Nutrient Inputs and Losses in Cassava-based Cropping Systems—Examples from Vietnam and Thailand

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ABSTRACT

Cassava (*Manihot esculenta* Crantz) can extract large amounts of nutrients from the soil and cause serious erosion when grown on slopes, resulting in degradation of the soil's physical and chemical properties. This paper examines in detail the nutrient losses resulting from the harvest of either cassava roots alone or together with stems and leaves, as practiced in some parts of Asia. It also reports on nutrient losses in eroded sediments and runoff.

It was found that in the root harvest of cassava, relatively large amounts of K and N are removed from the field, but removal of P is very low. Total nutrient removal per hectare is usually lower than for other crops, with the possible exception of K, while nutrient extraction t Dry Matter^{-1} in the harvested products is usually well below that of other crops. However, if stems and leaves are also removed from the field, the extraction of all nutrients increases, especially that of N and Ca. In this case nutrient losses may be greater than for other crops, and considerable nutrient inputs in the form of chemical fertilizers or manures are required to maintain a positive nutrient balance.

When grown on slopes cassava may cause more soil erosion than most other crops due to the wide plant spacing used and its slow initial growth. This can result in high nutrient losses in eroded sediments and runoff. Total nutrient losses in the eroded soil tend to be high in N and K, but relatively low in P. In comparison, nutrient losses in the runoff are smaller but tend to be relatively high in Ca and K, followed by N, Mg, and P. Thus, total nutrient losses due to cassava cultivation can be quite high, especially those of N and K, when cassava yields are high, or when the crop is grown on slopes. To maintain a positive nutrient balance it is important to apply enough fertilizers or manures that are high in N and K, and to use cultural practices that will reduce runoff and erosion.

In both Vietnam and Thailand farmers tend to apply too much P but not enough N and K. To maintain a positive balance of all three major nutrients it is recommended that farmers in Vietnam apply less P and farmyard manure (< 5–10 t ha^{-1}), but apply additional K in the form of chemical fertilizers. In Thailand, it is recommended that farmers shift from applying 15-15-15 to the use of a compound fertilizer high in K and N such as 15-7-18, applying at least 200 kg ha^{-1} to sustain an average cassava root yield of about 15 t ha^{-1}.

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INTRODUCTION

In 1997 the global harvested area and production of cassava (*Manihot esculenta* Crantz) in Asia amounted to 3.48 million ha and 18.07 million metric tonnes (mt), respectively. Southeast Asia alone accounted for 2.97 million ha and 14.33 mt. In Southeast Asia cassava is the third most important crop in terms of area, and the fourth in terms of dry matter (DM) production, after rice, sugarcane, and corn (FAOSTAT, 1999).

In Asia, cassava is usually grown in upland areas, above the lowland rice paddies, but below the forested areas found on the upper and steeper parts of the mountains. In Thailand, Malaysia, and India cassava is mostly grown in monoculture. In Indonesia cassava is frequently intercropped with upland rice, corn, and grain legumes, while in Vietnam, China, and the Philippines both systems are practiced extensively.

Cassava in Asia is usually grown from sea level up to 500 m above sea level, indicating that, unlike Africa and Latin America, there is basically no highland cassava cultivation in this continent. In Asia the crop is grown mostly on Ultisols (55%), followed by Inceptisols (18%), Alfisols (11%), Entisols (9%), and other types of soils (7%) (Howeler, 1992). The soil texture ranges from sandy loams (Thailand), sandy clay loams (Thailand, Vietnam), clay loams (China, Vietnam) to clays (Indonesia, China, Vietnam, Philippines). Most of the light-textured soils are acid and very low in nutrients with the heavier soils tending to have better fertility.

Nutrient Balance

A nutrient balance is usually considered to be the difference between nutrient inputs and outflows (or losses). If the balance for a particular nutrient is positive, that nutrient will accumulate in the soil. In contrast, if the balance is negative depletion occurs, and the soil's fertility status may deteriorate. In this case the production practices are unsustainable and the soil may eventually not be able to maintain adequate levels of available nutrients required for crop production. During plant growth, nutrients are taken up from the solution phase of the soil, which is replenished through ion exchange, by dissolution from the solid mineral phase, or by mineralization of organic compounds. A portion of the nutrients will be returned to the soil in the form of crop residues. The remainder will be removed from the field in the form of harvested products. Nutrients can also leave the field via erosion, either in the form of water runoff or soil sediments. In addition, nutrients are lost through leaching (mainly N and K) and volatilization (mainly N). The loss of nutrients is partially countered by biological N-fixation, atmospheric deposition (mainly N and S) in rainfall, and by deposition of soil eroded from upper slopes. In addition, nutrient losses can be countered by the application of chemical fertilizers, animal manures, compost or mulch (collected elsewhere) and industrial by-products. Fallow rotation, green manuring, *in-situ* mulching, intercropping, and incorporation of crop residues may improve the N status of the soil through biological N fixation. Although these practices may also bring up P and K from the subsoil to the topsoil, this does not add nutrients to the system, but merely recycles those nutrients within the system. In this case there is no net gain.

