from the two gardens, expressed as tonnes per hectare.

in Table 1 that the number of plants surviving for harvest each year was not always 38. During analysis of data we occasionally examined the correlation of environmental variables using an 'adjusted' annual yield scaled by the number of plants lost. Thus, in 2003 only 20 plants of the original 38 survived. So the adjusted yield = 7.41 × 38/20 = 14.08 tonne/ha. Unless otherwise stated in what follows, 'yield' = the non-adjusted yield as given in Table 1.

From the graph in Figure 2, it is tempting to think that there are signs of decreasing yield over time at Robin Hood Bay; however, the degree of annual variation makes this very unlikely. To check, the correlation coefficient was calculated, which was −0.38 ± 0.23. This is barely above zero, and is not significant p = 0.5. The yield at Whatarangi also shows no sign of significant trend over time (r = +0.15 ± 0.20, not significant p = 0.5).

The lack of decline in yield over time at these two garden plots is a highly significant result, casting considerable doubt on whether serial cropping and fallow were necessary in these poor sandy coastal soils. This issue is returned to later.

The mean yield at the two gardens over the periods of this experiment was 10.15 and 7.53 tonne/ha (same as Mg h^{-1}). Helen Leach has reviewed published literature on kūmara yields in various countries and documents a wide range from 5 to 50 t/ha, with a mean of 17.9 overall (Leach, H. 1976: 154). She suggests that a best estimate for prehistoric New Zealand kūmara cultivation of 10 t/ha (Leach, H. 1976: 181), and a fallow period of 14 years (*ibid.*: 179). The mean yield we have obtained at Whatarangi is precisely as she suggests, with Robin Hood Bay slightly lower.

However, the large annual fluctuations from one year to another require explanation. Crop failure and great hardship are documented by Colenso and others in the early 1840s among southern North Island Māori communities (Leach *et al.*, 2023: (#89, #102, #104 Appendix 2). Since a rigid procedure was followed in these two experimental gardens, fluctuations in yield must have a cause or causes. One factor might be changes in climate from one year to another. This is carefully considered below. Another factor relating to yield might be soil nutrients. Our expectation was that the yield would consistently fall over the years as nutrients were depleted, until fallowing was necessary. With this in mind we carried out soil nutrient analysis for the first 14 years from 2000 to 2014 (see Appendix 2).

Basic Statistical Data from the Two Gardens

Each garden was planted close to mid October each year and harvested close to mid May the following year. The actual dates varied by a few days, depending on circumstances, such as weather conditions. Thus, the growing seasons averaged *c.* 180 days. The Robin Hood Bay garden was maintained for 13 years from 2000 to 2014, and the garden at Whatarangi for 23 years from 2001 to 2023, making a total of 38 harvests. For the first 33 harvests, each tuber from each mound was weighed to 1 g precision, and records kept as to which of the 38 mounds they belonged to. The largest tuber recovered weighed 796 g, and was from the Whatarangi garden (mound 4 during the 2003 harvest). Analysis of tuber weights from these 33 crops gave some interesting insights into results of gardening kūmara in these southern latitudes. Basic details are provided in Table 2 and Figure 3.

Table 2 shows that close to a tonne of kūmara was harvested from the two 5 × 5 m experimental gardens during the period of research. Many of the tubers were quite small compared with modern kūmara grown in New Zealand. About 11% of all tubers weighed less than 10 g. For this reason the size frequency histogram is presented with a log Y axis. In the lower part of Figure 3 the cumulative weight diagram is given. This dramatically illustrates the preponderance of small tubers. Although a few tubers grew to over 400 g and one close to 800 g, the bulk are small by modern commercial standards. More than 90% of all tubers weighed less than 100 g (See Figure 4).

Table 2. *Analysis of Tuber Weights from both gardens combined over 33 harvests. Tubers from the final five harvests were not weighed individually.*

Tuber	<10 g	≥10 g	Total g
Numbers	2,052	16,560	18,612
Weights g	8,133	750,094	758,227
Last 5 harvests	–	–	141,861
Totals	**10,185**	**766,654**	**918,700**

WHAT FACTORS MIGHT CAUSE ANNUAL FLUCTUATIONS IN YIELD?

Several possible factors can be suggested, each deserving separate attention. N = number of days during the period between planting and harvest.

1. variation from one crop to another in total rainfall during N Days
2. number of days with no rain (drought) during N Days
3. number of days with rain during N Days
4. mean air temperature during N Days
5. mean soil temperature at 15 cm during N Days

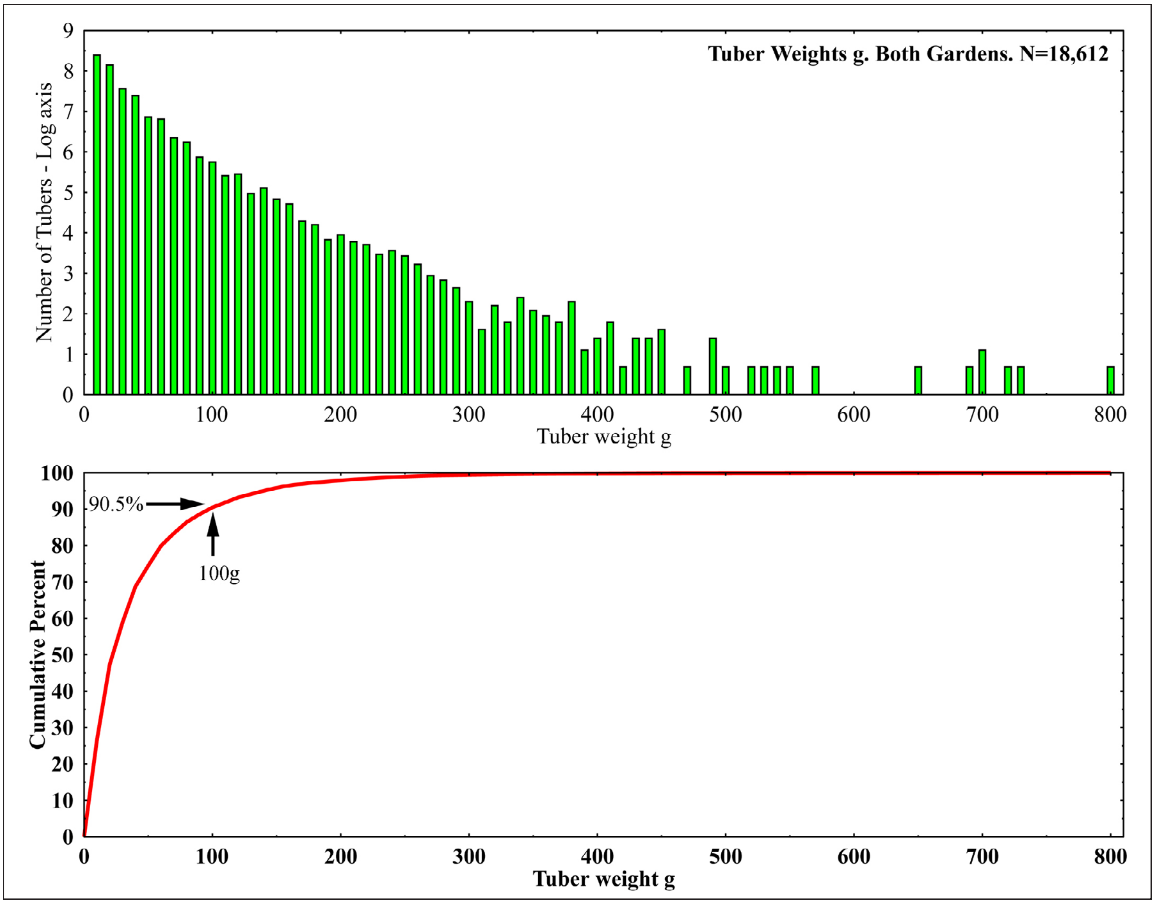

Figure 3. Upper is a histogram of individual tuber weights for the first 33 harvests. Lower shows the cumulative weight-percent of tubers.

An ancillary variable to both 4 and 5 is the number of days spent below 10°C[3]. Thus:

6. number of hours/days when air temperature falls below 10°C
7. number of hours/days when soil temperature falls below 10°C
8. number of hours of sunshine during N Days
9. annual changes in soil nutrients, such as reduced N, P, K values.
10. changes in yield from one plant to another, and the reason for this, *e.g.*: seed size

One possible factor not considered here is the effect that wind damage might cause on kūmara gardens. There are two ways this can happen; one is physical damage from wind, and the other is from increased rate of transpiration that follows sustained periods of wind. Palliser Bay is an exposed coastline where wind damage could be a problem in kūmara gardens. It would have been very difficult for pre-European Māori to protect large areas of garden from wind. Our experimental gardens were surrounded by fences, mainly to prevent damage by rabbits. They were therefore protected from wind, and in this respect are different to those in the pre-European era. A 19th century painting by Brees of the Palliser Bay coastal platform shows abundant low scrub (Leach and Leach, 1979: 228), and analysis of land snails in the archaeological sites provides a reconstruction of local flora that is consistent with this vegetation pattern (*ibid.*: 225 ff).

Figure 4. a typical kumera tuber weighing 100g. Match box for scale (55 mm width).

Influence of Rainfall on Crop Yield (factors 1–3)

Fortunately there is a climate station close to Whatarangi at Ngawi, with rainfall records. These were extracted from Cliflo, a national climate database run by NIWA. Daily rainfall records were collated for the periods of each garden from planting to harvest (15 October to 15 April the following year) for the years 2001 to 2023, and compared with the harvest yield for each crop. The results are provided in Figure 5.

Annual rainfall varied from 165 to 932 mm over the 23 year period, with a mean of 455 ± 44 mm, and a standard deviation of 209 mm. Figure 5 shows fairly stable rainfall until 2011, with substantial fluctuations thereafter (Figure 5, left graph). The right graph shows the annual rainfall

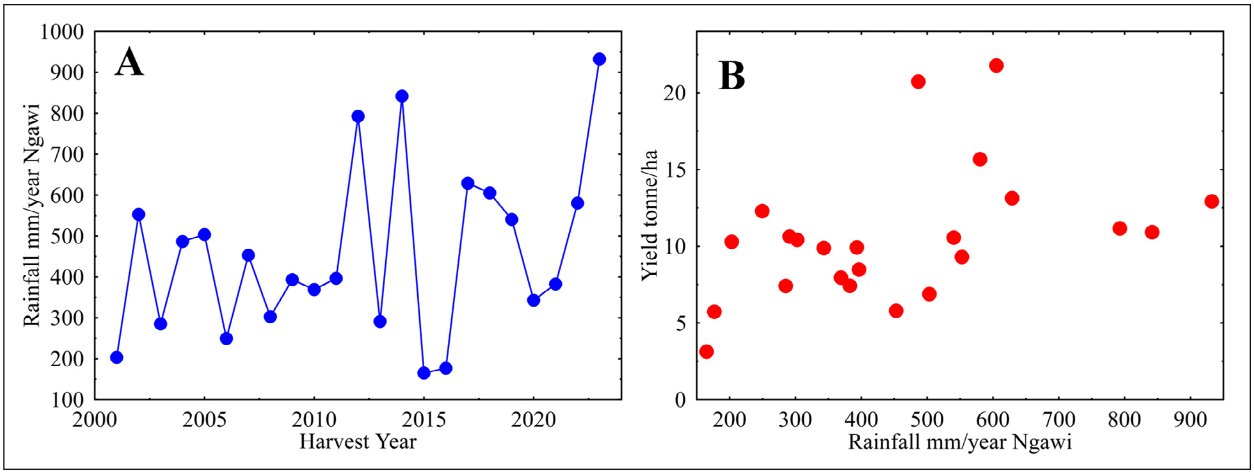

Figure 5. Annual rainfall mm at the Ngawi climate station compared with the kūmara yield.

