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Yield decline of sweet potato in the humid lowlands of Papua New Guinea

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Abstract

Sweet potato (*Ipomoea batatas* (L.) Lam) is the major staple crop in Papua New Guinea and experiments were conducted investigating factors affecting yield decline. Yields of unfertilized plots were related to rainfall and measured changes in soil properties, nematode (*Meloidogyne* sp., *Rotylenchulus reniformis*) and sweet potato weevil (*Cylas formicarius*) populations. The research took place at two locations (Hobu and Unitech) on Eutropepts and Fluvents, respectively. Yields at Hobu decreased from 18 Mg ha^{-1} in the first season to around 7 Mg ha^{-1} in the third season, but no significant yield trend was observed at Unitech. Vine biomass was not affected by the number of cropping seasons at Hobu but it decreased at Unitech with time. Marketable tuber yield at both sites was significantly correlated to rainfall, i.e. the more rain the lower the yield. Significant changes in soil chemical properties included a decrease in pH and base saturation (Hobu) and a decrease in CEC and exchangeable K (Unitech). No significant changes in soil bulk density were found and no obvious pattern was found in the nutrient concentrations of leaf samples with time. Nematode populations were high and tripled between the first and third season at Hobu. Half of the vines at Hobu and all of the vines at Unitech were damaged by sweet potato weevils, but tuber damage was higher in Hobu although the damage was only superficial. Despite the considerable variation in yield and yield determining factors, the study showed that the decline in sweet potato yield may be attributed to the high nematode infestation, accompanied by an increase in vine damage by weevils and a declining soil fertility. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Sweet potato; Yield decline; Yield variation; Soil fertility decline; Weevils; Nematodes; El-Niño effect; Papua New Guinea

1. Introduction

In many tropical regions, increased pressure on the land has resulted in the shortening of fallow periods in slash-and-burn agricultural systems and an increase in the cultivation of marginal lands. This has caused land degradation and a decline in crop production (Greenland et al., 1997). There is a need to develop continuous cultivation systems which sustain crop yield but the development is a fundamental challenge facing both farmers and agronomic researchers in tropical regions (Lal and Ragland, 1993).

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There is a fair body of knowledge of indigenous cultivation systems in which crop rotation, composting, and mixed cropping form important components (Torquebiau, 1992). Such systems are generally believed to be sustainable although crop yields are low. As population increases crop production needs to be increased either through a larger area under cultivation or through intensification and continuous cultivation. Sustainable indigenous cropping systems may, however, disintegrate when continuously cultivation is practised which may result in declining crop production. Therefore, for the development of sustainable intensified cropping systems, knowledge is required as to why and how much crop yields will decline under continuous cultivation. This has been investigated for some food crops in tropical regions, for example, rice (Cassman et al., 1997) and cassava (Howeler, 1991).

There is limited literature on factors controlling yield decline under continuous sweet potato (*Ipomoea batatas* (L.) Lam), which is an important crop throughout the Pacific region (Parkinson, 1984). Average tuber yields in the Pacific region are below 5 Mg ha^{-1} (de la Peña, 1996). In Papua New Guinea, sweet potato is the major staple crop (Bourke, 1985) but as a result of land-use intensification many agricultural systems are unstable (Allen et al., 1995). As a consequence, sweet potato yields are either declining or almost static and there is tremendous scope for yield improvement (O'Sullivan et al., 1997).

This paper presents yield patterns from continuously cultivated and non-fertilized sweet potato plots with the aim to investigate biophysical factors (soil, pests and diseases) that contribute to yield decline in sweet potato. Data were used from different experiments at two sites and these were collected as part of medium-term experiments dealing with integrated nutrient management strategies for which results have been published elsewhere (e.g. Hartemink et al., 2000). Yields are related to rainfall and the number of cropping seasons, followed by nutrient availability, nutrient removal and nematode and weevil infestation. The relationship between pests and disease and yields have been poorly investigated for sweet potato (Horton, 1988), especially in Papua New Guinea (Bourke, 1985). Although weeds are an important factor in determining sweet potato yields (Levett, 1992), they were not included in the study as all plots were kept weed-free to reduce yield variability which is common in field experiments with sweet potato (Bourke, 1985; Martin et al., 1988).

2. Materials and methods

2.1. Research sites

The research took place at two sites in the humid lowlands of the Morobe Province of Papua New Guinea. Experiments were conducted on farm at Hobu village and at the experimental farm of the University of Technology (Unitech) in Lae (Fig. 1). At Hobu experiments lasted from October 1996 to November 1998 and at Unitech experiments were conducted from June 1996 to November 1998.