NUTRIENT LOSSES IN CASSAVA PRODUCTION SYSTEMS

Nutrient Uptake and Removal by Cassava

Nutrient Uptake and Distribution in the Plant

Like any other plant, the growth and nutrient uptake of cassava depends on the climatic conditions and nutrient status of the soil. When these are favorable, growth, and consequently, nutrient uptake are enhanced. Figure 1 and Table 1 show that total dry matter (DM) production was markedly enhanced by irrigation as well as by fertilizer application of cassava grown in Carimagua, Colombia. At time of harvest, DM was found mainly in the roots, followed by stems, fallen leaves, leaf blades, and petioles.

Table 1. Dry matter and nutrient distribution in 12-month-old cassava cv. M Ven 77, grown with and without fertilizer in Carimagua, Colombia.

		Nutrient Status kg ha^{-1}										
	DM (mt ha^{-1})	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
Un-fertilized												
Top	5.11	69.1	7.4	33.6	37.4	16.2	8.2	0.07	0.03	0.45	0.33	0.26
Roots	10.75	30.3	7.5	54.9	5.4	6.5	3.3	0.08	0.02	0.38	0.02	0.10
Fallen leaves	1.55	23.7	1.5	4.0	24.7	4.0	2.5	0.04	0.01	-	0.37	0.18
Total	**17.41**	**123.1**	**16.4**	**92.5**	**67.5**	**26.7**	**14.0**	**0.19**	**0.06**	**-**	**0.72**	**0.54**
Fertilized												
Top	6.91	99.9	11.7	74.3	55.0	15.3	9.6	0.08	0.03	0.78	0.57	0.30
Roots	13.97	67.3	16.8	102.1	15.5	8.4	7.0	0.07	0.03	0.90	0.06	0.17
Fallen leaves	1.86	30.5	2.0	7.1	31.9	4.7	2.6	0.05	0.02	-	0.46	0.19
Total	**22.74**	**197.7**	**30.5**	**183.5**	**102.4**	**28.4**	**19.3**	**0.20**	**0.08**	**-**	**1.09**	**0.66**

Source: Howeler, 1985a.