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[3] It has been shown in previous research that kūmara tubers quickly die if their surrounding temperature falls below 10°C for any length of time (Yen 1974: 216–218; Davidson, *et al.*, 2007: Figure 15; Woolfe 1992: 222; Arinz and Smith, 1982, cited by Woolfe 1971).

values plotted against the yield of kūmara. As mentioned earlier, yields also fluctuate considerably. There does not appear to be a consistent relationship between harvest yield and rainfall (r = 0.43 ± 0.17, Student's T = 2.3, with 21 degrees of freedom). This is significant .05, but not significant .01). It is interesting that this small positive relationship between yield and rainfall contrasts with an experimental kaukau/kūmara garden project in Papua New Guinea, where the higher the rainfall the lower the yield (Hartemink, *et al.*, 2000: 259). The present analysis shows, if anything, that modest rainfall of 500–600 mm per annum gives the highest yields, although this is not strongly supported by statistics.

Influence of Air and Soil Temperature on Crop Yield (factors 4–7)

Data loggers were installed at the Whatarangi garden to collect information on both air and soil temperature (the latter at 15 cm depth). Measurements were recorded every 10 seconds, beginning 2005 and ending 2018. The integrated mean temperature (IMT) was obtained by summing all values for any one growing period and dividing by the number of measurements made. This measure is a suitable proxy for the total thermal energy provided to the plants. The results are provided in Table 3, and plotted in Figure 6. Air temperatures fell below freezing on three occasions, and once as low as −2.3°C. The lowest soil temperature was 4.2°C, and the maximum for both air and soil was 42.9°C.

Our working hypothesis was that crop yield would increase with environmental temperature, and while the largest annual yield (the 2017–18 crop in Table 3) is associated with the highest average temperature recorded, there is considerable variation between yield and temperature, as is seen in Figure 6C and 6D. The correlation coefficients between yield and these environmental variables are provided in Table 4. Even though correlation is confirmed by all pairs except one, the scatter of values is considerable and other factors must also be playing a part in determining annual yield.

Figure 6B shows a small sample of the fluctuations between air and soil temperatures over a period of seven days, highlighting the benefit of planting the seed tubers in a mound of soil. During each diurnal period of air temperature, the soil temperature also rises, but with a pronounced time lag. The soil temperature eventually rises well above the daily air maximum, and then falls much more slowly than air temperature. Heat retention in the soil is such that the soil temperature never falls below about half the minimum nightly air temperature. Although this phenomenon is well known (described as amplitude dampening and phase shifting (Hollmuller, 2003: 4303), it is instructive to see the process at work in this experimental kūmara garden.

The final two issues concerning the thermal environment of kūmara gardens are about the length of time that either air or soil temperature falls below 10°C (factors 6 and 7). The thermal monitors in the Whatarangi garden captured uninterrupted readings throughout 13 harvests from 2006 to 2018. The accumulated data was examined for any events where temperatures fell below 10°C, and for how long each of these events continued. For example, if the temperature fell below 10° for a period of 5 hours it would count as 1 event lasting 5 hours. The results are presented in Figure 7. For example, in Figure 7A it will be observed that the crop with the highest yield (21.8 tonne/ha in 2018) experienced a total of 169 hours when the air temperature was below this threshold. By contrast, in Figure 7B, relating to soil temperature, the crop harvested in 2009 with 9.9 tonne/ha experienced a total of 149 hours when soil temperature was below this threshold. The upper two graphs show very clearly the benefits of kūmara being planted in these sandy soils.

Figures 7C and D plot the contrasting thermal experi-

Table 3. *Integrated mean temperatures, and other thermal measures for 13 kūmara crops at Whatarangi (see text).*

Harvest Date	Air Mean	Air Minimax	Soil Mean	Soil Minimax	Air %<10°C	Soil %<10°C	Air Hours <10°C
10-4-2006	17.1	4.2 to 33.2	20.9	12.2 to 29.9	7.1%	0.0%	282.8
17-4-2007	14.3	0.3 to 30.3	18.5	9.0 to 31.7	21.5%	0.9%	991.3
16-4-2008	14.3	−2.4 to 32.3	19.6	6.6 to 31.1	24.0%	2.6%	1359.8
21-4-2009	14.2	−2.0 to 33.6	19.3	5.8 to 32.8	24.3%	2.0%	1380.5
13-4-2010	15.0	1.2 to 31.9	20.9	11.0 to 31.5	16.6%	0.0%	665.5
14-4-2011	15.6	2.5 to 31.5	21.4	9.8 to 33.2	16.9%	0.1%	717.7
15-4-2012	14.3	2.5 to 29.5	18.9	11.8 to 29.1	18.0%	0.0%	782.3
15-4-2013	15.3	1.2 to 33.2	21.3	10.2 to 33.2	18.1%	0.0%	776.2
9-4-2014	15.2	1.2 to 32.3	20.8	4.2 to 32.3	11.7%	0.2%	460.4
8-4-2015	15.8	2.5 to 31.2	21.4	10.6 to 31.2	14.8%	0.0%	602.7
7-4-2016	17.6	−0.6 to 32.0	21.7	9.8 to 32.0	12.8%	0.0%	516.8
26-4-2017	19.2	11.8 to 42.9	20.0	11.8 to 42.9	0.0%	0.0%	0.0
17-4-2018	21.4	5.4 to 42.4	22.8	13.9 to 32.7	4.1%	0.0%	169.0

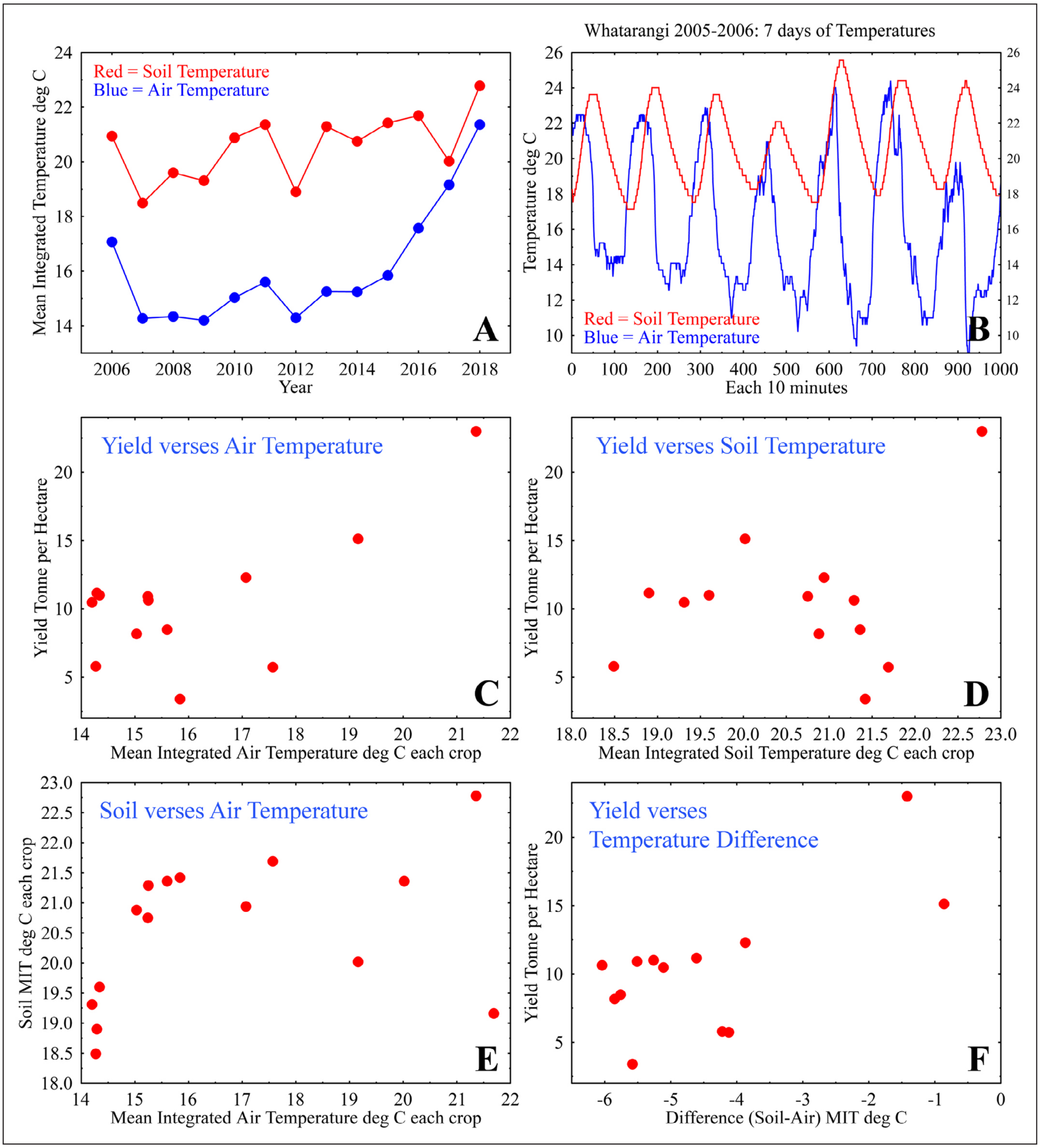

Figure 6. Scatterplot of kūmara yield against air and soil temperatures.

