A REVIEW OF COFFEE NUTRITION RESEARCH IN PAPUA NEW GUINEA

Paul E. Harding[1] and Potaisa H. Hombunaka[2]

ABSTRACT

Research on coffee nutrition conducted in Papua New Guinea between 1954 to 1998 is reviewed and deals with arabica coffee with and without shade and under both smallholder and plantation conditions. Coffee leaf nutrient contents can respond within eight months to fertilizer applications but seasonal variation in leaf nutrient contents is large. Leaf nutrient contents are generally higher in shaded coffee. Unshaded coffee nearly always responds to N fertilizers although two or more years are required before the response occurs. Without N fertilizers, coffee will die within a few years when there is no shade. Large applications of N have, however, been shown to strongly acidify the soils which is accompanied by a decrease in exchangeable cations. The application of K fertilizers is beneficial in some soils although negative effects on the uptake of Ca and Mg have been found. In some soils positive reponses to P fertilizers occur with young coffee but no significant response to Mg fertilizers have been recorded in Papua New Guinea. Shaded coffee rarely responds to N fertilizers and negative effects have also been found. Shaded coffee commonly responds to K fertilizers up to 400 kg K_2O/ha. Positive reponses to Zn and B have also been recorded. Although substantial yield increases may be obtained with inorganic fertilizer applications, recycling of coffee litter, prunings and processing waste products, can reduce fertilizer applications by up to 20%.

Keywords: *arabica coffee, nutrition, fertiliser, shade, waste products, plantations, smallholder gardens, Papua New Guinea.*

INTRODUCTION

Coffee is PNG's most important rural export earner, and is the major source of income for one-third of the country's population. About 1 million bags (or 60,000 tonnes) of green bean are exported each year. Both arabica (*Coffea arabica* L.) and robusta (*Coffea canephora* Pierre ex Froehner) coffee are grown in PNG. The main arabica and robusta coffee growing areas in PNG have been identified by Harding (1985a). Robusta coffee accounts for less than 5% of PNG's total coffee production, and is grown below 600 m a.s.l. The bulk of PNG's coffee is arabica coffee, and is grown above 600 m a.s.l. in thirteen of the nineteen Provinces. More than 80% of the total production is grown by smallholders, of which there are approximately 280,000, about 15% is grown by around 100 plantations, and the balance is grown by several hundred managed blocks. The total area under coffee probably exceeds 55,000 ha equivalent of pure stand coffee (Robinson 1983).

Following the Second World War, coffee was not an immediate priority for the Department of Agriculture. However, as the coffee industry grew, the need for coffee research was recognised by the Department. Thus, formal coffee research in PNG was initiated by the Department of Agriculture in 1954 (Carne and Charles 1966). The arabica coffee research programme was based at Aiyura Highlands Agricultural Experiment Station (HAES), and supplemented by trials at the Agricultural Extension Centres at Goroka (EHP) and Korn Farm (WHP). A relatively small robusta coffee research programme was based at Kerevat LAES, with a few activities undertaken at Saramandi Research Station (East Sepik Province) and Bubia Research

[1] Lumle Agricultural Research Centre, PO Box 1, Pokhara, Nepal.
EMAIL: dirlarc@mos.com.np
[2] Coffee Industry Corporation Ltd, PO Box 105, Kainantu, Papua New Guinea.

Station (Morobe Province), but this ceased in 1980 (Byrne 1984). Coffee research continued to be a priority throughout the 1950s and 1960s, but during the seventies other commodities, particularly food crops, were given a higher priority by the Department. With limited resources available, the Department considered that cash crop research should be supported by the cash crop industries themselves. Thus, in 1981 the Coffee Industry Board established a small coffee research department, based at its Headquarters in Goroka.

In early 1986, the PNG Coffee Research Institute (CRI) was established at Aiyura HAES, using land and facilities provided by the Department, but funded by a "research cess" collected by the CIB from every kg of green bean coffee exported. The old coffee trials were adopted by the CRI, and a new coffee research programme commenced in 1986. The CRI subsequently established a Highlands Substation at Panga, Western Highlands Province in 1988, and a Lowlands Substation at Omuru, Madang Province in 1993. Coffee nutrition research in PNG has therefore been undertaken almost exclusively with arabica coffee, and in this review the word coffee may be read as arabica coffee.

Initially, since the coffee industry in PNG was primarily plantation based, and most plantations grew shaded coffee, coffee research was undertaken in shaded plantation coffee conditions at Aiyura, Goroka and Korn Farm. Later, as plantation managers removed their shade trees to increase coffee yields, research was also undertaken in unshaded plantation conditions, on Aiyura and also several plantations. Little or no research has been carried out under traditional smallholder conditions, since these were seen as a low-input, low-output, management system which was apparently self-sustaining. Recent modelling of N dynamics by Harding (1994) has tended to confirm this to be true, at least in the absence of major pests or diseases. However, the outbreak of coffee leaf rust (*Hemileia vastatrix*) in 1986, necessitated the rehabilitation of thousands of traditional smallholder coffee gardens. Such improved coffee gardens, with reduced shade, formal pruning systems, and higher yields, were no longer necessarily self-sustaining. Thus, in 1986 the CRI began coffee nutrition studies in rehabilitated smallholder coffee gardens.

THE SOIL UNDER COFFEE

Harding (1984) and Harding (1985 b) have described the arabica and robusta coffee soils of PNG respectively. The most common coffee soils are deep, well to imperfectly drained, fine textured, ash-derived soils with high P-retention capacities and high organic matter contents (Hydrandepts, Eutrandepts and Dystrandepts which are all classified as Andisols in the recent USDA Soil Taxonomy); deep, well to imperfectly drained, fine textured, non-ash soils with low to moderate P-retention capacities and high organic matter contents (Humitropepts, Eutropepts and Dystropepts); poorly to very poorly drained, fine textured, non-ash soils with high organic matter contents (Tropaquepts); and shallow, well to imperfectly drained, medium to coarse textured, soils on steep slopes (Troporthents). The Hydrandepts and Humitropepts in particular, are also acidic to strongly acidic, with a low base saturation.

Hart and Southern (1969) described coffee soil sample preparation and analytical methods. Harding (1986) compiled guidelines on collecting and preparing coffee soil samples, analytical methods, and interpretation of the analytical results (Table 1).

SOIL RESPONSES TO NUTRIENT APPLICATIONS

Shaded coffee

Parfitt (1976) recorded an increase in total soil nitrogen under *Casuarina oligodon* of 0.015-0.018% per year. Thiagalingam and Fahmy (1981) recorded increases in both soil nitrogen and carbon levels under mature *Casuarina oligodon* when compared with levels under young trees. During the first five year cycle (1986-1991) of a smallholder fertiliser trial in the Eastern Highlands (SPN 2.01), no significant fertiliser effects on soil properties were recorded. During the second production cycle (1991-1997) however, soil exchangeable K levels declined in the absence of K fertiliser (Hombunaka unpublished data).

In a series of nutritional studies (Harding 1993 a, b, c) this author (Harding (1993 c) reported that in a fertiliser trial under shaded coffee on Koban Plan-

Table 1. **Ctritical levels for interpretetation of Soil Analytical Data (Source: Authors' values, based on reconciliation of published data).**

	units	very low	low	medium	high	very high
pH H_2O[1]		<4.5	4.5-5.2	5.3-6.5	6.6-7.5	>7.5
Total N	%	<0.10	0.10-0.19	0.20-0.49	0.50-1.00	>1.00
Organic C	%	<2.0	2.0-3.9	4.0-9.9	10.0-20.0	>20.0
Exch. K	cmol/kg	<0.10	0.10-0.19	0.20-0.59	0.60-1.20	>1.20
Exch. Ca	cmol/kg	<2.0	2.0-4.9	5.0-9.9	10.0-20.0	>20.0
Exch. Mg	cmol/kg	<0.3	0.3-0.5	0.6-0.9	1.0-6.0	>6.0
Exch. Na	cmol/kg	<0.10	0.10-0.29	0.30-0.69	0.70-2.00	>2.00
CEC	cmol/kg	<5	5-10	11-25	>25	-
ECEC	cmol/kg	<2	2-5	6-10	11-20	>20
Base Satn.	%	<10	10-19	20-60	>60	-
Al Satn.	%	<20	20-39	40-59	60-80	>80[3]
Avail P.	µg/ml	<10	10-19	20-30	>30	-
P retn.	%	<10	10-59	60-84	85-95	>95
Reserve K[4]	cmol/kg	<0.10	0.10-0.19	0.20-0.34	0.35-0.50	>0.50
Reserve Mg[5]	cmol/kg	<3.0	3.0-6.9	7.0-14.9	15.0-30.0	>30.0
Soluble B[6]	µg/g	<0.50	0.50-0.99	1.00-1.99	2.00-5.00	>5.00
Sulphate-S[7]	µg/g	≤5	5-14	15-49	50-150	>150
DTPA[9] Fe	mg/kg	<4.5				-
DTPA[9] Mn	mg/kg	<3.0				>140[8]
DTPA[9] Cu	mg/kg	<0.6				>11[8]
DTPA[9] Zn	mg/kg	<0.5				>7[8]