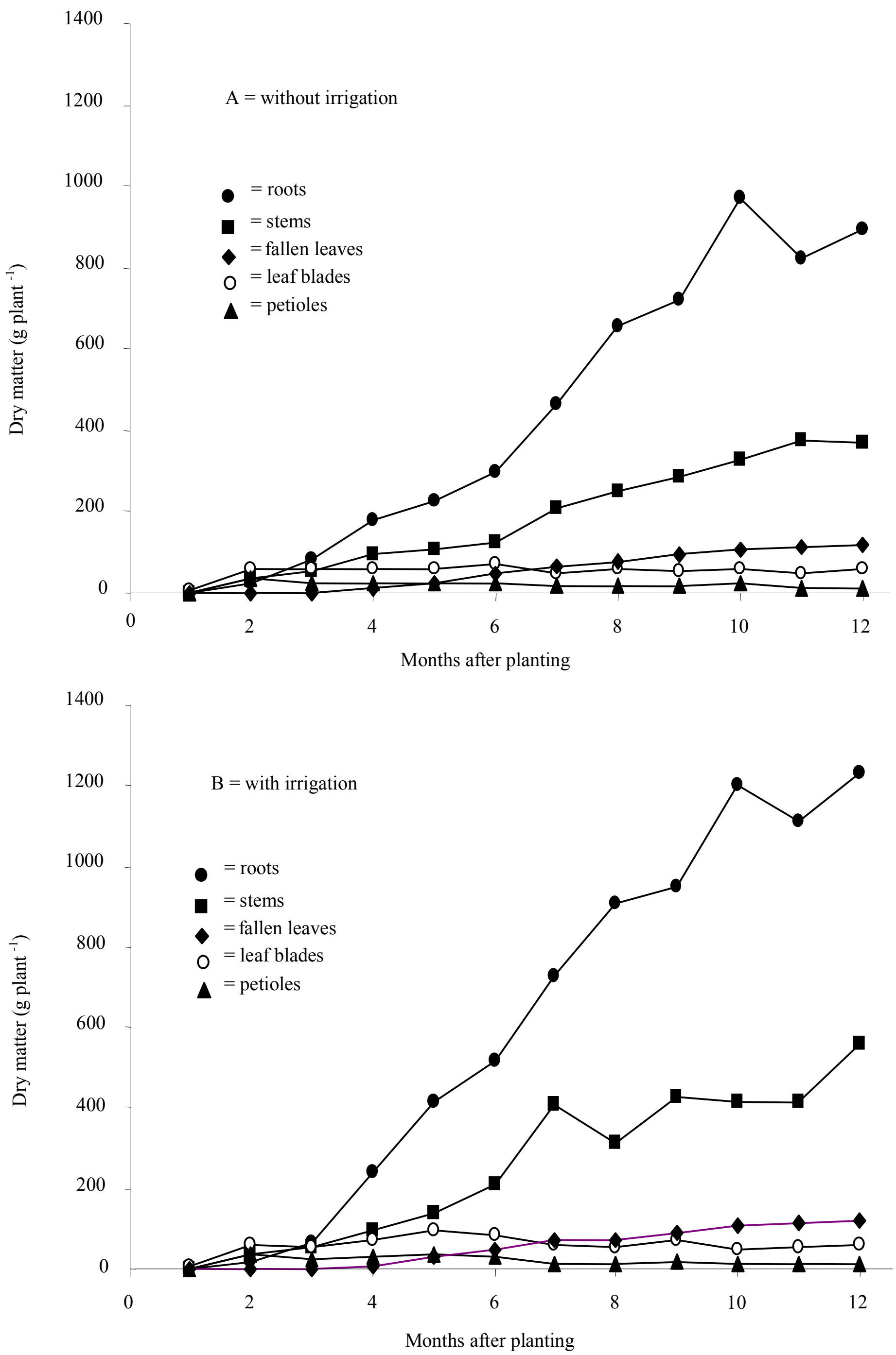

Figure 1. Dry matter distribution among roots, stems, leafblades, petioles, and fallen leaves of fertilized cassava during a 12-month growth cycle in Carimagua (Colombian Eastern Plains), without (A) or with (B) irrigation in 1983/84. Source: CIAT, 1985b

Nutrients Removed from and Returned to the Field

Table 1 shows that if only roots are harvested and removed from the field, as practiced in Thailand, only about 60 % of total DM produced, 25–30 % of total N, 45–55 % of total P, and 55—60 %t of total absorbed K are removed from the field. In contrast, in areas where leaves are also harvested for animal feed, the stems are used for firewood, and the fallen leaves for kindling, as in parts of north Vietnam practically all DM produced and all nutrients absorbed will be removed from the field. In the latter case, nutrient removal by the harvest of all of these cassava products will be substantial.

The amount of nutrients absorbed and removed also depends on the variety used and the yield levels obtained. Table 2 shows the yields obtained and the amount of nutrients in either the roots or the whole plant (without fallen leaves) at time of harvest for 19 experiments reported in the literature, with fresh root yields ranging from 6.0 to 64.7 mt ha^{-1}. Obviously, nutrient absorption and removal increase as yields increase. Based on the data in Table 2, Table 3 shows the average values for nutrients removed in the roots or in the whole plants in terms of kg ha^{-1}, as well as in terms of kg mt fresh or dry roots. According to these data, approximately 37 % 49 % and 56 % of absorbed N, P and K is found in the roots and will be removed if only roots are harvested, respectively. However, when the nutrients in the roots or whole plant are plotted against yield (Figures 2 and 3) it is clear that the nutrient removal is not proportional with yield as plants with a high root yield also tend to have higher nutrient concentrations in the roots as well as in the leaves and stems (Howeler, 1985). Thus, if we base our nutrient removal calculations for a particular situation on the average removal data shown in Table 3, we would overestimate nutrient removal if yields are low and underestimate removal if yields are high (Figures 2 and 3). For instance, assuming an average fresh root yield of 15 mt ha^{-1} (as obtained in Thailand) and that only roots are removed from the field, we would calculate a removal of about 34.8 kg N, 5.85 kg P, and 45.7 kg K ha^{-1} using the average values in Table 3, while Figure 2 shows that actual removal is likely to be about 30 kg N, 3.5 kg P, and only 20 kg K ha^{-1}.

Table 2. Fresh and dry yield, as well as nutrient content in cassava roots and in the whole plant at time of harvest, as reported in the literature.

Plant part	**Yield (mt ha^{-1})**		**Nutrient content (kg ha^{-1})**					**Source/Cultivar**
	fresh	**dry**	**N**	**P**	**K**	**Ca**	**Mg**	
Roots	64.7	26.59	45	28.2	317	51	18	Nijholt, (1935) cv. Sao Pedro Preto
Whole plant	110.6	39.99	124	45.3	487	155	43	
Roots	59.0	21.67	152	22.0	163	20	11	Howeler and Cadavid, (1983) fertilized MCol 22
Whole plant	-	30.08	315	37.0	238	77	32	
Roots	52.7	25.21	38	27.9	268	34	19	Nijholt, (1935) cv. Mangi
Whole plant	111.1	44.65	132	48.5	476	161	52	
Roots	50.0	-	153	17.0	185	25	6	Cours, (1953) Madagascar
Whole plant	-	-	253	28.0	250	42	29	
Roots	45.0	-	62	10.0	164	12	22	Amarisisi and Pereira, (1975) Sri Lanka
Whole plant	-	-	202	32.0	286	131	108	