Table 4. *Correlation matrix between Yield and environmental variables.*

Variable Pair	r ± SE	Student's T	Deg Freedom	Significance
Yield and Air Temperature	0.68 ± 0.15	3.32	11	0.01
Yield and Soil Temperature	0.28 ± 0.26	1.06	11	0.40
Yield and Temperatures Diffs	0.68 ± 0.15	3.37	11	0.01
Air and Soil Temperature	0.66 ± 0.16	3.17	11	0.01

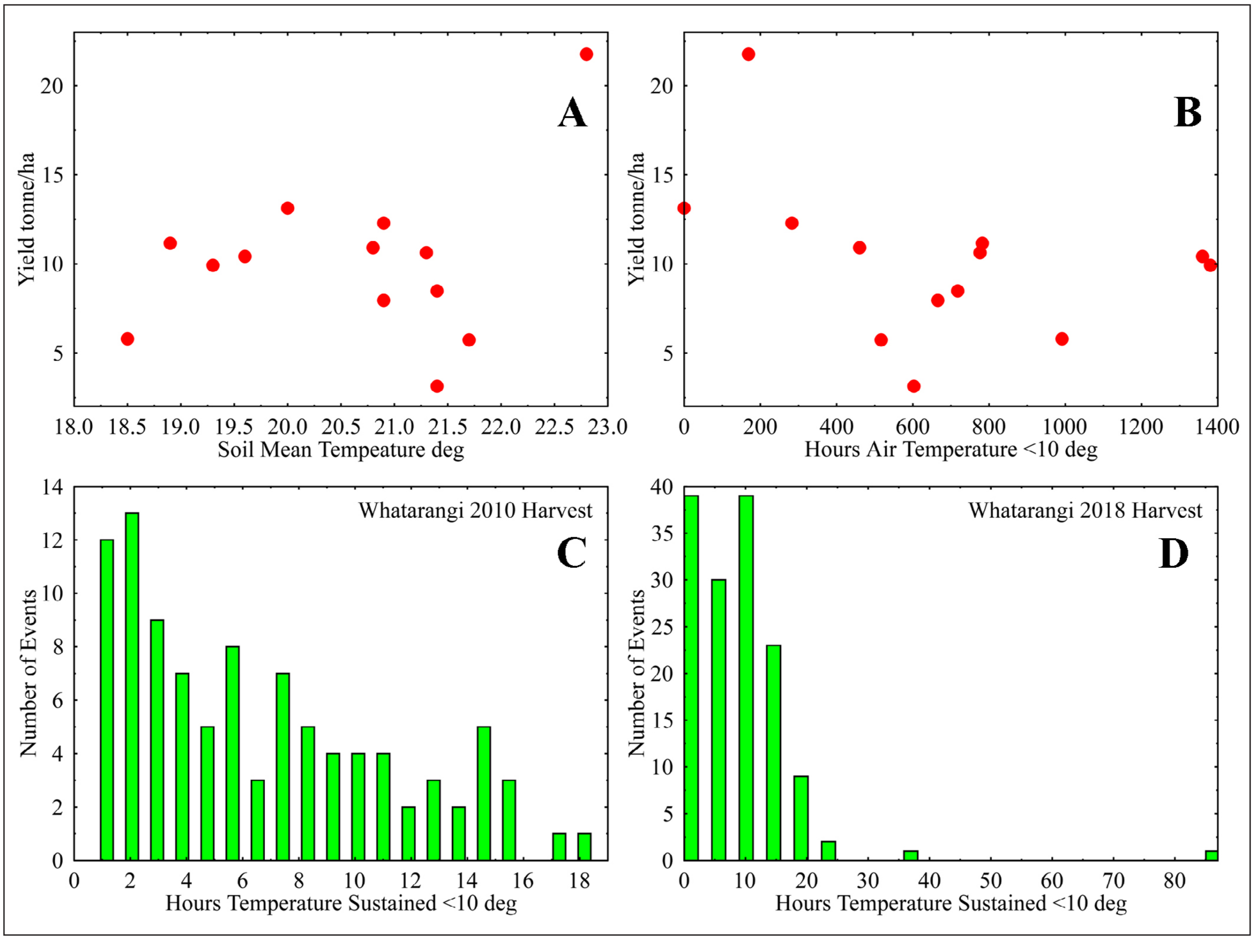

Figure 7. Analysis of air and soil temperatures which fell below 10°C for 13 kūmara crops at Whatarangi from 2006 to 2018.

ence of two crops. Figure 7C shows number of times low air temperatures were sustained for various lengths of time for the 2010 crop. On two occasions the air temperature fell below 10° for a sustained period of 18 hours. In Figure 7D an example is shown of the 2008 crop where the garden stayed below 10° for 86 hours.

The question remains: does this threshold air temperature have an effect on annual yield? The data in the top left part of Figure 7 was examined for this. The correlation r = −0.40 ± 0.23, with 11 degrees of freedom, is not significant p = 0.05. Although we have shown elsewhere that this threshold temperature is very important for storing kūmara (Davidson, *et al.*, 2007), this current experiment has shown that even a modest amount of sandy soil covering a crop is enough to ward off crop loss from cold weather at this latitude in a coastal environment.

Influence of Sunshine Hours on Crop Yield (factor 8)

The nearest useful climate station to the Whatarangi garden is at Kelburn in Wellington 42 km distant, which is expected to have similar exposure to sunshine. Historical data is available for the period of interest. Daily sunshine hours were obtained from Cliflo, the National Climate Database of New Zealand hosted by NIWA (Station 3385 at https://cliflo.niwa.co.nz/). Kelburn has a mean annual sunshine hours of 2053 per annum.

Daily sunshine hours were extracted from the database for the period of each growing season from planting to harvest (15 October to the following 15 May). These are plotted out for the 20 year period from 2000 to 2020 in Figure 7. The mean sunshine hours in the series extracted is 1417.3 hours (SD = 26.1). The correlation coefficient between harvest yield and sunshine hours, r = −0.01 ± 0.2, T = 04 with 18 DF. That is not significant p = 0.5.

We can confidently assert that at this latitude there is no relationship between yield and sunshine hours. Considering that this plant has a tropical origin, this is a little surprising; however, it appears that so long as sunshine is adequate, other factors contribute to variations in yield. As Hartemink *et al.* have pointed out, kūmara is a light-loving plant and sensitive to shading. Their finding that kūmara yield can be negatively correlated with rainfall is attributed to increased cloud cover rather than the rain *per se* (Hartemink, *et al.*, 2000: 267).

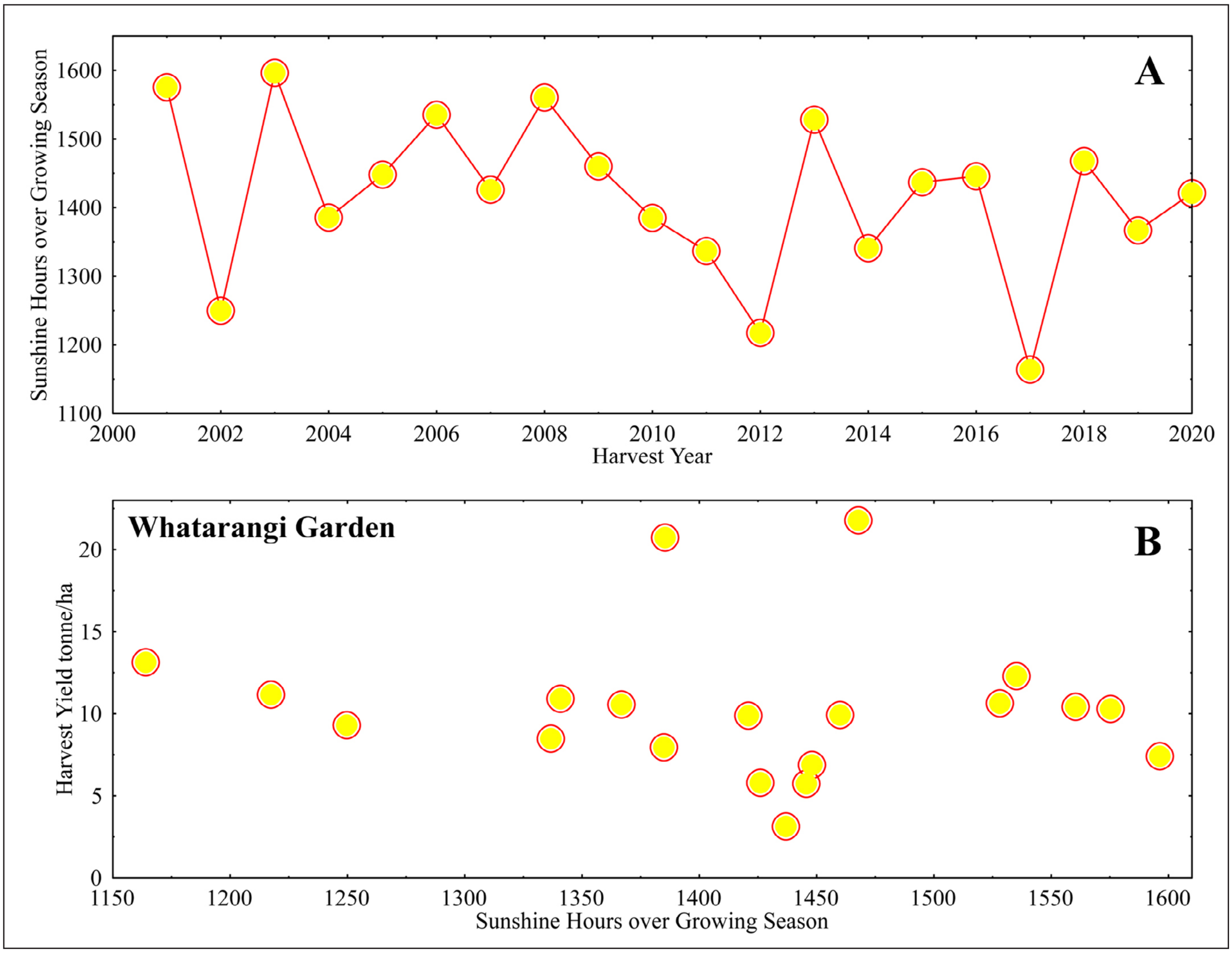

Figure 8. Sunshine hours over the growing season (upper) for the period 2001 to 2020, using Kelburn as a proxy for Whatarangi. Lower: Sunshine hours plotted against kūmara yield for the same period.

Influence of Soil Nutrients on Crop Yield (factor 9)

Soil samples were regularly taken from both gardens and submitted to Hill Laboratories, Auckland, for a series of 16 standard soil tests. Samples were taken from the same mound (Mound 18), and a composite from several locations in the gardens. Whenever possible, samples were taken twice a year (at planting and harvesting); so in many cases four samples were tested for each year. Sampling ceased after 2014 when a total of 12 years had been accomplished, and as funds were exhausted. The purpose of these analyses was to determine the effect of kūmara growing on the fertility of the soil, expecting to observe a decline. In addition, we expected crop yield to decline in concert with this. The former expectation was realised but the latter was not.

The results of the soil tests are summarised in Appendix 2, which provide mean, SD and SE of the Mean for each test for each garden for each year. In addition, we examined each time series for any correlation. Any significant changes through time are shown in bold in Appendix 2 ($p = 0.05$). These changes are summarised in Table 5, and six of the most notable time trends are illustrated in Figures 9–11.

These analyses show significant changes in all soil nutrients over time. Twelve markers indicate decline in soil fertility, while three, surprisingly, show increase. The garden at Robin Hood Bay did not show these changes as dramatically as at Whatarangi, and in several cases tests of statistical significance failed. This is not surprising, since the general character of the soil at the two locations is quite different. The garden at Whatarangi is located on an uplifted sandy beach within 30 m of the present-day high tide, and the soil is dominated by sand. The garden at Robin Hood Bay is more than 200 m inland on a silty clay loam.