Hobu (6°34′S, 147°02′E) is located 25 km north of Lae at the footslopes of the Saruwaged mountain range. The altitude at the site is 405 m asl. Rainfall records were only available from the start of the experiments in November 1996 and the monthly pattern is depicted in Fig. 2. In 1997, there was a total rainfall of 1897 mm which is well below the long-term average because of the El-Niño weather phenomena which hit the Pacific severely in 1997–1998. In the first 5 months of 1998, however, nearly as much rain fell as in the whole of 1997.

The experimental farm at Unitech (6°41′S, 146°98′E) is located 9 km north of Lae on a nearly flat alluvial plain. The altitude of the farm is about 65 m asl. Mean total annual rainfall is about 3789 mm but in the past 25 years it varied from 2594 to 4918 mm. Average daily temperatures at Unitech are 26.3°C and are slightly higher than at Hobu. During the experiments monthly rainfall was higher at Unitech than at Hobu with the exception of the beginning of 1998 (Fig. 2). The amount of rain received for the individual experiments is discussed in Section 3.

The Hobu site is located on an uplifted alluvial terrace with a slope of less than 2%. Soils at Hobu are derived from a mixture of alluvial and colluvial deposits and gravelly and stony soil horizons occur at about 0.2 m depth. Effective rooting depth is well over 0.7 m. The soils are fertile with moderately high organic carbon contents and high levels of exchangeable cations (Table 1). Topsoils are clayey and have bulk densities between 0.6 and 0.8 Mg m^{-3}. The soils are classified as mixed, isohyperthermic, Typic Eutropepts

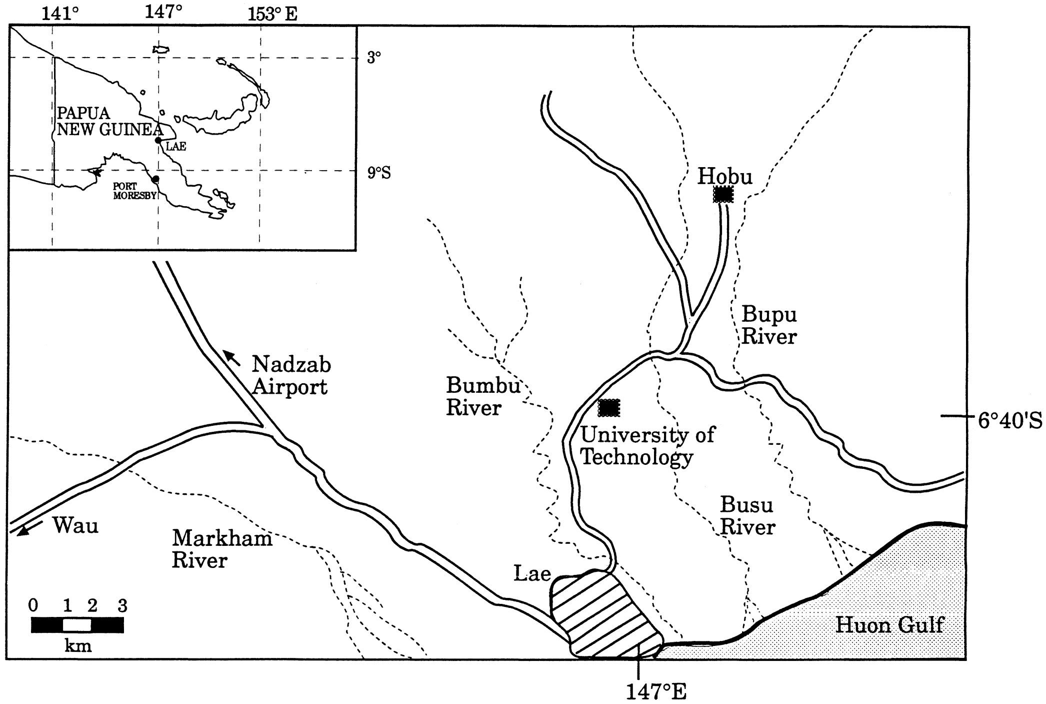

Fig. 1. Location of the research sites in the Morobe Province of Papua New Guinea.

(USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base).