Table 2. Continued

Roots	37.5	13.97	67	17.0	102	16	8	Howeler, (1985b) unfertilized MCol 22
Whole plant	-	22.74	198	31.0	84	102	28	
Roots	~36.0	12.60	161	10.0	53	16	12	Paula et al., (1983) fertilized Branca St. C.
Whole plant	-	20.92	330	20.5	100	88	30	
Roots	32.3	15.39	127	19.1	71	6	5	Cadavid, (1988) fertilized CM523-7
Whole plant	-	25.04	243	34.4	147	56	25	
Roots	31.0	-	31	1819	47	-	-	Sittibusaya and Kurmarohita, (1978)
Whole plant	-	-	73	31.9	72	-	-	
Roots	~28.5	10.28	100	8.7	107	15	13	Paula et al., (1983) fertilized Riqueza
Whole plant	-	19.56	353	24.8	174	133	37	
Roots	26.6	12.81	91	11.3	47	5	6	Cadavid, (1988) unfertilized CM523-7
Whole plant	-	19.10	167	19.1	76	32	19	
Roots	26.0	10.75	30	8.0	55	5	7	Howeler, (1985a) unfertilized MVen 77
Whole plant	-	17.41	123	16.0	92	67	27	
Roots	21.0	-	21	9.2	44	8	10	Kanapathy, (1974) Malaysia, peat soil
Whole plant	-	-	86	37.2	135	45	34	
Roots	18.3	5.52	32	3.6	35	5	4	Sittibusaya (unpublished) fertilized Rayong 1
Whole plant	-	9.01	95	9.9	65	37	15	
Roots	16.1	3.64	30	4.7	45	9	5	Putthacharoen et al., (1998) 1990/91 Rayong 1
Whole plant	-	10.55	193	27.0	137	122	27	
Roots	~15.9	5.58	66	2.7	17	8	5	Paula et al., (1983) unfertilized Riqueza
Whole plant	-	10.62	197	8.1	61	100	20	
Roots	~9.0	3.24	37	1.5	23	4	2	Paula et al., (1983) unfertilized Branca St. C
Whole plant	-	6.54	93	4.0	40	30	9	
Roots	8.7	2.68	13	0.9	4	3	2	Sittibusaya (unpublished) unfertilized Rayong 1
Whole plant	-	4.23	39	3.2	10	21	8	
Roots	6.0	1.52	18	2.2	15	5	2	Putthacharoen et al., (1998) 1989/90 Rayong 1
Whole plant	-	4.37	91	12.2	55	46	15	
Roots	30.8	-	67	11.7	92.7	-	-	Average 19 sources
Whole plant	-	-	174	24.7	162.4	-	-	

Nutrient Removal by Cassava as compared with other Crops

Earlier reports on nutrient removal by cassava as compared with other crops (Amarasiri and Perera, 1975; Howeler, 1981, 1991a; Putthacharoen et al., 1998) have generally used data from experiments done on experiment stations where yields tend to be much higher than those obtained by farmers. This has resulted in nutrient loss data well above those normally encountered in farmers' fields. Thus, Howeler (1991a) reported that nutrient removal t DM^{-1} of root harvest was on average 4.5 kg N, 0.83 kg P, and 6.6 kg K ha^{-1} as based on an average fresh root yield of 35.7 mt ha^{-1}. If these data had been based on a root yield of 15 mt ha^{-1} (Figure 2) the removal would have been about 5.4 kg N, 0.63 kg P, and 3.6 kg K ha^{-1}, i.e. considerably lower in P and K than previously reported, and well below those of most other crops (Amarasiri and Perera, 1975; Howeler, 1991a). Similar results were reported by Putthacharoen et al., (1998), who compared the nutrient removal of cassava with that of five other crops grown for two consecutive years in the same experiment (Table 4).

Table 3. Average fresh and dry root yield, as well as the amount of nutrients removed when cassava roots or the whole plant are harvested based on data from the literature[1)].

Plant part	Yield (mt ha^{-1}) fresh	Yield (mt ha^{-1}) dry	Nutrient removal	N	P	K	Ca	Mg
Roots	28.87	11.43	kg ha^{-1}	67.1	11.2	88.1	13.5	7.9
Whole plant		18.99		179.5	22.7	156.1	81.8	25.8
Roots	28.87	11.43	kg mt^{-1} fresh roots	2.32	0.39	3.05	0.47	0.27
Whole plant		18.99		6.22	0.79	5.41	2.83	0.89
Roots	28.87	11.43	kg mt^{-1} dry roots	5.87	0.98	7.71	1.18	0.69
Whole plant		18.99		15.70	1.99	13.66	7.16	2.26

See Table 2. Data are average of 15 data sets which have yields reported in dry weight.

Table 4. Major nutrients removed in the harvested products and returned in the nonharvested products of various crops grown during 22 months in Sri Racha, Chonburi, Thailand from 1989–1991.

Crop	No. of crop cycles	Nutrients removed (kg ha^{-1})					Nutrients returned (kg ha^{-1})				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
Cassava for roots	2	48	7	60	14	6	236	46	132	154	35
Cassava for forage	1	363	43	240	162	62	17	4	16	24	5
Corn	2	118	44	87	6	11	101	13	269	34	28
Sorghum	2	79	25	51	10	9	147	27	304	51	37
Peanut	2	213	19	53	6	8	133	12	183	87	28
Mungbean	3	117	15	62	9	11	54	7	66	51	14
Pineapple	1	83	15	190	51	19	160	31	176	85	24

Source: Putthacharoen et al., 1998.

Thus, while cassava has a reputation to “exhaust” soil nutrients by excessive nutrient removal in the crop harvest, this is clearly not the case, as N and P removal in the cassava root harvest is much less, and K removal is less or similar to that in the harvested products of other crops. However, if all plant parts are removed from the field (as often practiced in Vietnam and Indonesia) nutrient removal can be substantial and may be similar to, or higher than, those of other crops (Putthacharoen et al., 1998; Amarasiri and Perera, 1975).