Of those that show significant change, some deserve individual comments. For example, the pH in both gardens became increasingly acidic over more than a decade of harvesting kūmara. The mean pH of the two gardens was similar at 4.83 and 4.80, but both fell by *c.* 0.5 units in 12 years (Figure 10). This could in theory reduce the avail-

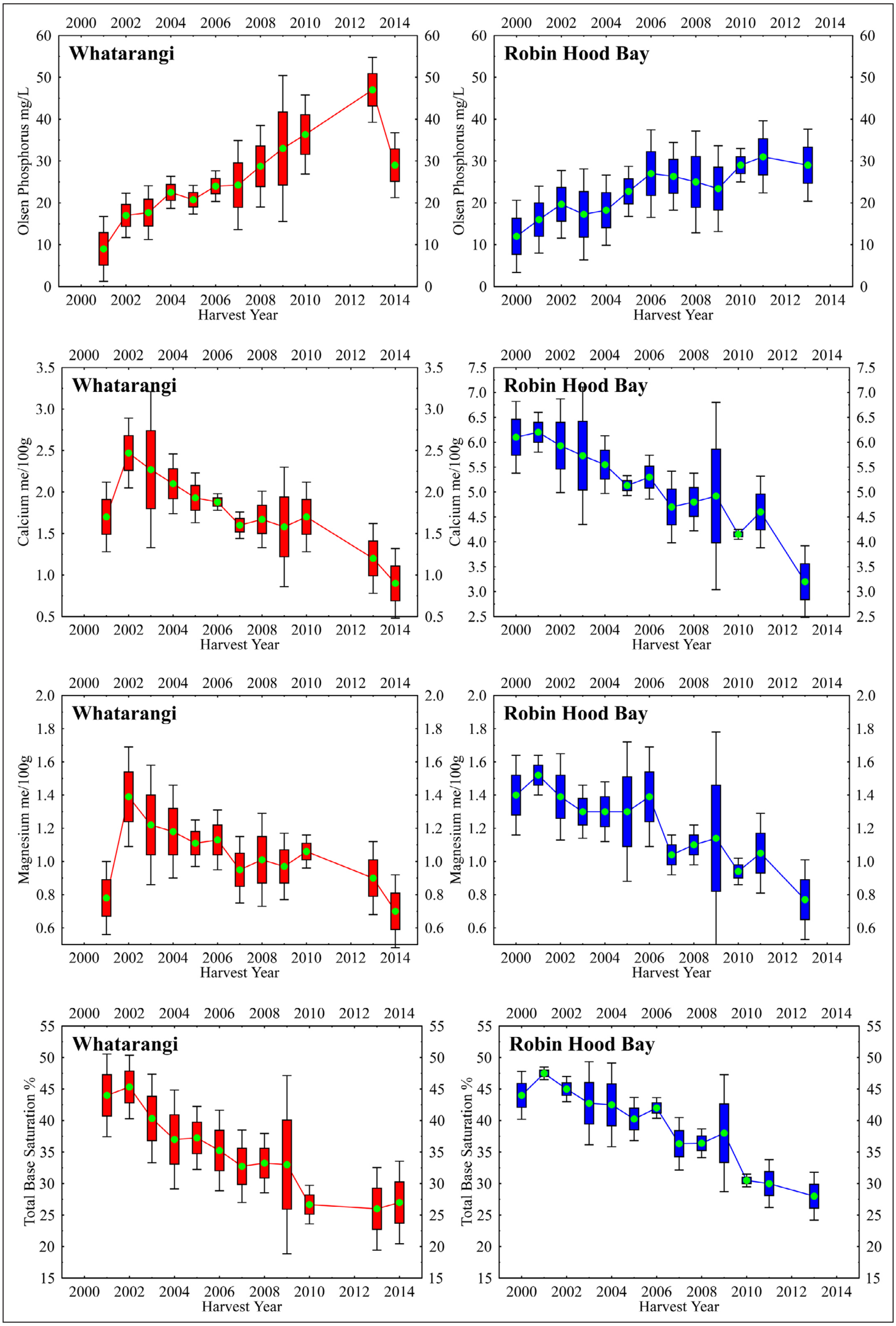

Figure 9. Changing levels of soil nutrients over time at the kūmara gardens. The confidence bars shown are one and two standard deviations.

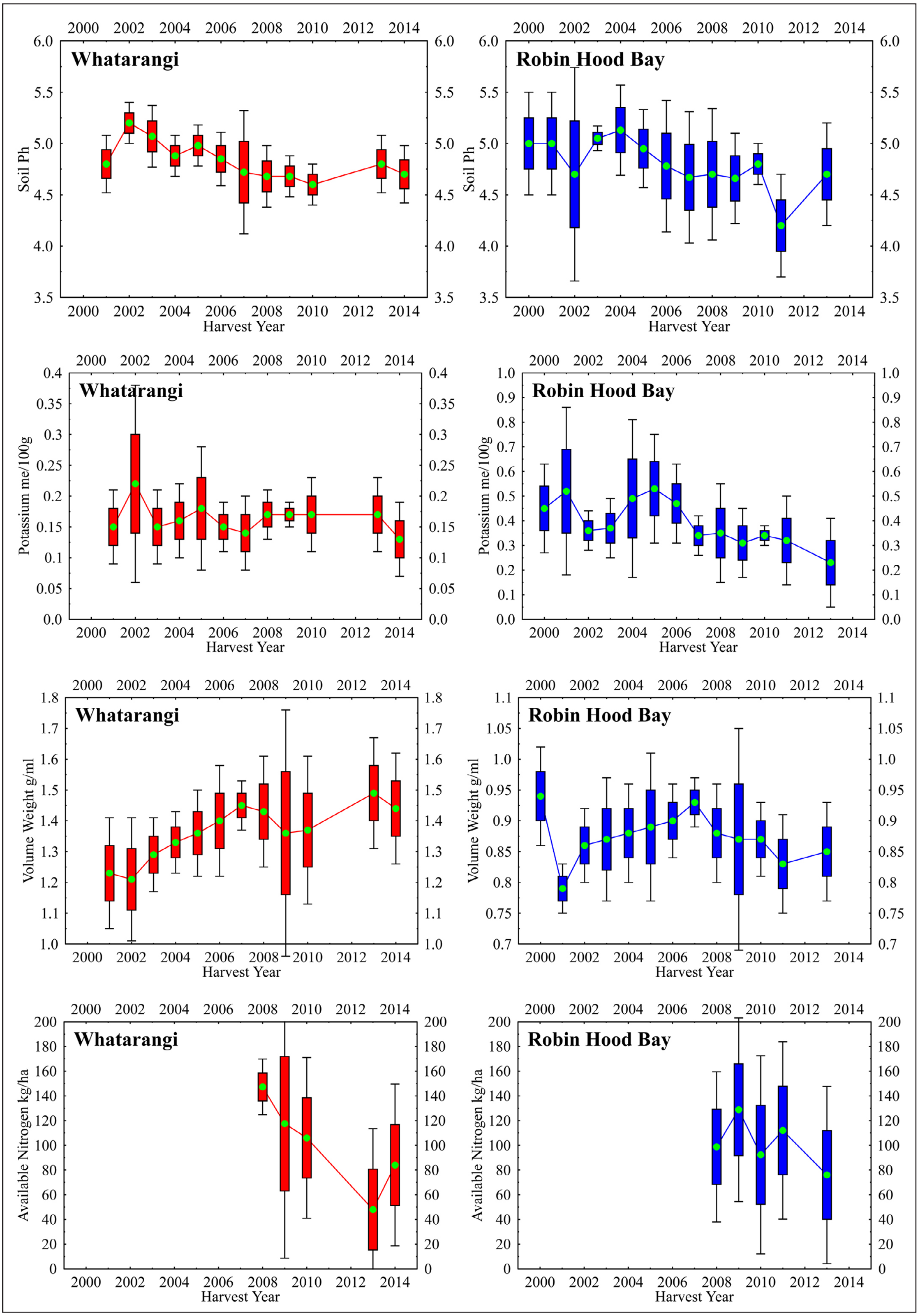

Figure 10. Additional changes in the levels of soil nutrients over time at the kūmara gardens. The confidence bars shown are one and two standard deviations.

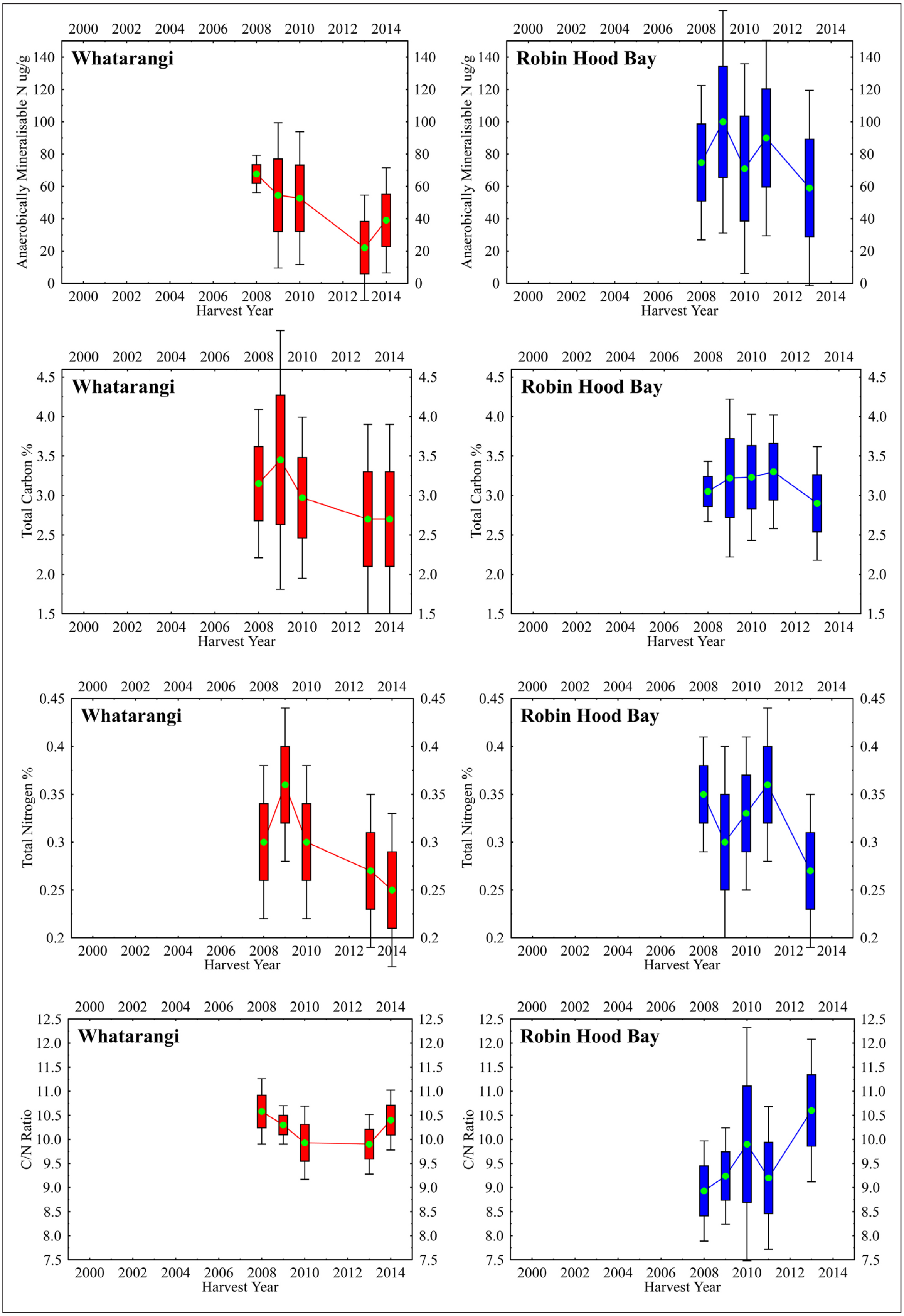

Figure 11. Additional changes in the levels of soil nutrients over time at the kūmara gardens. The confidence bars shown are one and two standard deviations.