[1] Soil:water ratio of 1:5
[2] Exch. K should also represent at least 3% of total exchangeable bases
[3] Al saturation greater than 80% is toxic to coffee.
[4] Extracted in boiling nitric acid.
[5] Extracted in boiling 1M hydrochloric acid.
[6] Determined in hot water extract.
[7] Extracted with 0.04M calcium phosphate and the sulphur extract measured turbidimetrically following treatment with charcoal and an acid digestion to remove organic matter.
[8] Trace element contents in excess of these values may be toxic.
[9] Determined in diethylene triamine pentacetic acid using the method of Lindsay and Norvell (1978). Figures are only tentative.

tation (SPN 1.02), application of sulphate of ammonia produced a pronounced negative effect on topsoil pH, which decreased with increasing applications of nitrogen, up to 400 kg N/ha/y. At this application rate topsoil pH decreased from 5.2 to 4.3 over four years (Table 2). The acidification effect was recorded to depths of at least 60 cm below the soil surface (Table 3). Nitrogen did not produce a significant negative effect on topsoil exchangeable potassium levels (Table 2), although leaching of potassium down the soil profile occurred because of the soil acidification (Table 3). Similarly, nitrogen applications induced leaching of magnesium and calcium down the soil profile, much of the magnesium and calcium being leached below 60 cm from the surface (Table 3). Harding (1993 c) also reported significant negative nitrogen effects on topsoil exchangeable magnesium and calcium contents (Table 2).

Potassium applications resulted in a significant positive effect on topsoil exchangeable potassium levels (Table 4), but also tended to have a negative effect on topsoil exchangeable magnesium and calcium levels (Harding 1993 c). Applications of phosphorus fertiliser produced a significant positive effect on topsoil available phosphorus levels. When these effects are compared with those from an

Table 2. **Nitrogen fertiliser effects on topsoil properties after four years of nitrogen applications (data from 1991).**

kg N/ha/y	Number of plots	pH			Total N(%)			Exchangeable cations (cmol/kg) K			Mg			Ca		
		KS[1]	KU[1]	AU[1]	KS	KU	AU	KS	KU	AU	KS	KU	AU	KS	KU	AU
100	12	5.0	4.8	4.8	0.96	0.77	0.54	0.37	0.49	0.63	0.40	0.45	1.01	2.0	1.6	3.5
200	12	4.7	4.5	4.6	0.91	0.80	0.62	0.32	0.39	0.40	0.26	0.30	0.80	1.3	1.2	3.3
300	12	4.4	4.3	4.4	0.95	0.79	0.55	0.33	0.42	0.42	0.13	0.21	0.54	0.7	0.8	2.2
400	12	4.3	4.2	4.1	0.88	0.78	0.55	0.35	0.41	0.36	0.11	0.16	0.35	0.4	0.5	1.3
F-prob.[2]		***	**	**	ns	ns	ns	ns	**	ns	***	**	**	***	**	**
S.E.D.[3]		0.04	0.05	0.10	0.04	0.022	0.020	0.020	0.016	0.099	0.040	0.043	0.137	0.20	0.18	0.50

[1] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee.
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1%
[3] Standard error of the means (16 *df*)

Table 3. **Nitrogen and potassium fertiliser effects on pH and exchangeable cations at four depths under coffee at Koban Plantation and Aiyura HAES (1991 data).**

		N=0, K_2O=0 kg/ha/y				N=100, K_2O=400 kg/ha/y				N=400, K_2O=400 kg/ha/y			
	Depth		ex. Cations (cmol/kg)				ex. cations (cmol/kg)				ex. cations (cmol/kg)		
Location	(cm)	pH	K	Mg	Ca	pH	K	Mg	Ca	pH	K	Mg	Ca
Koban shaded	0-15	5.7	0.23	1.20	6.1	4.6	0.65	0.18	0.5	4.2	0.57	0.08	0.6
	15-30	5.6	0.17	0.71	3.1	5.2	0.32	0.49	2.9	5.1	0.81	0.34	4.9
	30-45	5.7	1.04	1.28	3.3	5.2	0.40	1.48	4.9	5.0	0.64	1.81	6.2
	45-60	5.4	0.90	0.96	3.8	5.2	0.13	1.51	4.6	5.1	0.36	2.23	5.7
Koban unshaded	0-15	5.0	0.24	0.23	0.8	4.8	0.70	0.49	1.6	4.2	0.64	0.14	0.3
	15-30	5.2	0.17	0.27	1.7	5.2	0.38	0.83	2.8	4.5	0.42	0.17	0.8
	30-45	5.3	0.26	0.73	3.6	5.1	0.75	2.50	5.8	4.9	0.47	1.47	5.3
	45-60	5.1	0.21	0.87	3.4	5.0	0.67	2.15	4.8	4.9	0.51	1.93	5.0
Aiyura unshaded	0-15	5.3	0.23	1.34	4.8	4.8	1.99	0.56	3.3	4.1	0.63	0.22	0.4
	15-30	5.0	0.12	1.02	2.5	4.9	0.58	1.35	4.1	4.3	0.59	0.31	1.3
	30-45	5.2	0.15	1.39	2.4	4.9	0.44	1.77	4.2	4.7	0.31	0.78	2.0
	45-60	5.1	0.19	2.41	2.4	4.9	0.13	1.51	3.0	4.9	0.36	2.69	5.1

[1] Soil properties measured in September 1991 after four years of fertiliser applications.

Table 4. **Potassium fertiliser effects on topsoil properties after four years of potassium applications.**

kg K_2O/ha/y	Number of plots	Exch. K (cmol/kg)			Exch. Mg (cmol/kg)			Exch. Ca (cmol/kg)		
		KS[1]	KU[1]	AU[1]	KS	KU	AU	KS	KU	AU
0	16	0.19	0.23	0.17	0.26	0.32	0.65	1.3	1.2	2.7
200	16	0.36	0.44	0.38	0.25	0.28	0.75	1.1	1.1	2.7
400	16	0.48	0.61	0.81	0.17	0.23	0.62	0.9	0.8	2.4
F-Prob.[2]		***	**	**	ns	**	ns	ns	**	ns
SEM[3]		0.020	0.014	0.086	0.030	0.037	0.18	0.16	0.18	0.43

[1] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[3] Standard error of the means (16 *df*)

adjacent unshaded trial, it would appear that the shade trees have a moderating effect on soil acidification, but reduced topsoil exchangeable potassium and magnesium contents more rapidly.

Unshaded coffee

In fertiliser trials under unshaded coffee on Aiyura and Koban Plantation (SPN 1.03 and 1.01), Harding (1992 a and 1993 b) reported that application of the nitrogenous fertiliser (sulphate of ammonia, SoA) produced a pronounced negative effect on topsoil pH, which decreased with increasing applications of nitrogen, up to 400 kg N/ha/y (Table 2). The acidification effect was recorded to depths of at least 60 cm below the soil surface (Table 3). Nitrogen also produced a highly significant negative effect on topsoil exchangeable potassium levels (Table 2), due to leaching of potassium down the soil profile because of the nitrogen induced soil acidification. Similarly, nitrogen applications induced leaching of magnesium and calcium down the soil profile (Table 3), much of the magnesium and calcium being leached below 60 cm from the surface. Application of potassium produced a highly significant positive effect on topsoil exchangeable potassium levels (Table 4). On Koban Plantation, those plots receiving no potassium fertiliser, topsoil exchangeable potassium contents decreased from a mean of 0.79 cmol/kg to only 0.23 cmol/kg over a four year period - that is from a high level to the lower end of the medium range (Table 1). Applications of 400 kg K_2O/ha/year were sufficient to maintain high levels of topsoil exchangeable potassium. Potassium also tended to have a negative effect on topsoil exchangeable magnesium and calcium levels (Table 4), although the effect was not always statistically significant.