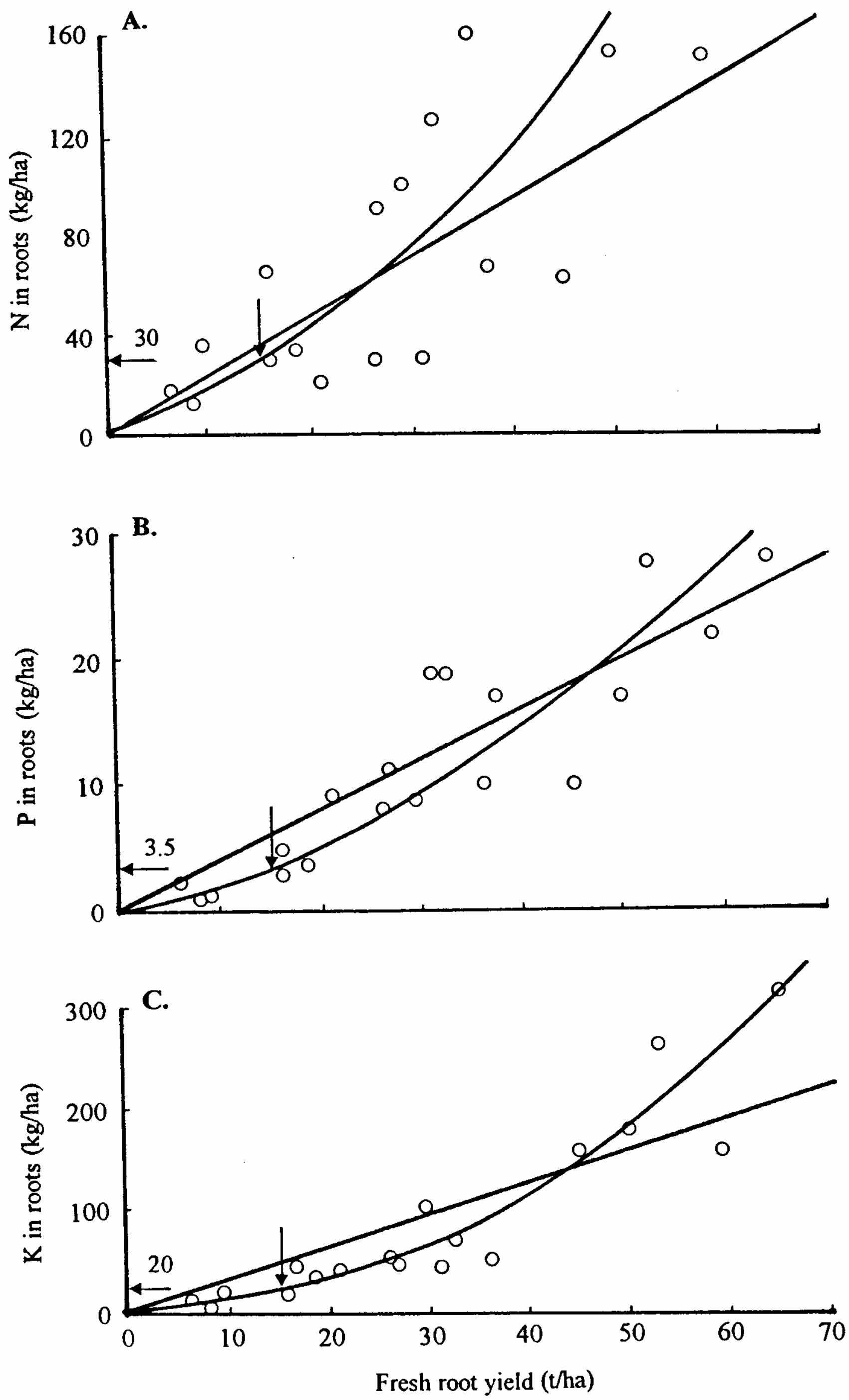

Figure 2. Relation between the N, P and K contents of cassava roots and fresh root yield, as reported in the literature (see Table 2). Arrows indicate the approximate nutrient contents corresponding to a fresh root yield of 15 t ha^{-1} The straight lines indicate the relationship based on the average yield and nutrient contents (see Table 3).
***Source:** Howeler, 2001.*