Table 5. *Of the 16 variables tested, 12 showed significant change over time. All except three showed declining values.*

	Significant Decline		**Significant Increase**	
Soil Test	**Robin Hood Bay**	**Whatarangi**	**Robin Hood Bay**	**Whatarangi**
1. pH	Yes	Yes	–	–
2. Olsen Phosphorus	–	–	Yes	Yes
3. Potassium	Yes	–	–	–
4. Calcium	Yes	Yes	–	–
5. Magnesium	Yes	–	–	–
8. Total Base Saturation	Yes	Yes	–	–
9. Volume Weight	–	–	–	Yes
10. Available Nitrogen	–	Yes	–	–
11. Anaerobically N	–	Yes	–	–
13. Total Carbon	–	Yes	–	–
14. Total Nitrogen	–	Yes	–	–
15. C/N Ratio	–	–	Yes	–

ability of some nutrients to plants. However, the change in pH is not great, and not likely to have been significant. Ila'ava *et al.* have shown that both leaf and tuber mass of kūmara increases dramatically as pH rises from 3.5 to 4.5 and thereafter is optimal for plant growth (Ila'ava, *et al.* 1995: Figure 1). The reason why pH became slightly more acidic over time at both these gardens is unclear.

The Olsen P test is a measure of the plant-available phosphate in soil. The mean values for the two gardens were 25.8 and 22.8 mg/L, which is a little lower than optimal for horticulture. The most notable feature of the results from the gardens is the dramatic rise in available phosphate through time from c10 mg/L to as high as 50 at the end of a 13 year cycle (See Figure 9). The reasons for this are not obvious, but there is some evidence that kūmara roots are invaded by a ubiquitous fungus (vesicular-arbuscular mycorrhizae, VAM) to feed on plant sugar, and in return assist with the capture of phosphorus from soils (ALHadidi, *et al.*, 2021: 7, Yuan *et al.*, 2023: 2). Moreover, endophytic nitrogen-fixing organisms have been isolated on kūmara potato (Yonebayashi, *et al.*, 2014: 275), and are thought to be partly responsible for the ability of this plant to mine Phosphorus from soil (Ueda and Yano, 2023: 1).

Our hypothesis is that soil P-mobilizing microbial communities around the roots of the plant provide available phosphorus in the soil surrounding the root system. Recently published research identified nine genera of soil bacteria known to assist in the accumulation and uptake of phosphorus in a trial plot where only organic fertiliser was applied. Crop rotation was used in these trials with wheat following kūmara (Wang *et.al.* 2023: 3, Fig 5). Whatever the explanation is for the consistent increase in available phosphorus that we have observed in our two experimental gardens, it will have been beneficial to the kūmara plants.

The Whatarangi garden revealed a clear increase over time for the volume-weight values (Figure 10), but this did not occur in the Robin Hood Bay Garden. The soils in these two gardens are quite different, and this is clear in the volume-weight figures. The Whatarangi soil is a sandy loam, while at Robin Hood Bay the soil is a silty clay loam. The reason for the change at Whatarangi towards an ever lighter soil may simply reflect the repeated physical cultivation during planting and harvesting.

Finally, the C/N ratio has increased slightly over time at Robin Hood Bay, but not at Whatarangi. Although the trend is statistically significant, the amount of change is minor, possibly reflecting a small amount of Nitrogen depletion.

It is hardly surprising that these indicators of soil nutrition show declining fertility over a period of 23 years intensive kūmara cultivation and harvesting. The two gardens are a mere 25 m² each. At Whatarangi over the period of 23 years, 606 kg of tubers have been removed, and 263 kg over 14 years at Robin Hood Bay (see Table 1).

The all important point, however, is whether loss of fertility has resulted in a decline in harvest yield. The answer is a definite No. As earlier pointed out, although annual yield fluctuated considerably, no overall diminishing trend has been observed.

By way of contrast, the fertility of these two New Zealand kūmara gardens can be compared with the Kohala field system on the island of Hawaii, which has seen soil nutrient research. For example, Kagawa *et al.* suggest that there is a threshold of base saturation of *c.*30% below which Hawaiian's did not intensify rain-fed horticulture (Kagawa *et al.*, 2012: 165). The Papua New Guinea experimental kūmara garden had values of 63–93%, well above this threshold (Hartemink *et al.*, 2000: 264). Kagawa *et al.* also found that the lowland agricultural systems of Hawaii have very high levels of available phosphorus (130–180 ppm), compared with both wet upper elevation areas (<10 ppm), and dry lowland areas (~40 ppm (Kagawa *et al.*, 2015: 165). Vitousek *et al.* considered that exchangeable calcium values above or below ~10 mq/100 g constitute a well defined threshold in soil fertility separating the different types of agricultural system (2014: 55). At Whatarangi, base saturation values fell below 30% after nine years of harvesting, and after 11 years at Robin Hood Bay (Figure 9). By contrast, calcium values were always less than 6.5 me/100 g at Robin Hood Bay and less than 3.5 me/100 g at Whatarangi. Both gardens had phosphorous levels comparable to the dry lowland areas at Kohala.

Influence of Seed Tuber Size on Crop Yield (factor 10)

In an important published description of early historic Māori kūmara gardening, Walsh observed that 'the seed consisted of the tubers which were too small to be eaten' (Walsh, 1902: 18). In one of our earlier publications on our experimental gardens we examined this with the data from two harvests and found a weak positive correlation (r = 0.43) that larger tubers produced a larger yield (Burtenshaw *et al.*, 2003: 179). For a community hard pressed to maintain a viable economy in the Cook Strait region having to set aside larger tubers for planting, would represent a considerable sacrifice. We felt it was desirable to examine this issue with a larger data set. With this in mind, each year when the seed kūmara were planted, the seed tubers were carefully selected to ensure they were in good condition and each one was weighed ± 1 g. Each was logged according to which of the 38 mounds it was buried in, so that when it came to harvesting, the yield from each plant could be examined against the size of the seed. Over the course of 23 years, a database of 1095 values was accumulated.

On the left of Figure 12, the yield from each mound is plotted against seed weight. It will be noticed that the largest seed, which weighed 654 g, produced a total yield of only 665 g. Clearly there was no value in planting very large tubers. By contrast, the largest yield from any one plant was 3,640 g, and the seed only weighed 210 g. In spite of the large spread of results, a weak positive correlation exists between seed size and yield. The coefficient is significant p = .01 and has a value of +0.25. On the right of Figure 12 the seed weight is plotted against the yield/seed ratio. The largest ratio was 94 to 1, achieved by a seed weighing only 30 g, with a yield of 2,823 g at harvest. The mean ratio is 11.2 ± 0.3. The largest yield from one plant was 3,640 g.

The two most important statistics in this analysis are the mean seed size and the mean yield that was achieved. These determine two of the parameters mentioned above concerning human population estimates. They are parameters S and Y (see Appendix 1). The mean seed size over the 23 year experiment was 74.0 ± 1.5 g, and the mean yield per plant was 656.8 ± 14.2 g. So the ratio of return for investment was 656.8/74.2 = 8.85[4]. Scaling up from our 25 m^2 experimental plot to a hectare, is a factor of 400. Thus, the seed required per Ha would be 74.0 g × 38 plants × 400 = 1,124,800 g (1.1 tonne). This is considerably less than the estimate suggested by H. Leach of 2 tonne/Ha (Appendix 1). More seed would need to be stored than this to offset spoilage during the winter months (estimated as 10%). Our estimate of yield per hectare is 656.8 × 38 plants × 400 = 9,983,360 g (*c.*10 tonne/ha). H. Leach's estimate of yield was 17.9 tonne/ha. We will return to this subject later.

The degree of variability which appears in the two graphs above (Figure 12) suggests that there are many factors involved in producing high yield from any one plant, and seed size is not the most important. One issue, perhaps not given the attention it may have deserved, is exactly where the seed tuber is placed in each mound (*puke*). The method of preparing each mound involved heaping up soil from the surrounding area, and when completed, a planting recess was made in the top of the mound on the north side, the seed inserted, and then covered over. Even though each mound was of uniform size, the precise amount of soil covering each seed may have varied somewhat. Thus, the

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[4] This mean ratio of 8.85 can be compared with the value cited above of 11.2. It is a moot point which of these ratios is the best to use in cost/return analysis. This is further discussed below.

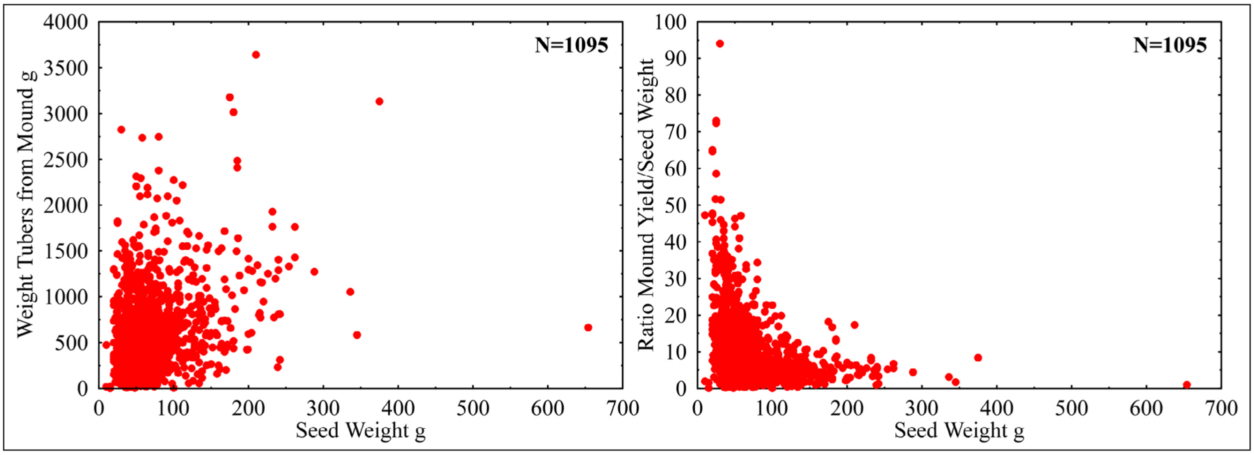

Figure 12. Relationship between planted seed weight and yield.

amount of thermal protection each seed had from adverse weather conditions may also have varied a little. A more consistent planting method might be to make a hole in the top of each mound and insert the seed, and then heap up soil from the sides.