The soils at Unitech are derived from alluvial deposits. The topsoils are slightly gravelly and have sandy loam textures. The stratified subsoils have fine gravel at irregular depth and sand content is above 50% (Table 1). The moderately acid topsoils are low in organic carbon, and have bulk densities of 1.10 Mg m^{-3}. The soils are classified as sandy, isohyperthermic, Typic Tropofluvents (Soil Taxonomy) or Eutric Fluvisols (World Reference Base).

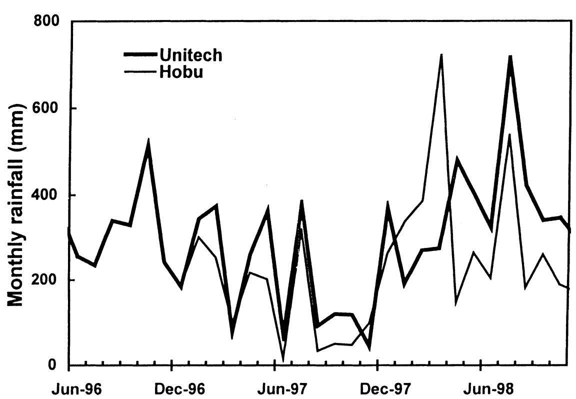

Fig. 2. Monthly rainfall at the experimental sites at Hobu (November 1996–December 1998) and Unitech (June 1996–December 1998).

2.2. Experiments

The experiments at Hobu and Unitech were part of nutrient management trials which had a slightly different experimental design at each site. At Hobu, 4-year-old secondary vegetation (mainly *Piper aduncum* L.) was slashed manually in October 1996. At Unitech, the experimental site had been under grassland since 1990 and was chisel ploughed in June 1996. All experiments at Hobu and Unitech were laid out in randomized complete block designs. Plot sizes at Hobu were 4.5 m×4.5 m or 6.0 m×6.0 m with planting distances of 0.75 m×0.75 m (17,778

Table 1
Soil chemical and physical properties of the research sites at Hobu and Unitech

Soil type	Sampling depth (m)	pH H_2O 1:5	Organic C ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Olsen P ($mg\,kg^{-1}$)	CEC pH 7 ($mmol_c\,kg^{-1}$)	Exchangeable cations ($mmol_c\,kg^{-1}$)			Base saturation (%)	Particle size fractions ($g\,kg^{-1}$)		
							Ca	Mg	K		clay	silt	sand
Hobu (Eutropepts)[a]	0–0.12	6.2	54.6	5.0	9	400	248	78	16.9	86	480	160	360
	0.12–0.23	6.3	25.4	2.3	2	355	220	84	1.9	86	620	110	270
	0.23–0.39	6.6	13.7	1.3	1	338	200	105	1.4	91	600	140	260
	0.39–0.99	7.4	2.1	0.3	4	357	189	99	1.4	82	340	110	550
Unitech (Fluvents)[b]	0–0.23	5.9	23.8	2.0	12	289	212	49	5.1	92	80	130	790
	0.23–0.42	6.1	5.0	0.4	3	303	216	46	2.2	88	140	190	670
	0.42–0.57	6.4	4.8	0.4	3	352	256	70	0.9	94	140	360	500
	0.57–0.66	6.6	5.5	0.5	7	435	334	109	0.8	100	140	130	730

[a] Samples taken from a soil pit in April 1996; grassland since 1990.
[b] Samples taken from a soil pit in February 1997; bush fallow since 1992.

plants ha^{-1}). Plot sizes at Unitech were 3.2 m×4.0 m and the sweet potato was planted at 0.4 m×0.8 m (31,250 plants ha^{-1}). All experiments at Hobu were planted with the locally important cultivar 'Hobu1' and planting material consisted of 0.3 m vine cuttings. The experiments at Unitech were planted with sweet potato cultivar 'Markham'.

At both sites, cropping seasons lasted 170 to 190 days. At harvest, vines were cut at ground level, weighed, and removed from the plot. Tubers were manually dug, counted and separated into marketable tubers (>100 g) and non-marketable tubers (<100 g). Plots were replanted directly after a harvest. Weeds were pulled out manually and not removed from the plots. No pesticides were used.

2.3. Soil and plant sampling

Soil samples for chemical analysis were taken before the planting of the first crop and after each season. Samples were collected with an Edelman auger at 9–12 random locations in a plot, mixed and a subsample of about 1 kg was taken. Air dried samples were ground, sieved (2 mm) and analyzed at the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H_2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1 M NH_4OAc percolation (pH 7.0); particle size analysis by hydrometer. Bulk density was measured using 100 ml cores at 0–0.15 m depth before the first crop and before each harvest. Cores were ovendried at 105°C for 72 h.