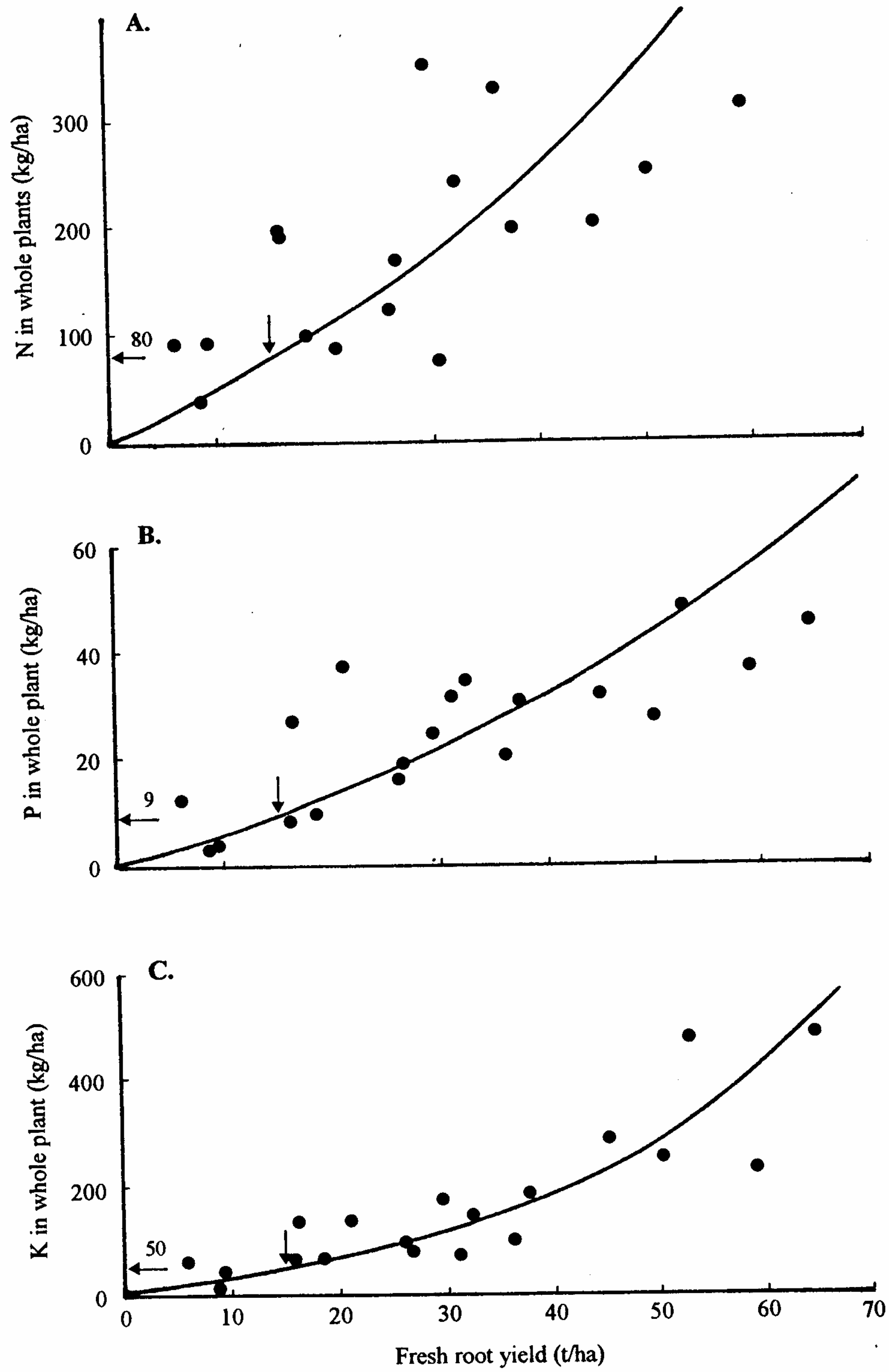

Figure 3. Relation between the amounts of N, P and K in the whole cassava plant at time of harvest and the fresh root yield, as reported in the literature. Arrows indicate the approximate nutrient contents corresponding to a fresh root yield of 15 t ha.$^{-1}$ ***Source:*** *Howeler, 2001.*

Nutrient Losses by Erosion

Nutrients can be removed from the field by soil erosion, either as part of the eroded sediments and crop debris, or dissolved in the runoff water. It is difficult, however, to quantify these losses as soil erosion is highly variable, both over space and time. Nutrient losses may occur in one part of the field where soil is washed away, while they may accumulate in another part of the field or landscape where sediments are deposited. Only a small fraction of sediment losses measured in erosion trials will actually be lost from the landscape and be carried out to sea. Some nutrients dissolved in runoff water may infiltrate into the soil elsewhere and be absorbed by plants, but a large proportion will either seep down below the rooting zone or be transported to the sea. Moreover, erosion depends largely on the frequency and intensity of rainfall, which varies greatly over time. Much of the soil and nutrient loss by erosion may occur during only one or two rainfall events during the year. Thus, nutrient losses by erosion will vary greatly from year to year and from place to place.

Erosion Losses in Cassava as Compared with other Crops

Cassava is often grown on highly eroded slopes, but it is uncertain whether cassava is the cause of erosion or the result, as cassava may be the only crop that can tolerate the low soil fertility and high acidity that are often the result of erosion, especially if the topsoil has been washed away and the subsoil exposed.

Comparing 12 different crops or cropping systems, grown on 8–13 percent slopes in three types of soils for several years in Brazil, Quintiliano et al., (1961) reported that cassava was the third most erosive crop, after castor bean and *Phaseolus* bean (Figure 4). Similarly, Putthacharoen et al., (1998) reported that during a four-year period, four crops of cassava for root production caused 2.5 times more soil loss due to erosion than six crops of mungbean, 3–4 times more erosion than five crops of corn, sorghum or peanut, and five times more erosion than two crops of pineapple, all grown in the same experiment on 7 percent slope in Sri Racha, Thailand (Table 5). Because of the wide plant spacing used and the crop's slow initial growth, cassava plants leave much soil exposed to the direct impact of rainfall during the first 3–4 months of establishment. If this period corresponds with that of heavy rainfall, erosion in cassava fields can be quite severe, especially when the crop is grown on light-textured soils with low levels of OM (as in the east and northeast of Thailand).