A highly significant nitrogen x potassium interaction effect was also recorded in the topsoil exchangeable potassium contents, which increased most at low nitrogen and high potassium application rates (Harding 1993 b). Phosphorus and magnesium applications produced no significant effects on the soil, although topsoil available phosphorus and exchangeable magnesium levels respectively were increased.

LEAF NUTRIENT CONTENT STUDIES

Hart and Southern (1969) were the first in PNG to consider the most appropriate methods for collecting coffee leaf samples and analysing them in the laboratory. Southern (1966) and Hart (1969) provided early guidelines for interpreting the analytical results from coffee leaf analyses. Building on the pioneering work of Southern and Hart, and utilising results from other parts of the world, Harding (1986) compiled comprehensive guidelines on collecting and preparing coffee leaf samples, analytical methods, and interpretation of the analytical results (Table 5).

Table 5. **Critical levels of nutrients in arabica coffee leaves (Willson 1985).**

nutrient	unit	deficient	subnormal	normal	excess
N	%	<2	2.00-2.60	2.61-3.50	<3.5
P	%	<0.10	0.10-0.15	0.16-0.20	>0.20
K	%	<1.50	1.50-2.00	2.11-2.60	>2.60
Ca	%	<0.40	0.40-0.75	0.76-1.50	>1.50
Mg	%	<0.10	0.10-0.25	0.26-0.40	>0.40
S	%	<0.10	0.10-0.15	0.16-0.25	>0.25
Fe	mg/kg	<40	40-70	71-200	>200
Mn	mg/kg	<25	25-50	51-100	>100
Zn	mg/kg	<10	10-15	16-30	>30
Cu	mg/kg	<3	3-7	8-20	>20
B	mg/kg	<25	25-40	41-90	>90
Al	mg/kg				>60
Mo	mg/kg	<0.5	0.5-0.8		

Table 6. **Effects of nitrogen and potassium applications on leaf nutrient contents[1] in smallholder coffee gardens, 1991.**

kg N/ha/y	number of plots	N (%)	Mn (mg/kg)	Cu (mg/kg)
0 N	48	2.6	157	15
50 N	48	2.7	186	13
100 N	48	2.8	237	13
F-prob.[2]		**	**	**
SEM[3]		0.02	9.1	0.4
Kg K_2O/ha/y		K (%)	Mg (%)	B (mg/kg)
0 K_2O	48	1.5	0.5	33
50 K_2O	48	1.6	0.5	30
100 K_2O	48	1.8	0.4	29
F-prob[2]		**	**	**
SEM[3]		0.1	0.1	1.0

[1] Leaf nutrient contents in June 1991, after four years of fertiliser applications.
[2] ns = not significant; ** = significant at 1% level.
[3] Standard error of the means

Seasonal fluctuations

Southern (1969) was the first in PNG to show the existence of seasonal fluctuations in the nutrient contents of coffee leaves. His studies of research station trials extended over a period of almost three years, but unfortunately, it was not possible to collect leaf samples consistently throughout this period. More recently, three studies of coffee leaf nutrient contents were conducted over a three year period (1987 to 1990), with monthly sampling throughout the period. These studies involved twenty unfertilised smallholder coffee gardens in the Eastern Highlands (SPN 8.02) (Harding 1991 a); seven fertilised coffee blocks on Aiyura HAES (SPN 8.01); and six fertilised plantation blocks in the Western Highlands (SPN 8.03) (Harding 1991 b).

These studies clearly demonstrated that coffee leaf nutrient contents exhibit, often very pronounced, seasonal fluctuations. These fluctuations, which are not the same for all nutrients, can be related to the annual development cycle of the coffee, and the annual rainfall distribution pattern (Harding 1993 a). They are therefore relatively predictable. Meaningful interpretation of leaf analytical data is therefore only possible if the date of leaf sample collection is known, and the seasonal fluctuations in leaf nutrient contents are understood.

These studies greatly facilitate such interpretations. The studies also showed that fertiliser applications produced surprisingly little effect on the seasonal fluctuations of leaf nutrient contents, although leaf nutrient levels *per se* were increased by fertiliser applications. The seasonal fluctuations in leaf nutrient contents also provide some indications as to when particular nutrients are in shortest supply, and therefore likely to be most efficiently utilised if applied as fertiliser. This has recently been confirmed in a fertiliser timing trial (SPN 1.04) on Ondu Plantation (Hombunaka and Harding 1994).

Leaf nutrient content responses to fertiliser applications - Shaded coffee

A fertiliser trial under smallholder coffee in the Eastern Highlands (SPN 2.01) showed a significant leaf N response to applications of N, during the first five year production cycle, although this was not agronomically important since all leaf N levels were already in the normal range (Harding 1994). N applications also resulted in a significant, positive effect on leaf manganese contents, and a negative effect on leaf copper contents (Table 6). Similarly, potassium applications produced a significant, positive effect on leaf K contents, and negative effects on leaf magnesium and boron contents (Table 6).

Southern (1969) reported little or no effect on leaf nitrogen levels when nitrogen was applied to shaded plantation coffee at Goroka (ACA 21) or on Korn Farm (ACA 25). Leaf nitrogen did increase in a trial on Aiyura HAES (ACA 7), but only if severe potassium deficiency also existed. Harding (1993 c) reported a significant positive effect on leaf nitrogen contents, when nitrogenous fertiliser was applied to the Koban shaded trial (SPN 1.02), but since nitrogen contents were all in the upper part of the normal range, this was of little agronomic significance (Table 7).

Potassium applications increased leaf potassium levels at Korn Farm, even at 75 kg K_2O/ha, but there was little additional response above 225 kg K_2O/ha. At Aiyura, leaf potassium levels were increased by application of 225 kg K_2O/ha, but still did not reach the normal range (Southern 1969). On Koban Plantation, Harding (1993 a) showed that applications up to 200 kg K_20/ha/y produced a significant positive response in leaf potassium contents after only eight months of commencing fertiliser treatments (Table 8). Southern (1969) reported no consistent phosphorus effects. Harding (1993 c) also reported that applications of 50 kg P_2O_5/ha/y did not affect leaf phosphorus contents, which remained at adequate levels throughout the trial period. Magnesium, at a rate of 50 kg MgO/ha/y, produced a positive effect on leaf magnesium contents, although the effect was not significant until the fourth year of applications.

Indirect nutrient effects recorded in these trials include a negative N-K effect (Southern 1969); a negative N-Ca effect (Harding 1993 c); a positive N-Mn effect when sulphate of ammonia was the nitrogen fertiliser (Southern 1969 and Harding 1993 c); negative N-P and N-B effects (Harding 1993 c); a negative K-Mg effect (Southern 1969 and Harding 1993 c); a positive K-Zn effect; a positive P-Mn effect; and a negative Mg-Ca effect (Harding 1993 c). Several of these effects are illustrated in Tables 7 and 8.