Mid-season leaf samples were taken in the sweet potato plots at about 80–110 days after planting (DAP). The seventh to ninth leaf, starting from the first unfolded leaf were taken from 10 randomly selected vines within each plot. At harvest, samples of vines, marketable tubers and non-marketable tubers were taken for dry matter determination and nutrient analysis. Samples were rinsed with distilled water and ovendried at 70°C for 72 h. Plant samples were analysed for nutrient content at the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analyzed for P, K, Ca and Mg using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analyzed for N on an Alpkem Rapid Flow Analyser Series 300. Data from tubers and vines samples taken at the end of the seasons were used to calculate nutrient uptake.

2.4. Nematode and sweet potato weevil counts

Counts of nematode (*Meloidogyne* sp. and *Rotylenchulus reniformis*) populations were made on soil samples collected in continuously cultivated plots at the end of the cropping seasons in 1998. For both species, only juvenile stages were considered. In each plot, a composite soil sample was obtained from 12 locations using an Edelman auger. In the laboratory, 200 ml of each soil sample was evenly spread on prepared Baermann's trays. Tap water was added until the soil was moist and left for 72 h at temperatures of about 27°C. Nematodes were extracted on a 38 μm sieve and counted on a 20-gridlined counting slide under a light microscope at 40× magnification. The data were log-transformed before average counts of nematodes were calculated.

Sweet potato weevil (*Cylas formicarius* Fab.) were counted using 1 m^2 quadrats repeated three times in each plot before the harvest. Following the weevil counts, all vines were slashed to within 0.15 m of the tuber crown and removed from the plot. Three plants were uprooted and the remaining 0.15 m vine sections were cut and placed in a paper bag. The number of vines, number of damaged vines, number of life-stages in damaged vines and vine weight were recorded. Vines were dissected to assess damage and the number of weevil-stages. Tubers were sub-divided by external appearance of the periderm as either damaged (presence of feeding and/or ovipositor marks) or undamaged (no marks). Damaged marketable tubers were sliced at the zone of maximum surface damage and categorized using the rating scale of Sutherland (1986). Damaged tubers were sliced into 2–3 mm sections to count the weevil life stages.

3. Results

3.1. Yield patterns

At Hobu, in the first season after a 5-year fallow period, sweet potato yields varied from 13 to 18 Mg ha^{-1} (Table 2). In the second season, it was observed that marketable yield could decrease (Experiment 1), increase (Experiment 2) or remain about the same (Experiment 3) when compared with the first season. In the third consecutive cropping season (Experiments 1 and 2), however, yields declined to less than half of their levels in the first season. Marketable yield at Unitech after a 6-year fallow were much lower than at Hobu but varied from 4 to 16 Mg ha^{-1}. Tuber yield at Unitech showed no distinct pattern with time.

Sweet potato vine yield at Hobu was up to 40 Mg ha^{-1} (fresh weight) in the first two cropping seasons, but declined to 26 Mg ha^{-1} in the third season. Vine yield at Unitech was 30 Mg ha^{-1} in the first season but decreased to 13 Mg ha^{-1} in the fifth season. Non-marketable tubers ranged from 1.0 to 4.0 Mg ha^{-1} at Hobu and from 2.3 to 4.5 Mg ha^{-1} at Unitech. The sweet potato at Unitech produced relatively more non-marketable tubers than at Hobu. The harvest index (i.e. marketable tuber yield/total tuber yield+vines) varied from 0.18 to 0.47 at Hobu and from 0.14 to 0.48 at Unitech.

Table 2 showed a weak relationship between the number of cropping seasons and the yield of sweet

Table 2
Marketable sweet potato yields (in Mg fresh weight per ha±1 S.D.) in unfertilized, continuously cultivated plots[a]

Cropping season	Hobu			Unitech	
	Experiment 1	Experiment 2	Experiment 3	Experiment 1	Experiment 2
1	18.3±3.7 (1230)	18.3±6.2 (1028)	13.3±18.0 (1203)	9.0±3.8 (1759)	5.4±3.2 (1799)
2	14.5±2.6 (598)	24.7±9.2 (1034)	13.2±7.2 (2091)	5.8±1.3 (1261)	44±2.0 (1538)
3	7.8±0.5 (1894)	6.9±4.4 (2214)	–[b]	16.3±8.3 (811)	–
4	12.8±2.7 (1577)	–	–	5.7±2.4 (1838)	–
5	–	–	–	6.7±2.2 (2294)	–

[a] Total rainfall received (in mm) during the growing season in parentheses (note: experiments were not run simultaneously).
[b] No data available.