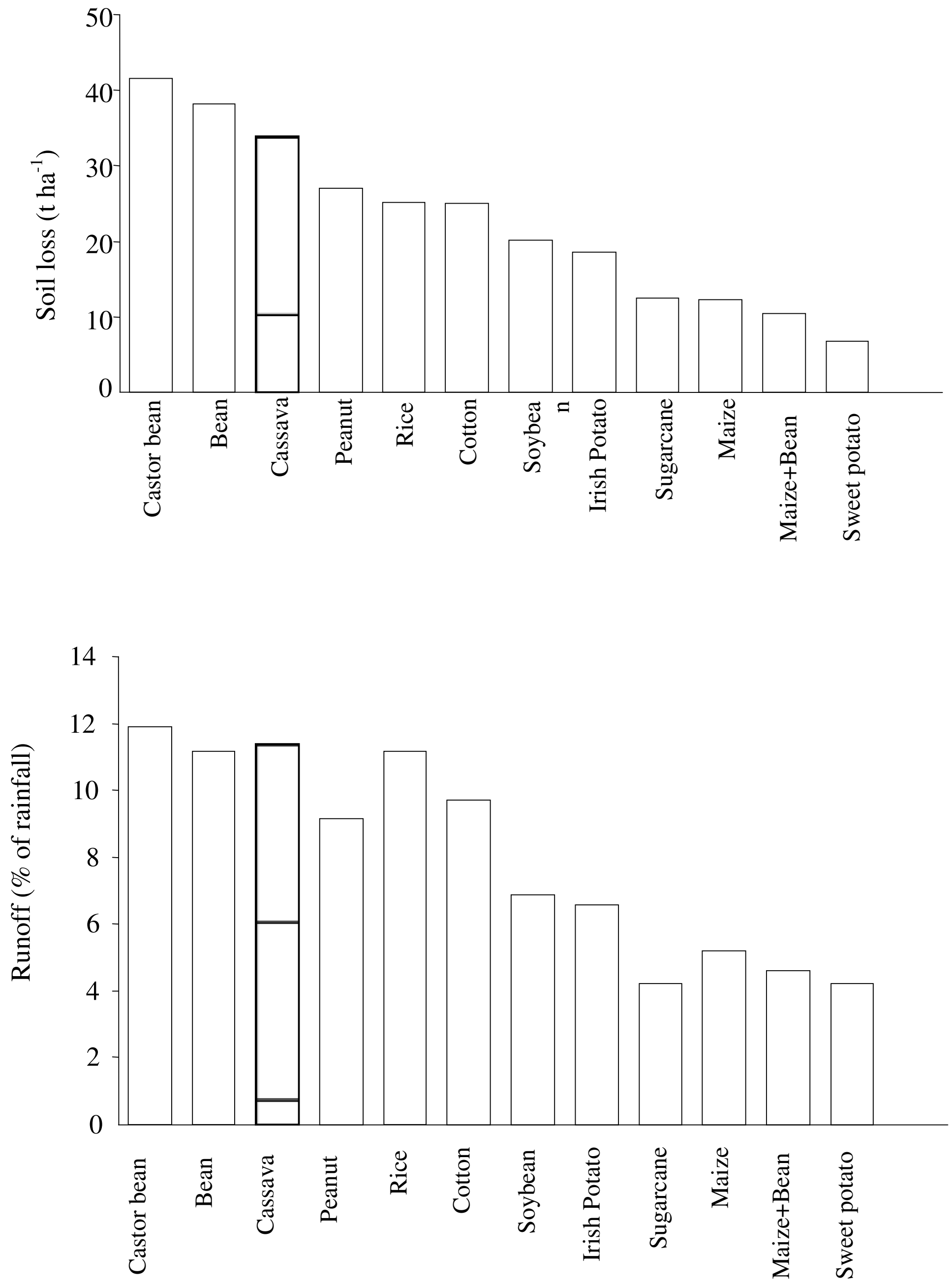

Figure 4. Effect of crops on annual soil loss by erosion (top) and on runoff (bottom). Data are average values (n=48) corrected for a standard annual rainfall of 1,300mm yr^{-1}.

Table 5. Total dry soil loss by erosion (mt ha^{-1}) due to the cultivation of eight crops during four years on 7% slope with sandy loam soil in Sri Racha, Thailand from 1989–1993.

	No. of crop cycles	First period (22 months)	Second period (28 months)	Total (50 months)
Cassava for root production	4	142.8 a	168.5 a	311.3
Cassava for forage production	2	68.8 b	138.5 ab	207.3
Corn	5	28.5 d	35.5 cd	64.0
Sorghum	5	42.9 c	46.1 cd	89.0
Peanut	5	37.6 cd	36.2 cd	73.8
Mungbean	6	70.9 b	55.3 cd	126.2
Pineapple[1)]	2	31.4 cd	21.3 d	52.7
Sugarcane[1)]	2	-	94.0 bc	-
F-test		**	**	
cv (%)		11.4	42.7	

[1)] Second cycle is a ratoon crop; sugarcane only during second 28-month period
Source: Putthacharoen et al., 1998.