Table 7. **Effects of nitrogen applications on leaf nutrient levels[1] of coffee at Koban Plantation and Aiyura HAES.**

kg N/ha/y	Number of plots	N (%)			K (%			Mn (mg/kg)			B (mg/kg)		
		KS[2]	KU[2]	AU[2]	KS	KU	AU	KS	KU	AU	KS	KU	AU
100	12	3.1	3.0	2.7	2.5	2.3	1.5	489	424	331	48	43	46
200	12	3.1	3.1	2.9	2.5	2.3	1.5	489	424	331	48	43	46
300	12	3.2	3.1	3.1	2.6	2.2	1.5	539	441	386	43	40	44
400	12	3.1	3.1	3.0	2.6	2.4	1.5	471	429	357	46	40	43
F-prob.[3]		ns	**	**	ns	*	ns	*	**	**	***	**	**
SEM[4]		0.10	0.03	0.05	0.10	0.08	0.09	25	15	35	2.0	1.0	2.2

[1] Leaf nutrient contents in June 1991, after four years of fertilizer applications.
[2] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee
[3] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[4] Standard error of the means (16 *df*)

Table 8. **Effects of potassium applications on leaf nutrient levels[1] of coffee at Koban Plantation and Aiyura HAES.**

kg K_2O/ha/y	Number of plot	K (%)			Mg (%)			Ca (%)		
		KS[2]	KU[2]	AU[2]	KS	KU	AU	KS	KU	AU
0	16	1.7	1.7	1.0	0.58	0.48	0.75	1.22	1.06	1.23
200	16	2.9	2.5	1.7	0.37	0.33	0.42	1.20	1.01	1.23
400	16	3.0	2.6	1.8	0.32	0.31	0.39	1.17	0.99	1.28
F-prob.[3]		***	**	**	***	**	**	ns	*	ns
SEM[4]		0.10	0.05	0.08	0.02	0.01	0.03	0.03	0.02	ns

[1] Leaf nutrient contents in June 1991, after four years of treatment applications.
[2] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee.
[3] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[4] Standard error of the means (16 *df*)

When the fertiliser treatment effects on the leaf nutrient contents are compared with those recorded by Harding (1993 b) in an adjacent unshaded trial, several differences are apparent. In the shaded trial, leaf contents of phosphorus, magnesium, calcium, sulphur, zinc, boron, iron and manganese were generally higher than in the unshaded trial; and a positive potassium effect on leaf potassium levels became significant sooner in the shaded trial.

Leaf nutrient content responses to fertiliser applications - Unshaded coffee

In unshaded plantation coffee increases in leaf nitrogen contents following application of nitrogen fertilisers have been recorded by Southern (1969), and Harding (1992 a and 1993 b) (Table 7). These can occur very rapidly, sometimes being observed within 8 months. Leaf potassium contents have been shown to increase as a result of applications of potassium fertiliser (Table 8), the effect sometimes being observed within 14 months. Responses to phosphorus, however, are less clear, with increases in leaf phosphorus contents being recorded after three years. Magnesium applications of 50 kg MgO/ha/y produced a positive response in leaf magnesium contents after 20 months.

In addition to the direct responses in the leaf nutrient contents to fertiliser applications, many indirect effects have also been recorded. Such effects may be synergistic or antagonistic, and are sometimes of greater significance than the direct response. Indirect effects of nitrogen fertilisers include decreases in leaf calcium and boron (Harding 1992 a and 1993 b); a decrease in leaf sulphur (Southern 1969); a decrease in leaf phosphorus (Harding 1992 a); and an increase in leaf manganese levels (Southern 1969 and Harding 1992 a and 1993 b). Several indirect effects of nitrogen are illustrated in Table 7.

Indirect effects of potassium fertiliser include a decrease in leaf nitrogen (Southern 1969); a decrease in leaf magnesium (Southern 1969; Harding 1992 a and 1993 b); a decrease in leaf boron (Harding 1992 a and 1993 b); decreases in leaf phosphorus and sulphur (Harding 1992 a); a decrease in leaf

***Table 9.* Effects of organic and inorganic phosphorus sources on the growth of coffee polypot nursery seedlings after twelve months.**

	Dry matter production[1], Plant P[2], and total P uptake[3] per seedling				
Treatments	Shoots dry matter (g)	Roots dry matter (g)	Total dry matter (g)	Plant P (%)	Total P uptake (g)
With coffee skins	8.27	4.86	13.12	0.24	0.033
Without coffee skins	6.23	4.09	10.32	0.24	0.026
F-prob.[4]	**	**	**	ns	-
SEM[5]	0.162	0.132	0.274	0.006	-
No fertiliser	5.52	3.94	9.46	0.26	0.026
Rock phosphate	7.06	4.13	11.19	0.22	0.026
Triple superphosphate	7.89	4.93	12.81	0.25	0.034
Single superphosphate	8.53	4.90	13.43	0.24	0.034
F-prob.[4]	**	**	**	*	-
SEM[5]	0.227	0.188	0.389	0.008	-

[1] Dry matters refer to average 105°C oven dry weight.
[2] Plant P is %P on a 6°C oven dry basis.
[3] Total P uptake calculated from plant P (%) corrected to a 105°C oven dry basis.
[4] ns = not significant; * = significant at 5% level; ** = significant at 1% level.
[5] Standard error of the means (14 *df*)

calcium, and an increase in leaf manganese levels (Harding 1993 b). Several indirect effects of potassium are illustrated in Table 8

COFFEE NURSERY FERTILIZER STUDIES

A coffee polypot nursery trial at Aiyura (SPN 3.02), in which soil with a medium to low level of available P (12 mg/kg by the Olsen bicarbonate extraction), and a high P-retention capacity (91% by the method of Blakemore *et al.* 1981), was used in the potting mixture, produced significant, positive responses in plant growth to applications of organic, and inorganic, phosphorus (Harding 1988). After twelve months, the total dry matter production of the coffee seedlings was 27% higher with coffee skins incorporated in the potting mixture, than without coffee skins (Table 9). The coffee skins provided 0.18 g P and 3.23 g N/seedling.

Significant, positive responses to inorganic fertilisers, each providing 0.30 g P/seedling, were also recorded (Table 9). Total dry matter production after twelve months was 18% greater with Christmas Island Rock Phosphate, 35% greater with triple super phosphate (TSP), and 42% greater with single super phosphate (SSP), than with no fertiliser. Plant P levels did not reflect dry matter production, but total plant uptake did (Table 9). Table 10 summarises the relative benefits of incorporating coffee skins, and/or SSP in the potting mixture. Incorporating coffee skins and SSP resulted in a 75% increase in dry matter production.

A follow up observation trial (SPN 4.01) was established on Aiyura in March 1987, in order to monitor any residual effects of the nursery fertiliser treatments, particularly with regard to the slower release of P from the rock phosphate treatments. Nine coffee seedlings from each nursery trial treatment were planted in the field, and their development measured for a further two years. No clear residual effects from the nursery treatments were recorded (Harding 1992 b).

COFFEE PLANTING HOLE STUDIES

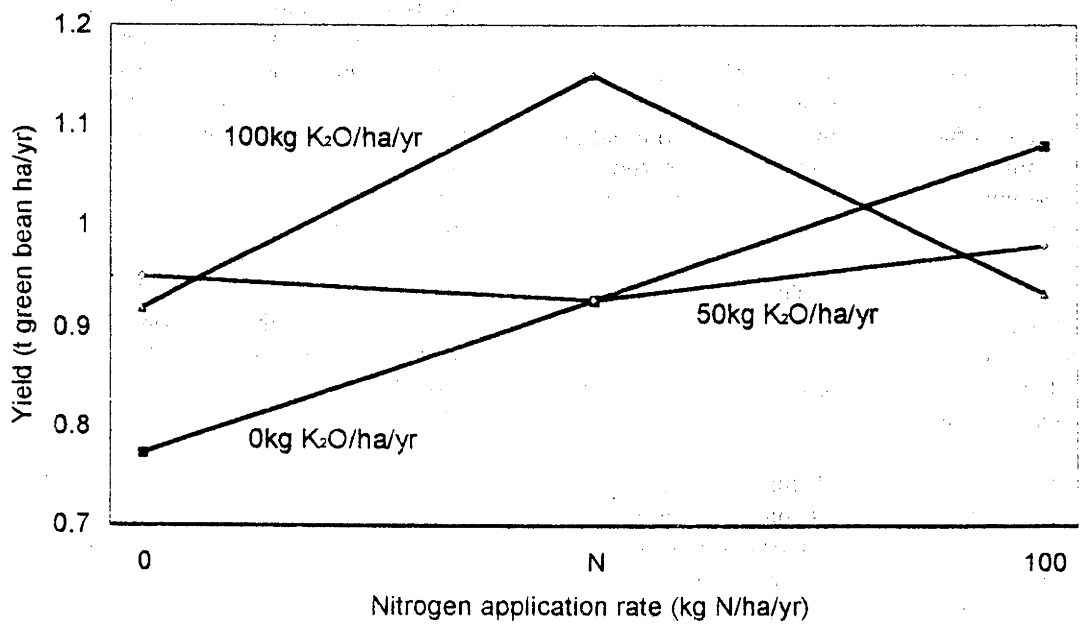
In March 1987, a planting hole trial (SPN 4.02) was established at Aiyura to investigate the optimum amount of phosphorus as TSP, to be applied to the planting hole when transplanting coffee seedlings from the nursery to the field. A location with a relatively high P-retention capacity was used, and the P treatments consisted of 0, 15, 30, 45, 60 and 75 g TSP per planting hole. All other recommendations were followed, including filling the holes with a 1:4 mixture of well rotted coffee skins and topsoil (to which was added the TSP), and timely applications of recommended amounts of nitrogen, potassium and micronutrients (Harding 1988). The results, although not statistically significant, suggested that 60 g TSP per planting hole resulted in the greatest dry matter accumulation.