Table 3
Correlation between rainfall, number of cropping seasons, sweet potato tuber yield and vine yield

Site		Marketable yield	Non-marketable yield	Vine yield
Hobu	Rainfall during the growing season[a]	−0.601**	−0.814***	0.866***
	Number of cropping seasons[b]	−0.556*	−0.622**	0.274
Unitech	Rainfall during the growing season[a]	−0.558**	0.085	−0.167
	Number of cropping seasons[b]	−0.202	0.018	−0.628**

*,**,*** Indicates significant correlation at $p<0.05$, $p<0.01$ and $p<0.001$ respectively.
[a] Covariate=number of cropping seasons (four at Hobu and five at Unitech).
[b] Covariate=rainfall received in the season.

potato at Hobu and Unitech. During the experiments the impression was formed that yields were generally higher in seasons with lower rainfall. Sweet potato is reported to be very sensitive to excess soil water during the first 20 days after planting when tubers are formed (Hahn and Hozyo, 1984) and a regression analysis between marketable yield and rainfall received during the first 20 days of growth was conducted (analysis not shown). No obvious relation was found, and instead correlation coefficients were calculated for the tuber yield, vine yield and total rainfall received in the season (Table 3). It was found that rainfall at Hobu was significantly correlated with the marketable and non-marketable tuber yield as follows: the higher the rainfall the lower the tuber yield. Vine yield was positively correlated with rainfall which suggests that the reduction in tuber yield in wetter seasons favours the growth of vine biomass. The number of cropping seasons at Hobu was significantly correlated with both marketable and non-marketable tuber yield, but not to the vine biomass: tuber yield declined under continuous cultivation but vine yield was not affected. At Unitech correlations among yield, rainfall and cropping seasons were weaker. The number of cropping seasons was not correlated with tuber yield. Marketable yield was also negatively correlated with the rainfall received during the cropping season.

3.2. Changes in soil properties and plant nutrients

Table 4 shows soil chemical properties before the first planting and after four seasons (±2 years) of continuous sweet potato cultivation. At Hobu, the topsoil pH had decreased by 0.4 units accompanied by a decrease in base saturation. Changes in topsoil properties at Unitech included a decrease in cation exchange capacity (CEC) and exchangeable potassium. Bulk density was not altered in the Hobu soils under continuous sweet potato cultivation but a slight decrease was found in the bulk density of the

Table 4
Changes in soil chemical properties under continuous sweet potato cultivation without fertilizers (sampling depth 0–0.15 m)

Site[a]	Sampling time	pH H_2O (1:5 w/v)	Organic C ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Olsen P ($mg\,kg^{-1}$)	CEC pH 7 ($mmol_c\,kg^{-1}$)	Exchangeable cations ($mmol_c\,kg^{-1}$)			Base saturation (%)
							Ca	Mg	K	
Hobu (Eutropepts)	Before planting	6.2	69.9	6.0	10	405	268	61	12.2	84
	After four seasons[b]	5.8	71.3	5.9	6	466	227	59	8.4	63
	Difference	$p<0.01$	ns	ns	ns	$p<0.01$	ns	ns	ns	$p<0.001$
Unitech (Fluvents)	Before planting	5.9	22.1	1.9	30	342	247	39	11.2	88
	After four seasons[b]	5.9	21.7	1.7	24	299	224	45	8.6	93
	Difference	ns	ns	ns	ns	$p<0.05$	ns	ns	$p<0.05$	ns

[a] Data from Experiment 1 at Hobu and Unitech; values are the arithmetic mean of four plots.
[b] One season is about 170–190 days.