The variable yield from one plant to another is instructive. This source of variation can not be attributed to over-arching effects, such as climate (rainfall, sunshine, air and soil temperature and soil nutrients). Instead, variation in yield from one plant to another might be attributed to subtle differences in the attention given to each plant, of which the precise amount of soil covering a seed tuber would be one factor. In reality, whereas pre-European gardeners would have regularly visited gardens and ensured that wind-blown disturbances of soil would be rectified. In the case of our experimental gardens, they were visited only twice between planting and harvesting for weeding (December and February), so minimal attendance was given to any disturbance of the mounds. What then was the amount of variation between plants? The accumulated data were examined to test this, and a histogram is presented in Figure 13.

Figure 13 shows that there was a very broad range of yield from individual plants, and this is reflected in the dispersion statistics. The mean weight of tubers per plant was 662 g ± 12.5, with a standard deviation of 460 g. The coefficient of variation over the 23 years is 69.5% ± 1.33. As earlier indicated, the crop from each harvest also varied a great deal from one year to another (see Figure 2). The coefficient of variation of the annual crops was earlier stated as 35.0% for Whatarangi, and 61.5% for Robin Hood Bay. Thus, the variation between plants and between crops was a similar order of magnitude. Since the former is unlikely to be attributed to macro-environmental factors, the similarity in scale of these two coefficients suggest that annual crop variation may be largely a result of care and attention to individual plants. It is worth noting that of the total of 1,474 plants grown, 70 were absent at harvest time (4.8%). Assuming that pre-European gardeners were on site throughout the year and were giving regular attention to their crops, some of this variation in yield could be reduced. Nevertheless, disastrous failures like that experienced at Robin Hood Bay in 2014 would be difficult to avoid. Clearly, such events resulted in extreme hardship, including starvation.

TARO EXPERIMENT

After considerable research relating to climate and soils in Palliser Bay H. Leach concluded 'Thus, it has been possible to establish that of all the Polynesian cultigens, modern conditions in Palliser Bay would support only the kūmara and gourd' (Leach, H, 1976: 191, see also Leach, H., 1979: 242). There are at least 40 cultivars of this species (Angami *et al.*, 2015), characterised by physical features not genetics. The current authors felt it was desirable to attempt to grow four different cultivars on both sides of Cook Strait as a starting point to promote further research on this. A minor experiment with taro was therefore carried out. Of some interest, starch grains of both taro and kūmara have recently been identified in Palliser Bay archaeological soils (Dodd, pers. comm. to BFL 2023, referring to analyses done by Horrocks).

A colleague at the Museum of New Zealand Te Papa Tongarewa, Grace Hutton, kindly gave us several specimens of taro from Rarotonga (Type #1 below) to grow in the personal garden of BFL and JD at Ngakuta Bay in the Marlborough Sounds. These were harvested the following year and 'taro babies' re-planted to increase the number of taro. After two years these produced massive foliage (Figure 14), reasonable sized corms, and abundant additional 'taro babies' (Figure 15). In 2006 we decided to add taro to both our experimental gardens to see how they might grow there. A second 5 × 5 m area was laid out and fenced

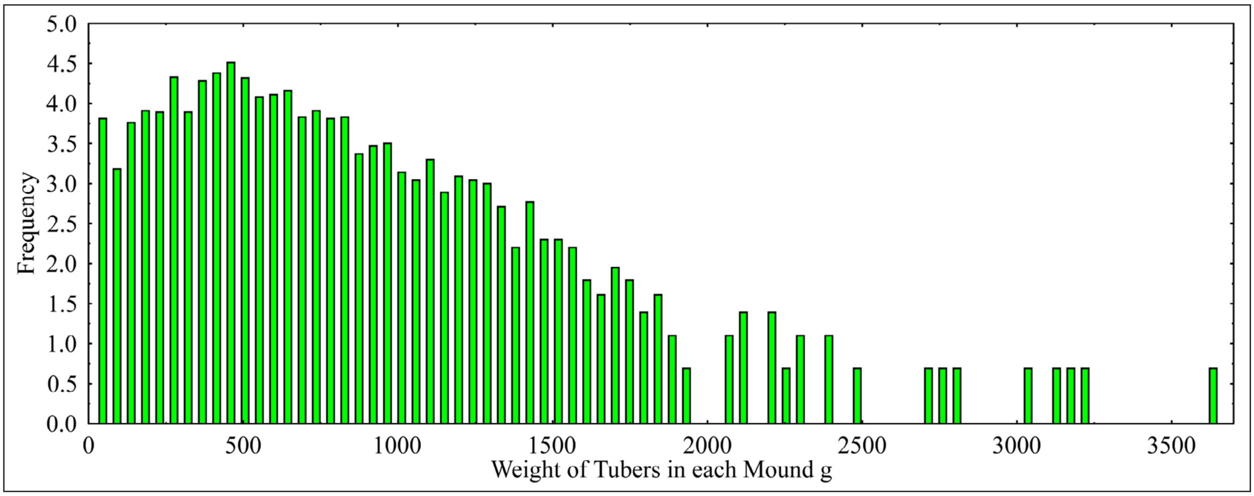

Figure 13. Histogram showing the distribution of weight of kūmara tubers in each mound.

at Whatarangi for the purpose, and also at Robin Hood Bay. We acquired specimens of three more cultivars of *Colocasia esculenta* from various sources: a specimen from Cyprus courtesy of Peter Matthews (Type #2), a specimen from Fiji which had a pink tinge (Type #3), and a Samoan specimen (Type #4).

When harvested, the specimens were re-weighed to monitor any increase in size. The results are presented in Table 6. Three corms died in the interval, one in each garden plot. The average weight gain was 91% over the growing periods of 4.6 and 5.6 months respectively. This is a large increase, considering that in the Cook Strait region this plant is considered to have been at the very limits of viability (depending on variety). Pacifica communities in the Hutt Valley area do plant taro today in personal gardens, and as noted above taro grew successfully at Ngakuta Bay. The limited experiment described here really needs extending. A suitable experiment would be to plant say 50 meristems in say five rows of 10, and each year dig up one row, and check the average progress of the 10 specimens over a five year period. Judging from the Ngakuta Bay experience, obtaining mature corms would take several years. Such serial planting and harvesting has an important bearing on human carrying capacity of an area of arable coastal land, as only a fraction of the planted area can be harvested each year.

Figure 14. Upper – *Colocasia esculenta*, Rarotongan cultivar, growing in the rich forest soils at Ngakuta Bay, Marlborough Sounds in 2008. Lower – the same cultivar growing in the dry sandy soils at the Whatarangi kumara research garden in 2006.

Figure 15. The Ngakuta Bay taro in 2006 after two years in the ground. Left: corms freshly dug up. Right upper: three reasonable sized corms after removing meristems. Right lower: Taro 'babies' ready for re-planting.

Table 6. *Results of Taro Experiment. Whatarangi corms were planted 28/11/2006 and harvested 17/4/2007 (139 days). Those at Robin Hood Bay were planted 31/10/2006 and harvested 18/4/2007 (169 days). Weights are g. The wet garden at Whatarangi, is a small swampy area beside a permanent spring. The dry plantings are part of the sandy coastal platform, adjacent to the main kumara gardens (See Figure 14 lower).*

Specimen	Planting wt	Harvest wt	Gain/Loss	Percent	No Babies
Whatarangi Dry					
#2	102	139	37	+36.3%	1
#3	632	dead	–	–	*
#4	723	940	217	+30.1%	2
#1	565	760	195	+34.5%	1
Whatarangi Wet					
#2	430	696	266	+61.9%	3
#3	588	dead	–	–	*
#4	650	770	120	+18.5%	0
#1	53	48	–5	–9.4%	0
Robin Hood Garden					
#3	468	1530	1062	+226.9%	3
#2	544	1342	798	+146.7%	4
#2	717	dead	–	–	*
Means	**497.5**	**778.1**	**336.3**	**90.9%**	**2.3**

POPULATION ESTIMATES OF PALLISER BAY PREHISTORIC GARDENERS

As pointed out above, the area of land available for cultivation of kūmara is instrumental in determining the size of a human population to be supported in any one area. The area from Palliser Bay northwards along the coast consists of a narrow uplifted coastal platform, typically 150 to 500 m wide. The adjacent marine environment is a rich source of sea food, and the rugged mountainous interior an excellent source of small birds for food. This coastal environment can be characterised as an inexhaustible source of protein rich foods. In any human economy, a limiting factor on whether occupation can be sustained is not access to protein, but the availability of fat and carbohydrate to provide a balanced diet. Most sources of marine and forest foods have less than *c.* 5% fat, consequently successful economies in places like Palliser Bay require reliable access to carbohydrate. That means kūmara and/or bracken fern rhizome (Leach *et al.*, 2023). From the foregoing, we are now in a position to evaluate the role that kūmara would have played in the economic system of pre-European people living in Palliser Bay and, in particular, population density in this region.

In 1976, Helen Leach provided a suitable model for estimating the human carrying capacity of the Palliser Bay coastal region. She defined a series of parameters which need to be estimated in order to calculate carrying capacity (Leach, H. 1976: Appendix 4: 214). The parameters she outlined are provided in Table 8 (Appendix 1).

Using these parameters, she then estimated P = the steady state population size which could be supported by a certain sized block of land. A worked example is given here in Appendix 1. Using her parameters in Table 8 (Appendix 1) and an estimated total area under cultivation of 93.36 Ha, She assessed the total population that could be supported in Palliser Bay as being *c.* 319 people[5].

Since permanent occupation and gardening were centered on a series of river valley systems, she estimated that each of these supported 30–40 inhabitants. These settlement units were effectively a series of exogamous village communities, linked by kinship ties to other valleys, including further along the east coast.

Following more recent research, some revisions are now required for the parameters listed above. For example, there have been several published estimates of nutrient values for New Zealand kūmara, and in general these support the value used by Helen Leach. Eight specimens of three different Māori traditional varieties of kūmara (*taputini, hutihuti, rekamaoroa*) from both our experimental gardens gave a mean gross energy value by wet weight of 113.8 kcal/100 g, with SD = 18.3 (Burtenshaw, *et al.*, 2003: 181). This is a little more than the value reported by the US Department of Agriculture of 105 kcal/g (*ibid*: 180), and used by Helen Leach.