A similar trial (SPN 4.03), using Catimor coffee seedlings, was established in January 1990 at the Western Highlands Substation. Treatments consisted of 0, 30, 60, 90, 120 and 150 g TSP per planting hole, with and without coffee pulp. Significant negative effects on soil and leaf zinc contents, and on growth parameters, were recorded, due to the high initial fertility of the peat soil used (Hombunaka 1997). The first crop (1990-1991) showed a negative yield response but in subsequent seasons there was no effect of the P application. Also the coffee pulp treatments yielded significantly lower between 1991 and 1993 but thereafter there was no yield effect.

***Table 10.* Effects of coffee skins and single superphosphate (SSP) on the growth of coffee polypot nursery seedlings after twelve months.**

Treatments	Total dry matter per seedling (g)	Plant P (%)	Total P uptake per seedling (g)
Soil only	8.70	0.25	0.023
Soil + coffee skins	10.22	0.27	0.029
Soil + SSP	11.84	0.24	0.030
Soil + SSP + coffee skins	15.02	0.24	0.038

Figure 1. **Yield response of rehabilitated, smallholder coffee to application of nitrogen and potassium.**



YIELD RESPONSES TO FERTILIZERS

Shaded coffee

A number of facts point to likely time lags in coffee yield responses to fertiliser applications, as reviewed in Harding (1994). These include the need for fertiliser applications to first affect shoot growth, the number of primaries per tree, flowers per cluster, and the precocity of flowering nodes, all of which subsequently determine the coffee cherry yield.

In the PNG context, the likely major effects of shade trees on coffee are to reduce yields, biennial bearing, overbearing and dieback; reduce the demands for nutrients; and thus reduce yield responses to fertiliser applications. Thus, yield responses to fertiliser applications in traditional smallholder coffee gardens are very unlikely. The only fertiliser trial conducted in improved smallholder coffee gardens (SPN 2.01) commenced in 1986 and was terminated in 1997. The trial originally consisted of a 3x3 factorial design, with one replicate located in each of twenty rehabilitated smallholder coffee gardens in the Kainantu area of Eastern Highlands Province. Three nitrogen treatments (0, 50 and 100 kg N/ha/y as sulphate of ammonia) and three potassium treatments (0, 50 and 100 kg K_2O/ha/y as muriate of potash) were applied in four equal doses in October, December, February and April each year. In addition to the nine rehabilitated plots, each garden also contained an unfertilised, unrehabilitated, external control plot, located in adjacent unrehabilitated coffee. The results from the first five year cycle have been reported in Harding (1988) and Harding (1994).

The yields from the trial are of interest because they are based on the only directly recorded long-term smallholder coffee yields in PNG. The average yield of all rehabilitated plots over the first five year production cycle was 1112 kg green bean/ha/y. However, the mean yields from individual gardens varied greatly, from as low as 100 to as high as 3300 kg green bean/ha/y. Yields also varied from year to year, with the lowest yields being recorded in the first year following rehabilitation, but then increasing each year to peak in the fourth year of the production cycle (when allowances are made for unusual weather conditions). When the yields from the unrehabilitated external control plots were compared with the unfertilised, but rehabilitated, plots in each garden, the rehabilitation alone was shown to have significantly increased cumulative yields over the first five year cycle by 46% (Harding 1994).

Significant fertiliser effects on coffee yields were also recorded during the first production cycle. When all the coffee gardens are analysed together, a significant positive nitrogen effect was recorded during the final year of the cycle, with yields peaking at a little above 50 kg N/ha/y. A potassium effect was also recorded, with yields increasing up to at least 100 kg K_2O/ha/y, although the response was not statistically significant. A significant NxK interaction was also apparent, highest yields being obtained when 100kg K_2O/ha/y and 50kg N/ha/y were applied (Figure 1).

When different groupings of gardens are analysed together, significant positive nitrogen and potassium effects on coffee yields are apparent during the fourth and fifth years in the less fertile gardens. Harding (1994) has shown by modelling the N dynamics of smallholder coffee gardens, that the efficiency of the shade trees in biologically fixing nitrogen from the atmosphere is likely to be a key factor in the response of individual coffee gardens to applications of nitrogenous fertilisers. The second production cycle commenced in 1991, utilising eight selected gardens from the first cycle. Similar trends to those during the first cycle have been recorded (Hombunaka unpublished data).

Much of the early coffee nutrition research was conducted in shaded plantation coffee. A positive yield response to nitrogen applications up to 256 kg N/ha/y was reported from a shaded coffee trial (ACA 25) on Korn Farm, in the Western Highlands. However, ten years were required before a statistically significant yield response was recorded (DASF 1972). The majority of fertiliser trials under shaded plantation conditions however, have either shown no response to nitrogen, or shown a negative response. Thus early fertiliser trials (ACA 4 and ACA 28) on Aiyura showed no response to applications of nitrogen (DASF 1965 b and 1966). Trial ACA 7 on Aiyura was reported as having a negative response to N applications by DASF (1965 b), and later Byrne (1984) reported a similar response for the period 1962-70 (Figure 2). A fertiliser trial (ACA 21) at Goroka also showed a negative response to N (DASF 1968). More recently, a five year factorial fertiliser trial (SPN 1.02) in lightly shaded coffee on Koban plantation, in the Western Highlands, showed a negative response to N applications above 100 kg N/ha/y, despite yields averaging 1972 kg green bean/ha/y over the five year cycle (Harding 1993 c). Green bean yields in this trial were 22.7% lower than in an adjacent unshaded trial.

***Table 11.* Micronutrient application effects on coffee yield (kg green beans/ha/y)**

	1992/93	1993/94	1994/95	1995/96	1996/97
no fertilizer	3172	2555	2508	2316	1088
no micronutrients	3662	2562	4895	2386	2428
foliar Zn	4438	3660	5297	2571	2702
foliar B	3070	4225	4027	2505	2012
foliar Zn + B	3919	3938	4876	2809	2326
soil Zn	3973	4312	4765	2698	2568
soil B	4076	3971	4400	2121	2628
soil Zn + B	2965	3658	4089	2310	2037
F prob.[1]	*	ns	**	ns	ns
SEM[2]	142	176	204	99	166

[1] ns = not significant; * = significant at 5% level; ** = significant at 1% level.