Table 5
Concentration of major nutrients (in $g\,kg^{-1}\pm1$ S.D.) in sweet potato leaves of unfertilized plots under different periods of cultivation[a]

Site	Cropping season	N	P	K	Ca	Mg	S
Hobu	1	33.0±2.8	3.7±0.4	36.4±2.1	11.7±1.2	4.6±0.4	2.7±0.1
	2	28.7±3.7	2.8±0.1	33.6±2.8	9.5±0.8	4.0±0.5	2.1±0.2
	3	19.4±0.7	3.2±0.3	31.3±3.4	8.1±0.6	3.8±0.2	2.9±0.1
	4	28.3±2.5	3.1±0.4	32.1±3.6	10.6±0.8	2.9±0.4	2.4±0.2
Unitech	1	26.6±6.3	3.8±0.4	32.7±1.4	9.6±1.2	2.6±0.3	2.1±0.3
	2	25.1±4.6	4.7±0.3	36.1±1.9	10.7±1.7	3.4±0.2	2.0±0.1
	3	26.9±1.0	5.4±1.1	36.3±2.6	12.9±1.9	3.8±0.6	2.7±0.1
	4	na[b]	4.3±0.2	19.9±8.9	12.6±1.8	4.0±0.3	2.0±0.2
	5	na	4.9±0.6	28.6±5.6	9.1±0.8	3.2±0.1	2.4±0.2
Critical concentration[c]		40.0	2.2	26.0	7.6	1.2	3.4

[a] Data from leaf samples taken in the middle of the growing season, i.e. between 80 and 110 DAP.
[b] Not available.
[c] Critical nutrient concentration for deficiency from O'Sullivan et al. (1997) based on experiments in solution culture.

Unitech soils up to the fourth season (data not shown). This can be expected as harvesting sweet potato involves topsoil digging with a fork to about 0.2 m depth.

Although no obvious pattern of decline was found in the leaf nutrient concentrations, the highest concentration of all major nutrients was found in the first cropping season at Hobu (Table 5). Nitrogen and sulphur were below the critical concentration for deficiency in all seasons (O'Sullivan et al., 1997) but other major nutrients were above the critical limits. Minor nutrient concentrations were exceeding the critical levels as given by O'Sullivan et al. (1997) except for boron which concentrations were only slight below the critical level (Table 6).

A decrease in leaf nutrient concentration was expected because large amounts of nutrient are removed with the sweet potato harvest. Table 7 shows the amount of nutrients removed with the first harvest at Hobu and Unitech. Considerable amounts of potassium are removed with the tubers and vines. The table shows that the largest amount of nutrients is removed with the vines. At Hobu, sweet potato removed per 10 $Mg\,ha^{-1}$ of fresh marketable tubers about 16 kg N, 7 kg P and 51 kg $K\,ha^{-1}$ and at Unitech this was found to be similar.

Table 6
Concentration of minor nutrients (in $mg\,kg^{-1}\pm1$ S.D.) in sweet potato leaves of unfertilized plots under different periods of cultivation[a]

Site	Cropping season	Fe	B	Mn	Zn	Cu	Mo
Hobu	1	159±48	47±4	57±3	39±6	13±2	1.2±0.3
	2	105±18	32±3	57±3	45±17	12±2	1.2±0.3
	3	106±17	31±6	42±4	20±2	8±2	na[b]
	4	270±115	39±2	52±10	33±2	15±2	0.5±0.2
Unitech	1	164±15	39±8	42±7	20±1	5±3	na
	2	225±165	33±6	42±3	23±3	5±2	na
	3	198±10	45±9	51±6	25±1	9±1	na
	4	99±31	35±7	40±5	27±3	9±1	na
	5	na	34±1	45±5	26±1	13±1	na
Critical concentration[c]		33	40	19	11	4–5	0.2

[a] Data from leaf samples taken in the middle of the growing season, i.e. between 80 and 110 DAP.
[b] Not available.
[c] Critical nutrient concentration for deficiency from O'Sullivan et al. (1997) based on experiments in solution culture.

Table 7
Nutrient uptake (in kg ha^{-1}±1 S.D.) of unfertilized sweet potato[a]

Site	Plant part	Fresh yield (Mg ha^{-1})	N	P	K	Ca	Mg
Hobu	Marketable tubers	18.2±3.7	30±6	12±2	93±20	5±1	5±1
	Non-marketable tubers	4.0±1.0	8±2	3±1	25±6	1±0.5	1±0.5
	Vines	26.2±4.8	80±8	18±2	180±30	61±13	20±2
	Total		118±10	33±3	298±46	67±12	26±2
Unitech	Marketable tubers	9.0±3.8	15±17	7±3	39±19	4±2	2±1
	Non-marketable tubers	2.9±1.3	5±5	2±1	12±5	1±0.5	1±0.5
	Vines	30.1±8.2	59±21	22±2	189±15	37±8	10±2
	Total		79±40	31±5	241±23	42±10	13±3

[a] Data from first cropping season of Experiment 1 at Hobu and Unitech.