Our experimental research above shows that her estimate of annual yield from kūmara crops requires no revision, but the length of time that any one garden can continue to produce adequate crops certainly does. The 23 year mean yield at Whatarangi was found to be 10.15 ± 0.95 tonne/ha, and over 14 years at Robin Hood Bay as 7.53 ± 1.24 tonne/ha (Table 1 above). Of perhaps greater significance than the mean value is the issue of crop failure, and this deserves further comment. On the issue of cropping period and fallow, H. Leach comments as following:

> The low to moderate fertility of soils in Palliser Bay suggests that the ethnographically recorded maximum fallow period of 14 years should be used, although the range might have been 7–25 years. A cropping period of 3 years may have been successful after initial land clearance. After fallow it is doubtful if two years' cropping would have been possible without significant reduction in yield. Overall a figure of 2 years is selected as a best estimate (Leach, H. 1976: 181, and Appendix 4).

In view of the foregoing evidence of the extended period of high yields at Whatarangi, we suggest that the choice of cropping period of two years (C = 2 years) needs to be greatly extended, at least for Palliser Bay. A modest revised suggestion would be 10 years. Regarding the period of fallow required, Hartemink *et al.* have suggested five to six years in Papua New Guinea (Hartemink *et al.* 2000: 263); however, very different soils are involved, and the cropping period is very short, so we see no reason to change H. Leach's suggestion for Palliser Bay.

One further parameter requires discussion: the energy per person per day from kūmara, which H. Leach estimated as E = 700 kcal. It has been shown elsewhere that for a kūmara based economy where there is abundant protein available from the marine environment, balancing nutrients so that protein poisoning is avoided (caloric intake from protein-rich foods less than *c.* 30%) requires a minimum weight ratio of kūmara to marine food of 1.5 to 1 (Leach *et al.* nd: 14). Using the mean energy assessments of kūmara cited earlier of 113.8 kcal/100 g and the mean value from a mix of marine foods from the Foxton site of 87.3 kcal/g (Leach and Davidson, n.d.: Table 4) we can calculate the daily weight of these two food sources that would provide 2000 kcal per day. Thus, 1164 g of kūmara and 776 g of marine food (a ratio of 1.5: 1.0), provides 2002 kcal, with the energy from protein from both sources of food just below 30%.

When our revised parameters are used (Table 8,

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[5] It needs to be noted that in Helen Leach's worked example the areas given are the yearly area under cultivation, not the total areas of garden available (T). The total in her tabulated areas on page 214 = 11.67 ha. Thus, the total area of gardens = (11.67×C+F)/(C×T). For C = 2, and F = 14, T = 93.36 ha, as specified at the bottom of page 213.

Appendix 1) we calculate the total population in Palliser Bay as 209 people, somewhat less than originally estimated by H.Leach as 319 people. Most of the parameter values provided in Table 8 (Appendix 1) are quite reliable. The two that are subject to debate are the cropping period C and the fallow period F. The question arises how sensitive is a population estimate to a chosen value for each of these parameters. Some simulations are provided in Figure 16. On the left, the effect of changing the cropping period is illustrated. If a garden patch were continuously cropped without respite for 24 years, the region would support 318 people (close to H.Leach's original estimate). On the right, the effect of increasing the fallow period is simulated. If this was shortened to 6 years, the region would support a population of 315 people.

In the above evaluation it has been assumed that the entire crop each year, when stored, will sustain a community until the following harvest when supplies will be replenished. This is very unlikely at this latitude. Additional experiments we have made in this project, described elsewhere (Davidson, *et al.* 2007), have shown that kūmara stored in subterranean pits will begin to rot when the storage temperature falls below 10° C. Intervention, in the form of a small fire inside a storage pit, quickly fills the enclosed space with dense smoke as oxygen is used by the fire, and the fire is soon extinguished. Moreover, the production of smoke in such a confined space is so severe it is not possible for a human to survive for more than a few minutes while trying to tend to a small fire. After five months in the experimental pit, 90% of all tubers were rotten. Further north in New Zealand, where air temperatures are more conducive to kūmara storage, this is not such a problem. In addition, the ameliorating effects of the sea help to make pit storage more effective when placed close to the coast. In Palliser Bay, and other areas in the vicinity of Cook Strait, pre-European Māori would have no choice but to find an additional source of carbohydrate for some period of the year. The only available option in New Zealand is bracken fern rhizome (Leach *et al.* 2023) , augmented from time to time by cooking the roots of *Cordyline australis*, the

Table 7. *Parameter definitions for population estimates from area under kūmara cultivation for Palliser Bay, showing H.Leach's estimates (Leach, H.: 1976: Appendix 4: 214), and our suggested revised values.*

Symbol	Explanation	H.Leach	This Paper
F =	fallow period required	14.0	14.0 years
C =	cropping period	2.0	2.0 years
Y =	yield	10.0	10.15 tonne/ha
L =	storage loss	10%	10%
S =	seed required	2.0	1.10 tonne/ha
E =	energy per person per day from kūmara	700	1325 kcal
G =	total energy needs per person per day	2000	2000 kcal
Cal =	caloric value of kūmara (wet weight)	1.0	1.14 kcal/g
T =	total area available for serial gardening	93.36	93.36 ha
A =	area of garden any one year	(T*C)/(C+F)	ditto

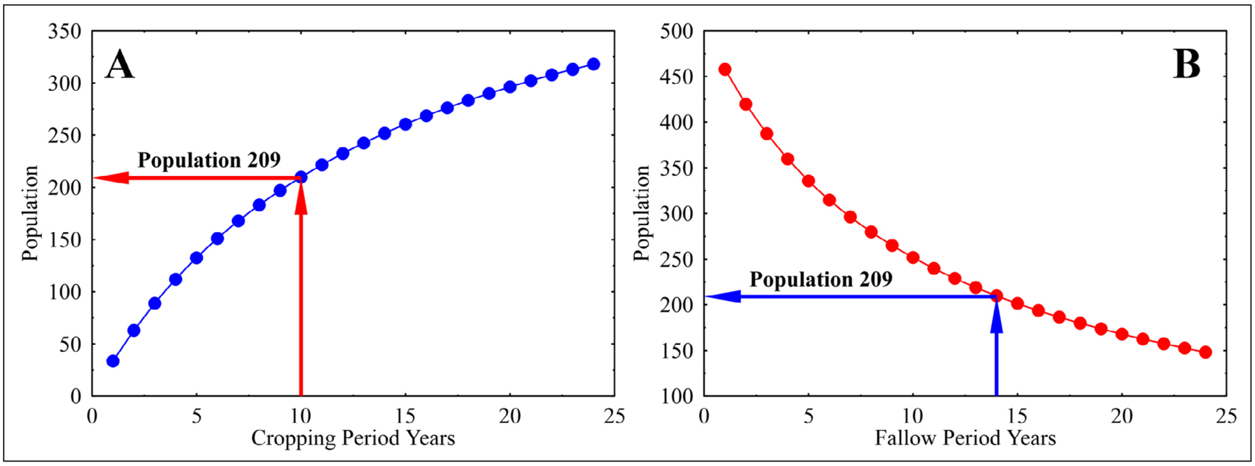

Figure 16. Testing the sensitivity of cropping and fallow period on modelled population size of Palliser Bay, using the additional parameters specified in Table 8 (Appendix 1).

New Zealand cabbage tree (Fankhauser, 1982, 1986, 1987, 1989, 1992). We have elsewhere described this period when kūmara stocks are depleted as a 'Hungry Gap' (Leach *et al.*, 2023: 18 ff).

What effect does this have on our population model? It does not mean diminishing the suggested steady-state population size. What it does mean is that not all of the harvested kūmara crop will be able to be eaten. The carbohydrate gap will need to be filled by bracken fern rhizome. The rhizome energy (108 kcal/a100 g, from Leach *et al.* 2023: 16, Table 2) is a little less than kūmara (mean 113.8 kcal/100 g cited earlier). Somewhat more rhizome would need to be beaten and roasted than kūmara. The daily requirement of kūmara above was 1164 g. An equivalent amount of energy from rhizome would be 1227 g. That is a substantial requirement, and explains why early European visitors to New Zealand often remarked about the incessant beating of fern-root by both adults and children (St George n.d.b.: 266; Leach *et al.*, 2023: #88–89,#102).

CONCLUSIONS

These two experimental gardens on either side of Cook Strait have shown that kūmara can be successfully grown and harvested in central New Zealand. The average yield was equivalent to 10.15 and 7.53 tonne/ha for the two gardens, but with very high coefficient of variations (35.0% and 61.5% respectively). Serial cropping presented a considerable challenge for communities living in this region, and the occasional crop failure meant periodic malnutrition and starvation. Even after 23 years of kūmara planting and harvest, no sign of consistent decline in yield was observed. All weeds and kūmara tops were removed from the gardens when found, and no fertiliser was added.

We found no correlation between seed tuber size and the yield from plants, with a high degree of variation. Tuber size varied a great deal up to *c.* 800 g, but more than 90% weighed less than 100 g.