[2] Standard error of the means (21 *df*)

Figure 2. **Yield responses of shaded and unshaded plantation coffee to applications of nitrogen.**

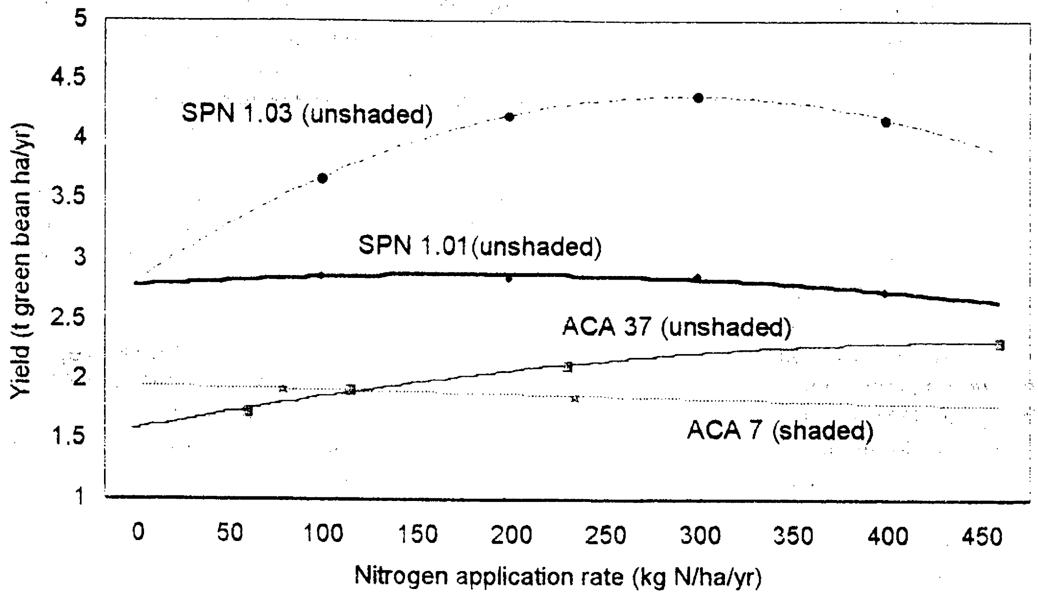
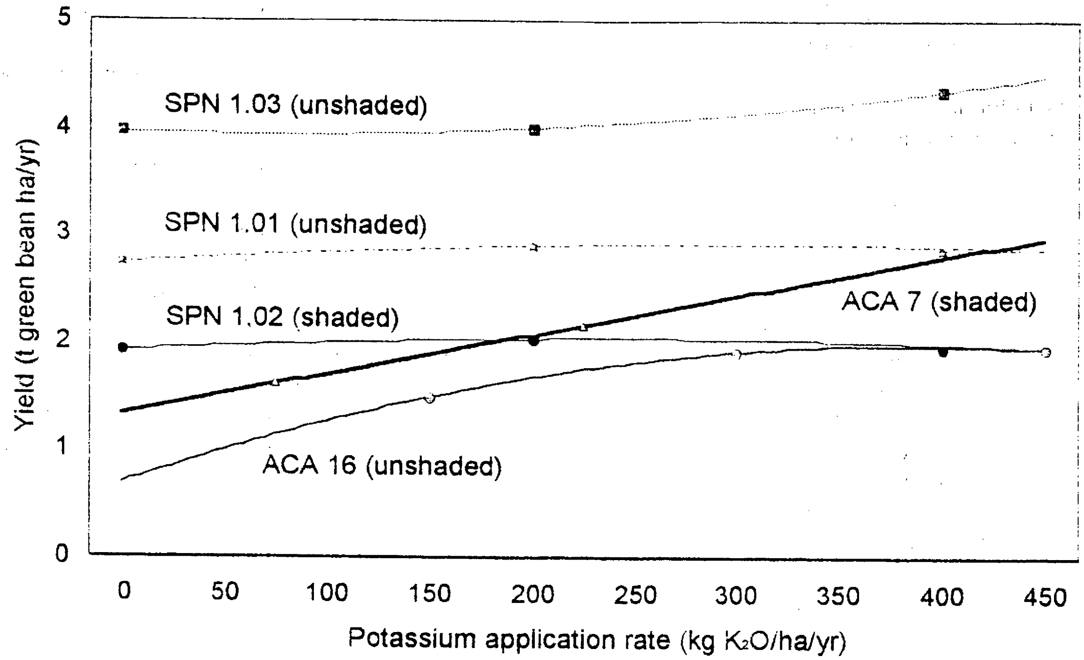


Figure 3. **Yield responses of shaded and unshaded plantation coffee to applications of potassium.**



In shaded coffee potassium is often the most limiting nutrient (Southern 1969) due to the plentiful supplies of nitrogen which are typically available under shaded conditions. Many authors have therefore reported positive yield responses to potassium, for example DASF (1965 b) and Byrne (1984) on Aiyura (ACA 7); DASF (1966, 1968, 1972) on Korn Farm (ACA 25); and Harding (1993 c) on Koban Plantation (SPN 1.02) (Figure 3). Application rates at which yield responses have been achieved have been rather high, such as 225 kg K_2O/ha/y (DASF 1965 b, 1966, 1968 and 1972); 300 kg K_2O/ha/y (Byrne 1984); and up to 400 kg K_2O/ha/y (Harding 1993 c). Considerable time may also be required before this response becomes apparent. Thus, trial ACA 7 first showed a significant potassium response during its fifth year (DASF 1965 b), and trial ACA 25 first recorded a significant response to potassium during its sixth year (DASF 1966). A few authors, for example DASF (1968) in trial ACA 21 at Goroka, have recorded a negative response to potassium, which suggests that the response of coffee to potassium is dependent on the soil type.

Yield responses to phosphorus in mature coffee are rare (Ling *et al.* 1990). In PNG, negative yield responses to phosphorus were recorded by DASF (1965 b), DASF (1972) and Byrne (1984) on Aiyura HAES (ACA 7); DASF (1968) at Goroka (ACA 21); and Harding (1993 c) on Koban Plantation (SPN 1.02). Indications of a positive response to phosphorus were reported for some years in trial ACA 25 on Korn Farm (DASF 1968). There are very few reports in the literature of coffee yield responses to applications of magnesium, although a non-significant positive yield response to 50 kg MgO/ha/y was apparent in trial SPN 1.02 on Koban Plantation (Harding 1993 c).

The importance of adequate micronutrient applications, particularly following a change in production cycle when new suckers are growing, has been demonstrated by Hombunaka (1997). Significant yield responses to zinc and boron were recorded during several years of a trial (SPN 4.06) under shaded coffee at Aiyura HAES. Zinc is most effectively applied as a foliar spray, while boron is best applied to the soil.

Unshaded coffee

Coffee yields respond more often to nitrogen than any other nutrient, particularly when grown under unshaded conditions. Many authors have reported positive yield responses to applications of nitrogen in PNG. An unshaded fertiliser trial on Aiyura HAES (ACA 37) showed a consistent positive yield response over seven years (1970-77) to annual applications of nitrogen up to 460 kg N/ha (Byrne 1984) (Figure 2); and on Korn Farm (ACA 25) a significant yield response to nitrogen was recorded in 1967-69 (DASF 1972).

More recently, Harding (1992a) reported that unshaded coffee on Aiyura HAES (SPN 1.03) responded positively to applications of up to 330 kg N/ha/y (as sulphate of ammonia) from the third year of treatment applications (Figure 2). The yields from this trial averaged a very high 4654 kg green bean/ha/y during the first five year production cycle. During its second five year cycle, nitrogen was applied as calcium ammonium nitrate (CAN). Yields continued to respond positively to nitrogen, and averaged more than 3000 kg green bean/ha/y (Hombunaka unpublished data). An unshaded trial on Koban Plantation (SPN 1.01) also showed a small positive response to N (Figure 2), with yields peaking at an application rate of 200 kg N/ha/y (Harding 1993 b). High fertiliser applications prior to the commencement of this trial reduced yield responses during the trial. Yields in this trial averaged 2551 kg green bean/ha/y during the five year production cycle.

Only rarely does unshaded coffee fail to respond to nitrogen. However, in unshaded trial ACA 16 on Aiyura HAES, a significant positive response to rates up to 104 kg N/ha/y was observed over the first six years (1963-69) (DASF 1972), but when rates were increased up to 460 kg N/ha/y, yields were depressed over the next five years (Byrne 1984). More recently, Hombunaka (1997) reported no response to N and K fertilisers (SPN 405) on peaty soils at the Western Highlands substation. Depending on the soil properties, unshaded coffee sometimes responds to applications of potassium. The only clear effect in an early nutrient omission trial (ACA 4) was in response to omitting potas-

Table 12. **Fertiliser timing effects on coffee yield (kg green beans/ha/y).**

fertiliser timing[1]	1992/93	1993/94	1994/95	1995/96
1	744	655	505	1523
2	1186	705	828	1574
3	1007	960	1438	2280
4	950	1030	1283	2153
5	785	890	1305	2216
6	970	896	11/5	2010
7	927	830	937	1949
8	1989	892	1285	2134
9	949	968	1531	2180
10	881	969	937	2284
F prob.[2]	*	**	ns	*
SEM[3]	35	26	78	64
kg N and kg K_2O/ha	1992/93	1993/94	1994/95	1995/96
100-100	930	760	918	1680
200-200	1010	926	1103	2080
300-300	1940	952	1352	2331
F prob.[2]	***	*	***	ns
SEM[3]	35	26	78	64

[1] the trial included 100, 200 and 300 kg N or K2O/ha/y given at different times for details see Hombunaka (1997).
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level.
[3] standard error of the means (58 *df*).

sium DASF 1965 a); and a significant response was obtained in a trial on Korn Farm (ACA 25) to applications of 375 kg K_2O/ha/y (DASF 1972). Unshaded trial ACA 16 on Aiyura, responded positively to applications of potassium up to 450 kg K_2O/ha/y over the five year period 1971-76 (Byrne 1984) (Figure 3). However, trial ACA 37 on Aiyura failed to produce a yield response to annual applications of up to 900 kg K_2O/ha/y over a seven year period (1970-77) (Byrne 1984).