3.3. Nematodes and weevils

Nematode counts in soil extracts from the Hobu site showed that the juvenile population of *Meloidogyne* sp. increased with increasing number of cropping seasons (Table 8). The increase in number of nematodes was significant between the first and second season but the number of nematodes in soils under three or four seasons did not differ significantly. Although the species of *Meloidogyne* could not be identified with certainty, common root-knot species under sweet potato in Papua New Guinea are *M. incognita* and *M. javanica* (Bridge and Page, 1984b). In the Unitech soils under sweet potato, no root-knot nematodes were observed but a high population of reniform nematodes (*Rotylenchulus reniformis*) was found.

At Hobu, the aboveground population of weevils at harvest was very low for both seasons but a considerable portion of the marketable tubers and vines was damaged (Table 9). Damaged tubers over both seasons were predominantly categorized in category 1, i.e. only superficial damage to the periderm (Sutherland, 1986). At Unitech, the aboveground population of weevils was relatively high. The degree of vine damage was very high at the end of the fourth season and slightly decreased in the following season. There was no reduction in the number of weevil life stages per damaged vine in the fifth season. The high level of vine damage was not reflected in tuber damage.

4. Discussion

Considerable yield variation was found within cropping seasons which is not uncommon in field experiments (de Steenhuijsen Piters, 1995) especially with sweet potato (Martin et al., 1988). Overall, sweet potato yields were lower at Unitech than at Hobu which could result from differences in soils, weather or the cultivar grown. Yields at both locations fall within the range given for lowland conditions in Papua New Guinea (Bourke, 1985) and are above the average given for Oceania (Horton, 1989; de la Peña, 1996).

Two important trends emerged from the statistics on the yield data. Firstly, it was noticed that yields were negatively affected by rainfall and secondly,

Table 8
Nematode counts (number 200 ml^{-1}±1 S.D.) in unfertilized soils under sweet potato

Hobu			Unitech		
Cropping season	Sampled plots	Nematodes[a]	Cropping season	Sampled plots	Nematodes[b]
1	12	65±52	4	4	1795±329
3	4	211±73	5	4	1208±250
4	4	157±52			

[a] Root-knot nematodes (*Meloidogyne* sp.).
[b] Reniform nematodes (*Rotylenchulus reniformis*).

Table 9
Weevil counts and vine and tuber damage in unfertilized sweet potato plots of different age[a]

Site	Cropping season	Weevil counts (No. m^{-2})	Tubers		Vines	
			Damage (%)	Life stages per tuber (No.)	Damage (%)	Life stages per vine (No.)
Hobu	3	0.0	78	0.25	52	1.5
	4	0.5	35	5.25	55	0.5
Unitech	4	12.8	0	0	100	3.5
	5	1.1	0	0	100	5.3

[a] Values are the average of four sampled plots.

tuber and vine yields declined under continuous cultivation. Both trends are discussed here.

4.1. Yield and rainfall

Marketable tuber yield was depressed in seasons with high rainfall which was observed at both sites regardless of the cropping history. Although there are cultivar differences (Ton and Hernandez, 1978; Martin, 1983) sweet potato is reported to be very sensitive to excess soil water during the first 20 days after planting but regression analysis failed to show a relation. The boundary of 20 days established in greenhouse trials is apparently different under field conditions. Later in the growing season sweet potato is susceptible to excess water because tubers may rot, but this did not occur in these experiments.

Excess soil moisture may also have indirect effects. In wet seasons, values up to 60% water-filled pores space (WFPS) were measured in the Hobu soils at which denitrification may become significant (Linn and Doran, 1984). In the sandy soils of Unitech, such high levels of WFPS were not found and the potential for denitrification is much lower. Denitrification means loss of nitrogen which may thus affect growth. At Hobu, the lowest leaf nitrogen concentration was found in the season with the highest rainfall (third season, Tables 2 and 5). It would be expected, however, that the loss of nitrogen would reduce vine yield but the opposite was found. It therefore seems likely that denitrification is not a major explanation for depressed yields in seasons with high rainfall.

There are generally lower levels of photosynthetically active radiation (PAR) because of cloud cover in seasons with high rainfall. Sweet potato is a light-loving plant and sensitive to shading (Roberts-Nkrumah et al., 1986). It is likely that reduced PAR would not only affect tuber yield but also vine growth. Statistics showed, however, that total vine yield was positively related to rainfall at Hobu whereas no significant correlation was found at Unitech (Table 4). This suggests that also a reduced PAR is possibly not a major factor explaining yield depression.