We examined a series of 10 possible reasons for such

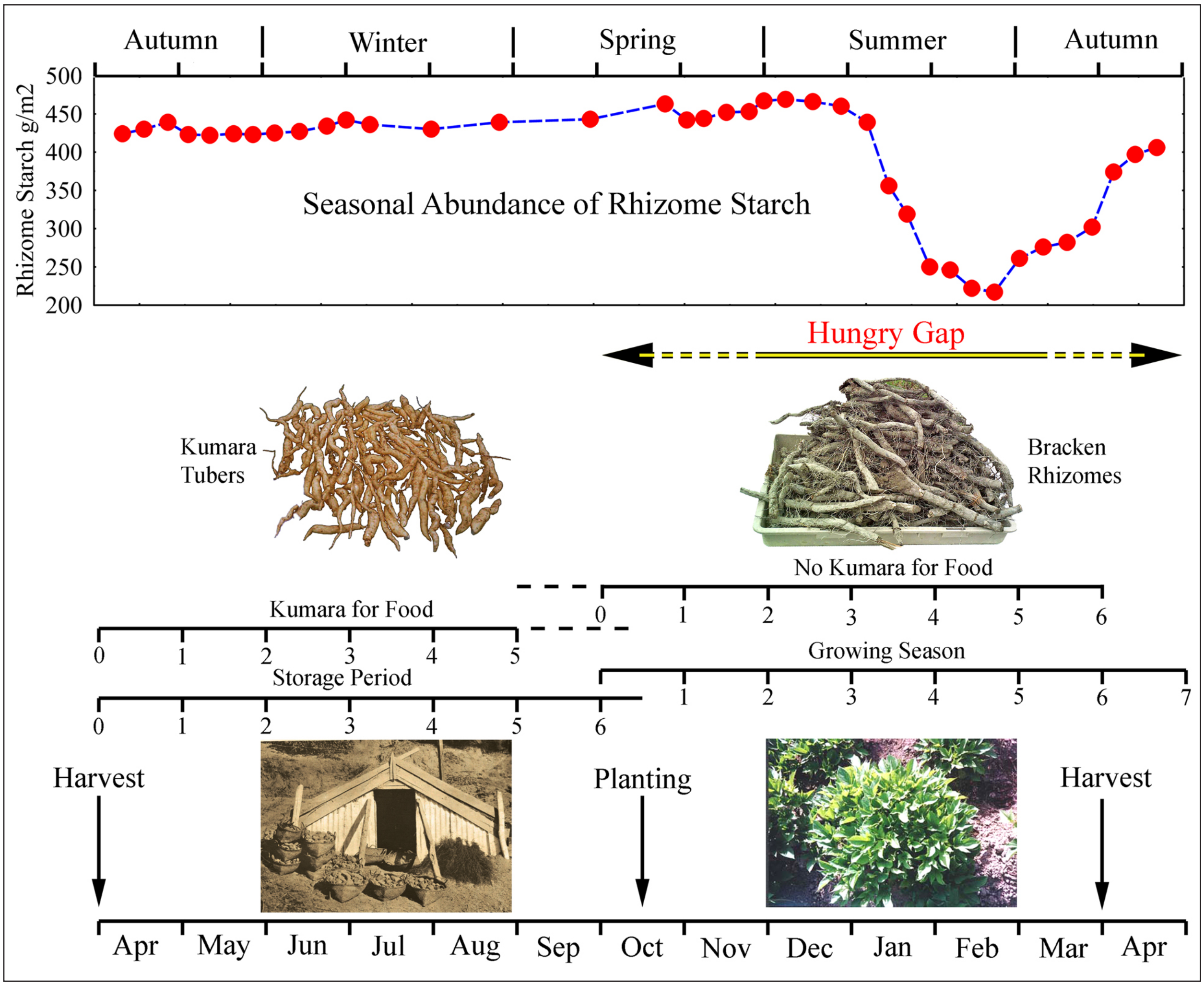

Figure 17. The kūmara cultivation, harvesting and storage cycle relevant to southern North Island, New Zealand. Note the *hungry gap* from mid October through mid April each year (From Leach *et al*. 2023: 20).

a high degree of variation in individual plant yield and overall annual yield. These included rainfall over the period of cropping, the number of days with no rain, the number of days with rain, mean air and soil temperature, the number of hours and days that air and soil temperature fell below a threshold of 10° C, sunshine hours, and 13 soil nutrient tests carried out several times a year for 14 years. None of these fully account for the variations in crop yield. Personal attention to individual plants during the growing season may reduce between plant variation in yield. We found no correlation between sunshine hours and yield, but significant correlation between air and soil temperature with yield. As with other tests, scatter-plots revealed high variability and many outliers. Most soil nutrient tests showed declining fertility over time. In spite of this, yield did not decline in concert. An unusual finding was Olsen P, a measure of available soil phosphorus, a key ingredient for kūmara survival. Soil phosphorus levels rose steadily every year at both gardens. At the end of 14 years the level was five times greater than when gardening began. This unexpected finding is attributed to the presence of a ubiquitous fungus (vesicular-arbuscular mycorrhizae, VAM) which assists kūmara to mine phosphorus for soil minerals. A weak but significant correlation was found between seed size and plant yield, with a mean of 11.2 to 1. Again, the spread of results is highly variable. One seed, weighing 30 g, produced 2,823 g of tubers at harvest.

We carried out a minor experiment with taro in Palliser Bay for one year, finding highly variable changes in final tuber size across four varieties, but with a mean increase in tuber weight of 91%. This shows that taro certainly can be grown in this area, and we suggest further experiments would be useful.

The observed highly variable annual yields of kūmara would have created enormous pressure on communities living in this central region of NZ. In spite of the super abundance of protein rich marine foods, a successful economy requires a balanced diet. In difficult years, when low returns from gardens prevailed, the lack of adequate carbohydrate and or fat would present danger to health, including 'rabbit starvation' from increasing reliance on marine food.

We revisited a population model suggested in 1976 by H. Leach, where she estimated a steady state population of 319 people in Palliser Bay. This was based on field documentation of 93.36 ha of pre-European kūmara gardens in this coastal area. From results from the experimental gardens, we revised some of the earlier suggested parameters in this model, particularly the period of cropping in any one garden. Our revised population estimate is somewhat lower at 209 people.

Although such a raw estimate of the human carrying capacity of this area of coastline may be perfectly reasonable, it does not convey a sense of how difficult life would have been along these shores. The variable annual yield that has been revealed by this 23 year-long experiment points to profound hardship for the 200 or so people living there for nine or more centuries. The experiment has shown occasional crop failure, and this would be devastating for the communities. Even without crop failure, storing all of the harvested kūmara until the following harvest, we think, would be virtually impossible. In a six month period, proposed as a 'hungry gap', between mid-October to mid-April, it would always be difficult to maintain a balanced diet between the sources of protein, fat, and carbohydrate available. Filling the gap with adequate carbohydrate would require preparing large amounts of bracken fern rhizome in this six months period. Our estimate of a balanced diet between kūmara and marine sea foods would be an average of 1164 g per day of kūmara and 766 g of sea food. During periods without kūmara, the gap would require 1227 g bracken fern rhizome. These values are per adult person per day, and assume 2000 kcal per person.

Acknowledgements

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APPENDIX 1. ESTIMATING POPULATION SIZE FROM STONE WALL KŪMARA GARDENS

Table 8. *Parameter definitions for population estimates from area under kumara cultivation for Palliser Bay (after Leach, H.: 1976: Appendix 4: 214).*

Symbol	Explanation	Worked Example in Appendix
F =	garden fallow	14 years
C =	cropping period	2 years
Y =	yield	17.9 tonne/ha
L =	storage loss	10%
S =	seed required	2 tonne/ha
E =	energy per person per day from kūmara	700 kcal
G =	total energy needs per person per day	2000 kcal
Cal =	caloric value of kūmara (wet weight)	1 kcal/g
T =	total area available for serial gardening	to be measured from stone walls
A =	area of garden any one year	(T*C)/(C+F)

As discussed in the main text above, the calculation below is based on Helen Leach's algorithm for this purpose (H.Leach, 1976: Appendix 4). A worked example follows:

A stone wall complex has an area T of 30.3 ha. The cropping period is 1 year, and the fallow period 14 years. The yearly plot, A, is therefore:
A = (T*C)/*C+F) = 2.02 ha
If the kūmara yield is 17.9 tonne/ha, then the total yearly crop, A*Y = 36.16 tonne. During winter storage the loss due to decay L = one tenth of the crop = 3.62, leaving a nett amount of 32.54 tonne. See requirements for the 2.02 ha at a rate of 2 tonne per ha is 4.04 tonne. That leaves 28.5 tonne for storage and consumption during the period between harvests. The caloric value of this is 28.5*106*1.0 kcal, since Cal above is 1 kcal/g. If this was the only food eaten by a group of people at 2000 kcal/day (G), it would feed 39.04 people for 365 days.

APPENDIX 2. RESULTS OF SOIL TESTS IN THE TWO KUMARA GARDENS

Dispersion statistics are provided in the tabulation below. Values rendered in red are statistically significant at least p = .05

Table 9. *Statistical data from 16 soil nutrient tests. Whatarangi: 2001 to 2014. Robin Hood Bay 2000 to 2013. Samples were taken two to four times per year. In most cases dual samples were taken each time: one from mound 18, and another composite sample.*

Soil Test No.	Soil Test Name	Units
1	pH	pH units
2	Olsen Phosphorus	mg/L
3	Potassium	me/100g
4	Calcium	me/100g
5	Magnesium	me/100g
6	Sodium	me/100g
7	CEC	me/100g
8	Total Base Saturation	%
9	Volume Weight	g/ml
10	Available Nitrogen 15 cm depth	kg/ha
11	Anaerobically Mineralisable N	mg/g
12	Organic Matter	%
13	Total Carbon	%
14	Total Nitrogen	%
15	C/N	Ratio
16	Anaerobically Mineralisable N/Total N	Ratio

Robin Hood Bay Kumara Garden

Test No.	N/DF	Mean	SD	SE Mean	R	SER	T
1	**13**	**4.80**	**0.24**	**0.07**	**–0.68**	**0.15**	**3.37**
2	**13**	**22.82**	**5.80**	**1.61**	**0.92**	**0.04**	**8.58**
3	**13**	**0.39**	**0.09**	**0.03**	**–0.71**	**0.14**	**3.64**
4	**13**	**5.10**	**0.85**	**0.23**	**–0.93**	**0.04**	**9.35**
5	**13**	**1.20**	**0.22**	**0.06**	**–0.90**	**0.05**	**7.42**
6	13	0.12	0.03	0.01	–0.27	0.26	0.99
7	13	17.52	1.07	0.30	–0.12	0.27	0.42
8	**13**	**38.71**	**6.18**	**1.71**	**–0.94**	**0.03**	**10.07**
9	13	0.87	0.04	0.01	–0.14	0.27	0.52
10	5	101.58	19.98	8.94	–0.49	0.34	1.27
11	5	78.95	16.16	7.23	–0.41	0.37	0.99
12	6	5.42	0.24	0.10	–0.21	0.39	0.53
13	5	3.14	0.16	0.07	–0.21	0.43	0.49
14	5	0.32	0.04	0.02	–0.43	0.37	1.06
15	**5**	**9.57**	**0.68**	**0.30**	**0.77**	**0.18**	**2.72**
16	5	2.38	0.29	0.13	–0.16	0.44	0.37

Whatarangi Kumara Garden

Test No.	N/DF	Mean	SD	SE Mean	R	SER	T
1	**12**	**4.83**	**0.18**	**0.05**	**–0.71**	**0.14**	**3.49**
2	**12**	**25.77**	**10.00**	**2.89**	**0.88**	**0.07**	**6.41**
3	12	0.16	0.02	0.01	–0.28	0.27	1.03
4	**12**	**1.75**	**0.43**	**0.12**	**–0.81**	**0.10**	**4.86**
5	12	1.03	0.19	0.06	–0.52	0.21	2.12
6	12	0.24	0.03	0.01	–0.53	0.21	2.16
7	12	9.30	1.45	0.42	0.22	0.28	0.76
8	**12**	**34.82**	**6.41**	**1.85**	**–0.97**	**0.02**	**13.04**
9	**12**	**1.36**	**0.09**	**0.03**	**0.84**	**0.08**	**5.39**
10	**5**	**100.55**	**37.19**	**16.63**	**–0.83**	**0.14**	**3.37**
11	**5**	**47.17**	**17.35**	**7.76**	**–0.82**	**0.15**	**3.19**
12	6	5.05	0.79	0.32	–0.06	0.41	0.15
13	**5**	**2.99**	**0.32**	**0.14**	**–0.82**	**0.15**	**3.19**
14	**5**	**0.30**	**0.04**	**0.02**	**–0.72**	**0.21**	**2.34**
15	5	10.22	0.30	0.13	–0.40	0.37	0.99
16	5	1.60	0.56	0.25	–0.68	0.24	2.07