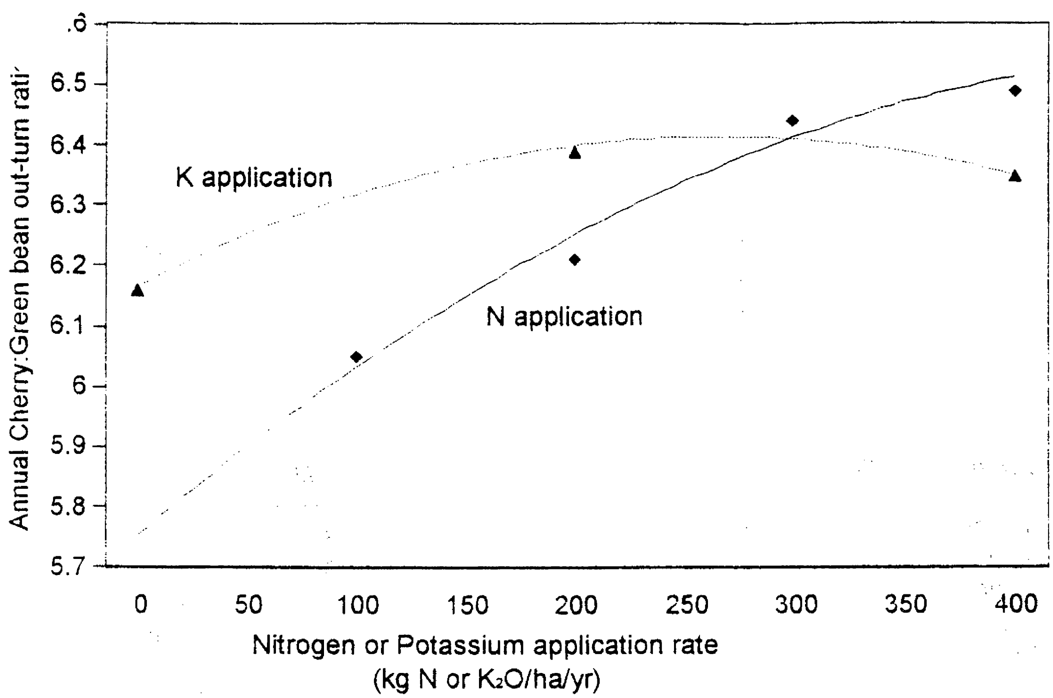
A significant positive yield response to potassium applications up to 200 kg_2O/ha/y was recorded in the unshaded Koban Plantation trial SPN 1.01 (Harding 1993 b); and Harding (1992 a) reported yields from an unshaded trial (SPN 1.03) on Aiyura responded positively, but not significantly, to applications up to 400 kg K_2O/ha/y during its first five year production cycle (Figure 3). During its second cycle, which begun in October 1991 a less acidifying N source (CAN) was used. It was found that in the second cycle yields were on average lower which could be due to Ca/K imbalances caused through the CAN application.

In PNG, no consistent, significant, positive yield response to phosphorus has been recorded. However, indications of a positive yield response to phosphorus were reported during some years in trials ACA 16 and SPN 1.03 on Aiyura (DASF 1972; Byrne 1984 and Harding 1992 a); and on Korn Farm (ACA 25) (DASF 1968). Negative yield responses to phosphorus have not been recorded in unshaded coffee trials in PNG. No significant yield responses to magnesium have been reported from unshaded coffee in PNG.

TIMING OF FERTILIZER APPLICATIONS

A fertiliser timing trial (SPN 1.04) was established on Ondu Plantation, in the Eastern Highlands Province, in 1988, in order to investigate the best time to apply nitrogen and potassium fertilisers. Taking

Figure 4. **Effects of applications of nitrogen and potassium on coffee cherry: green out-turn ratios, Aiyura HAES, 1990/91**



due account of the interpretation of fluctuations in coffee leaf nutrient contents described in a previous section, ten fertiliser timing schedules, and three application rates, were incorporated into the trial. The trial continued until mid-1997. Hombunaka (1997) reported significant responses to fertiliser timing and application rates for the 1992 to 1996 coffee seasons (Table 12). The trial demonstrated that nitrogen fertiliser is best applied soon after the rains begin (when flowering is triggered), during rapid cherry expansion, and just prior to the final ripening stage. Whereas potassium is required in two applications during rapid cherry expansion.

COFFEE OUT-TURN RATIO RESPONSES TO FERTILIZER APPLICATIONS

Harding (1992 a, 1993 b and 1993 c) has shown that as nitrogen applications increase, cherry : green bean out-turn ratios also increase significantly (Figure 4), that is, more pulp is produced relative to green bean. Potassium (Figure 4) and magnesium have also been shown to positively affect coffee out-turn ratios.

In a smallholder coffee fertiliser trial (SPN 2.01), no significant nutrient effect on out-turn ratios was recorded during the first production cycle (Harding 1994).

NUTRIENTS IN COFFEE WASTE PRODUCTS

Harding (1994) collected coffee prunings from six rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and three unshaded plantation plots receiving from 0 to 600 kg N and K_2O/ha/y, for two years. Dry matter (DM) and nutrient contents of each component of the prunings were determined, from which it was estimated that over a five year production cycle, smallholder coffee gardens produce between 10,000 and 32,000 kg DM of prunings/ha, containing 145 to 500 kg N, depending on the fertiliser applications. Unshaded coffee plantations were estimated to produce between 31,000 and 69,500 kg DM of prunings/ha over a five year cycle, containing 410 to 1300 kg N, the actual quantities being very influenced by fertiliser applications.

Although most coffee prunings are usually recycled, coffee stems are often removed for other purposes, such as fuel or fence construction. Willson (1985) presented data from PNG showing that the removal of only one stem per tree from coffee planted at 1350 trees/ha, represents a loss of 14.8 kg N, 2.8 kg P_2O_5 and 11.9 kg K_2O/ha. Hart (1969) reported the equivalent of 22.0 kg N, 4.6 kg P_2O_5, 20.4 kg K_2O and 3.3 kg MgO per 1000 kg green bean. Harding (1994) collected 5-10 kg samples of harvested ripe coffee cherries from nine rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and 14 kg samples from eight unshaded plantation plots receiving from 0 to 700 kg N and K_2O/ha/y, in 1991. Each sample was processed to the green bean stage, and the dry matter and nutrient contents of the green bean, pulp, mucilage, parchment and silverskins were determined. It was estimated that one tonne of fresh cherry from smallholder coffee gardens contains 200 kg dry matter and 4 kg N, about 50% in the green bean, 25% in the pulp, 10% in the mucilage, and 10% in the parchment and silverskins. One tonne of unshaded plantation cherry was estimated to contain 220 to 280 kg dry matter and 4 to 5 kg N, about 50% in the green bean, 25% in the pulp, 6% in the mucilage, and 15% in the parchment and silverskins. Fertiliser application rates significantly influenced dry matter and N contents of the unshaded plantation cherry (Harding 1994).