4.2. Yield decline

Continuous cultivation of sweet potato had different effects at the different sites: in the more fertile soils (Hobu) continuous cultivation decreased tuber yields but not vine yield. In soils with lower fertility (Unitech) continuous cultivation did not affect tuber yields which were already low, but significantly reduced vine yield. The reduction in vine biomass had no effect on tuber yield. It seems that continuous cultivation first reduces tuber yields and then reduces vine production.

Few changes were observed in most soil chemical properties despite the heavy drain of nutrients by the yield. This is probably because of the relatively short time between the sampling (2 years) as changes in soil chemical properties are commonly not detected with standard soil analytical methods within such periods (Young, 1997). Soil chemical properties had not declined to low levels. For example, the pH of 5.8 at Hobu and 6.0 at Unitech is still favourable for sweet potato (Constantin et al., 1975), as are the levels of available phosphorus and exchangeable cations (O'Sullivan et al., 1997).

Concentrations of major nutrients in the leaves were all adequate except for nitrogen and sulphur which were below the critical level of O'Sullivan et al. (1997) at both sites. Boron levels at both Hobu and Unitech were slightly below the critical level. Differences in leaf nutrient concentrations between the sites reflects soil, climatic and cultivar differences (Walker, 1987; Bruns and Bouwkamp, 1989). Despite the low leaf nitrogen levels fertilizer trials generally failed to show a tuber yield response to sulphur-containing nitrogen fertilizers (Hartemink et al., 2000) which supports the observation that sweet potato can produce reasonable yields in soils with low native nitrogen and without nitrogen fertilizer (Hill et al., 1990).

Declining yields could also result from decreasing levels of micronutrients, but no trend in the leaf nutrient concentrations was observed. Complete omission trials in the greenhouse with Hobu soil showed a vegetative growth response to zinc but field trials failed to show a response (Ila'ava and Hartemink, unpublished data). Although micronutrients limit sweet potato production in many areas of Papua New Guinea (Bourke, 1983; O'Sullivan et al., 1997) micronutrients are possibly not limiting at Hobu or Unitech.

Distinctly different nematode species were found in Hobu and Unitech soils. The difference could either be competition between the two species (Thomas and Clark, 1983) or differences in soil conditions (Barker and Koenning, 1998) and cultivars (Clark and Wright, 1983). Populations of *Meloidogyne* sp. and *R. reniformis* in the soils of Hobu and Unitech were high. Both nematode species have destructive effects on sweet potato, reducing yield and quality (Clark and Wright, 1983) as they have a root pruning and damaging effect. Clark and Wright (1983) found that 600–4000 *R. reniformis* per 200 ml significantly reduced tuber yield. Much lower threshold values have been reported for *Meloidogyne* sp. (Thomas and Clark, 1983). Nematodes levels exceeded the threshold values in the experiments at Hobu and Unitech and it is therefore likely that nematodes reduced sweet potato yields. This is in line with earlier reports on plant nematodes in Papua New Guinea (Bridge and Page, 1984a).

The situation for sweet potato weevils is less clear-cut as there seems to be little relation between number of weevils in the foliage (vines) and damaged tubers and vines. Factors which determine tuber damage are related to aboveground weevil population, soil type, rainfall and cultivar characteristics (Sutherland, 1986). At Hobu, weevil populations were far lower than at Unitech despite the fact that there is less rainfall at Hobu which generally favours weevil populations (Bourke, 1985). Weevils fail to penetrate in wet soil but can penetrate easily in dry soils (Teli and Salunke, 1994). The lower weevil populations at Hobu resulted in less vine damage but tuber damage was higher. The damage was superficial only and has limited effect on the marketability of the tubers. The higher vine damage at Unitech accompanying high number of weevils in the vines agrees with the findings of Sutherland (1986). The high degree of vine damage at Hobu (50%) and Unitech (100%) indicates that weevils were abundant at both sites and it is likely that the vine damage affected tuber yield.

In conclusion, soil and leaf data suggest that a declining soil fertility may not be the main cause for the decline in sweet potato yields. A combination of increased levels of nematodes, vine damage by the weevils, and a decline in soil chemical properties contribute to yield decline of sweet potato under continuous cultivation. In addition, it was found that dry weather conditions as a result of the El-Niño oscillation favoured sweet potato production under the conditions of the experiments. This is possibly related to better soil aeration and suggests that the conditions in the humid lowlands of Papua New Guinea are not optimal for sweet potato cultivation.

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