MODELLING COFFEE NUTRITION

Harding (1994) collected litterfall for a two year period (January 1991 to December 1992) from six rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and five unshaded plantation plots receiving from 0 to 600 kg N and K_2O/ha/y. Dry matter and nutrient contents of each component of the litterfall were determined, from which it was estimated that over a five year production cycle, smallholder coffee gardens produce 6,800-7,500 kg DM of coffee tree litter/ha, containing 170-250 kg N, and 34,400-40,700 kg DM of yar (shade) tree litter/ha, containing 460-600 kg N, depending on the fertiliser applications. Thus, total litterfall in smallholder coffee gardens over a five year production cycle was estimated to be 41,200-48,200 kg DM/ha, containing 637-761 kg N. Unshaded coffee plantations were estimated to produce 10,000-20,000 kg DM of litterfall/ha over a five year cycle, containing 188-456 kg N, the actual quantities being very influenced by fertiliser applications.

The litter, prunings and cherries taken together represent the above ground biomass production, if the growth of the woody material is ignored. If a typical average yield of 7 tonnes cherry/ha/y is assumed for the shaded coffee, the shaded coffee system produces 58,000-87,000 kg above ground biomass DM/ha, containing 900-1,400 kg N/ha, in a five year cycle. On an annual basis, this is 11,600-17,400 kg DM/ha, containing 180-280 kg N/ha, of which the harvested cherries account for about 10%. The above ground biomass production of the unshaded coffee, assuming an average yield of 29 tonnes cherry/ha/y, can be calculated in a similar way as 14,600-26,000 kg DM/ha/y, containing 240-500 kg N/ha/y. This is up to 50% more biomass, containing up to almost 80% more N, than the shaded coffee system. The harvested cherries account for a considerably larger 30% or more of the N contained in the above ground biomass production.

Harding (1994) modified the previously validated, empirical, N model of Wolf *et al.* (1989) to cater for the coffee management systems of PNG. Using coffee cherry, litterfall, prunings, stem and roots dry matter and nutrient contents, with soil and leaf analytical data, this PNG coffee N model was calibrated for PNG conditions. The model was then used to derive five year N balances which explained observed responses to N applications in shaded and unshaded coffee, and highlighted the crucial role played by the yar shade trees in smallholder coffee gardens. The PNG coffee N model was used to generate long-term (200 and 500 years) simulations of the N dynamics in selected plots of shaded and unshaded coffee fertiliser trials. These showed that in shaded coffee gardens where the N requirements of the coffee trees cannot be met from naturally occurring sources, the labile organic N (LON) and stable organic N (SON) pools are depleted, and N uptake (and hence yields) and N losses are reduced, until a new equilibrium is obtained. At this new steady state, the reduced N uptake and N losses are balanced by the N inputs from naturally occurring sources. Applications of N fertilisers in such gardens enables the LON and SON pools to equilibrate at higher levels, at which the potential N uptake, and hence coffee yields, are increased. In those gardens where the N requirements of the coffee are met by the naturally occurring sources, the LON and SON pools may, or may not, be depleted slightly. However, the new equilibrium occurs at such a level that the potential N uptake does not restrict the coffee yields (Harding 1994).

The long-term simulations also showed that in unfertilised, unshaded coffee, the LON and SON pools are so severely depleted, and the potential N uptake falls to such low levels, that the survival of the coffee trees as a commercial proposition is unlikely beyond a second production cycle. In high yielding (> 3000 kg green bean/ha/y) unshaded coffee receiving about 300 kg N/ha/y as fertiliser, the LON and SON pools may be depleted somewhat, but new steady state conditions are reached at a potential N uptake which is likely to be adequate for the survival of commercial coffee, although yields may fall somewhat. Applications of 600 kg N/ha/y would result in the LON and SON pools increasing to new equilibria, where potential N uptake is excessive and N losses are very high.

The long-term simulations of Harding (1994) were also used to investigate the consequences of three management options involving the recycling of waste products. These showed that unshaded, unfertilised coffee does not produce enough waste products to significantly affect the N balance, even if they were all recycled. In fertilised unshaded coffee, or in shaded coffee, however, the recycling of waste products, particularly the coffee pulp, does make a significant contribution to the N balance. As well as removing a major environmental pollutant, recycling waste products is likely to lead to reductions in N fertiliser requirements of up to 15 or 20%, and/or larger steady state LON and SON pools, and hence increased potential N uptake and coffee yields.

CONCLUSIONS

The seasonal fluctuations in coffee leaf nutrient contents are well understood, and guidelines for undertaking and interpreting coffee soil and leaf analyses have been established. Monitoring of coffee leaf nutrient contents can be a valuable aid to planning fertiliser requirements, providing seasonal fluctuations are understood. Coffee leaf nutrient contents can respond to applications of N or K within eight months. Responses to P and Mg are less likely and may take two or more years to become apparent. Considerable time lags, of two years or more, are usually required before coffee yield reponses to fertiliser applications. Similar delays may also occur before yield declines are apparent after reducing fertiliser applications. Fertiliser applications are utilised most efficiently when applied at the most appropriate times of year. Fertiliser timing studies have shown these to be at the flowering, rapid cherry expansion and final ripening stages for nitrogen, and during rapid cherry expansion for potassium. Nitrogen, K and Mg increase coffee cherry : green bean out-turn ratios, that is they produce more pulp relative to green bean. The beneficial effects of including well rotted coffee skins in coffee nursery potting mixtures, and planting holes in the field, have been demonstrated. Including up to 60 g TSP in each planting hole also results in improved growth and development of the coffee seedlings, except in very fertile soils, when negative effects on soil and plant zinc contents may occur reducing yields in the first cropping seasons.

Shaded coffee

Rehabilitation of smallholder coffee gardens can increase yields over a five year production cycle by almost 50%. Yields from rehabilitated smallholder coffee gardens can average as high as 3000 kg green bean/ha/y over a five year production cycle, although an average of 1000 kg green bean/ha/y is a more realistic target yield. Shaded plantation coffee yields can average 2000 kg green bean/ha/y over a five year production cycle. Field studies of shaded coffee show little evidence of N deficits. Leaf N contents, litterfall production, cherry partitioning, and out-turn ratios all show little or no positive response to N. The production of prunings does respond positively to N, and cherry and green bean yields respond positively in some shaded coffee but not in others. In some situations, applications of N result in a negative yield response. Most smallholder-shaded coffee in PNG could survive without applications of N fertiliser, although yields may decline to new equilibrium levels. Shaded plantation coffee is likely to require moderate applications of N fertiliser to maintain yields at commercial levels. Although shade appears to reduce the acidifying effect of N fertilisers, regular monitoring of soil pH should still be maintained. Responses to applications of potassium are likely in shaded coffee, since this is often the limiting nutrient under shaded conditions. Soil conditions may determine the extent of the yield response to potassium. Yield responses to P and Mg are rare in shaded coffee. The recycling of waste products, particularly the coffee pulp, can reduce the need for fertiliser N applications by up to 20%, and will increase potential yields in some coffee gardens. Coffee prunings contain significant amounts of nutrients, and should therefore be fully recycled if possible. The extent of biological N fixation by the "yar" trees is an important factor in determining the long-term sustainability of unfertilised shaded coffee.

Unshaded coffee

Unshaded plantation coffee in PNG can yield as high as 4000 kg green bean/ha/y over a five year production cycle, although average yields of 2500 or 3000 kg green bean/ha/y are more realistic target yields. Field studies of unshaded coffee provide strong evidence of the need for applications of both N and K. Leaf N contents, litterfall production, prunings production, cherry partitioning, outturn ratios, cherry and green bean yields all respond positively to applications of up to about 325 kg N/ha/y. No N fertiliser applications would probably result in the death of most trees within two production cycles. High rates of fertiliser N could lead to yield reductions if the trees produce too much foliage, at the expense of flowers. Soil acidification is a potential problem when acidifying N fertilisers like sulphate of ammonia are used and this may be accompanied by subsequent leaching losses of potassium, magnesium and calcium. Yield responses to potassium are also likely, up to about 400 kg K_2O/ha/y. Negative potassium effects on magnesium and calcium availability may become a problem. Yield responses to P or Mg are rare in unshaded coffee in PNG. The recycling of waste products, particularly the coffee pulp, can reduce the need for fertiliser N applications by about 15%. Prunings contain significant quantities of nutrients and should therefore be fully recycled if possible.

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