Nutrient Losses in Eroded Sediments

The amount of nutrients lost in eroded sediments depends on the amount of soil lost as well as on the nutrient status of the soil. Table 6 shows the loss of total N, available P, and exchangeable K and Mg reported for four experiments conducted in Thailand and Colombia. The amount of nutrients lost depended mainly on the extent of erosion. Management practices that reduced erosion automatically reduced nutrient losses. Annual losses of total N, exchangeable K and available P ranged from 3.5 to 37 kg ha^{-1}, 0.13 to 5.1 kg ha^{-1} and 0.02 to 2.2 kg ha^{-1}, respectively. However, when topsoil is lost by erosion, not only are the available or exchangeable nutrients lost but the total amounts of nutrients in the organic and mineral fraction are lost. Thus, losses of total P, K, and Mg could be considerably higher than those reported in Table 6 (see also Table 7).

Eroded sediments tend to have higher nutrient contents than the original soil they are derived from. This is due to preferential loss of, and nutrient release from, crop residues lying on the soil surface, of clay, and of applied fertilizers or manures. The ratio of organic matter or nutrients in the transported sediments over those in the matrix soil is called the “enrichment ratio”. In a cassava erosion control experiment conducted in Huay Bong, Thailand, the enrichment ratios were 2.0 for OM, 3.4 for available P, 2.0 for exchangeable K, 1.37 for Ca, and 1.06 for Mg (Howeler, 2000). These ratios are similar to those reported by Barrows and Kilmer (1963) and Lal (1976), but were generally higher than those reported by Reining (1992) and Ruppenthal (1995).

Table 6. Nutrients in sediments eroded from cassava plots with various treatments in Thailand and Colombia.

Location and treatments	Dry soil loss ($mt^{-1} ha^{-1} yr^{-1}$)	$kg^{-1} ha^{-1} yr^{-1}$			
		N[1)]	P[2)]	K[2)]	Mg[2)]
Cassava on 7% slope in Sri Racha, Thailand[3)]	71.4	37.1	2.18	5.15	5.35
Cassava on 5% slope in Pluak Daeng, Thailand[4)]	53.2	22.3	1.25	3.27	-
Cassava planted on 7–13% slope in Quilichao, Colombia[5)]	5.1	11.5	0.16	0.45	0.45
Cassava with leguminous cover crops in Quilichao, Colombia[5)]	10.6	24.0	0.24	0.97	0.81
Cassava with grass hedgerows in Quilichao, Colombia[5)]	2.7	5.8	0.06	0.22	0.24
Cassava planted on 12–20% slope in Mondomo, Colombia[5)]	5.2	13.3	1.09	0.45	0.36
Cassava with leguminous cover crops in Mondomo, Colombia[5)]	2.7	6.5	0.04	0.24	0.20
Cassava with grass hedgerows in Mondomo, Colombia[5)]	1.5	3.5	0.02	0.13	0.10

[1)] Total N; [2)] Available P, and exchangeable K and Mg; [3)] Source: Putthacharoen et al., 1998; [4)] Source: Tongglum et al., 2001; [5)] Source: Ruppenthal et al., 1997.

Nutrient Losses in Runoff

Table 7 shows nutrient losses, both in sediments and in runoff, from an upland rice experiment conducted on a 25 to35 percent slope in Luang Prabang, Laos, both for cropping under traditional farmers' practices and under alley cropping with double hedgerows of vetiver grass. Alley cropping reduced runoff and erosion substantially, especially in the second year of establishment of the treatment. Total N, P and K losses in the runoff ranged from 0.71 to 2.35 kg ha^{-1}, 0.083 to 0.85 kg ha^{-1}, and 6.7 to 26.1 kg ha^{-1}, respectively. Thus, K losses in runoff were much higher than those of N, which in turn were much higher than those of P. In contrast, N losses were sometimes higher than K losses in soil sediments. The losses of "total" P and K in Table 7 are much higher than the losses of "available" P and "exchangeable" K reported in Table 6.

Few reports exist on nutrient losses in runoff from cassava fields. Table 8 shows some data on nutrient losses in runoff and soil sediments during two years of cassava cropping on a 7 to 13 percent slope in Santander de Quilichao and on a 13 to 20 percent slope in Mondomo, both in Colombia (Reining, 1992). When cassava was grown on up-and-down ridges both soil loss and runoff were much higher than when the crop was grown on contour ridges. Losses of P in the runoff ranged from 0.08 to 0.47 kg ha^{-1} those of K from 0.61 to 3.96 kg ha^{-1} those of Ca from 1.29 to 7.56 kg ha^{-1} and those of Mg from 0.14 to 1.22 kg ha^{-1} . Thus, despite severe soil loss and runoff in both locations, nutrient losses in the runoff were minor compared to those in the eroded sediments.

Table 7. Effect of soil/crop management on runoff and soil loss by erosion, as well as the nutrients lost in runoff and eroded sediments during two years of cropping upland rice on 25–35% slope in Luang Prabang, Laos in 1994 and 1995.

	Farmer's practice		Alley cropping[1)]	
	1994	**1995**	**1994**	**1995**
Runoff (m^3 ha^{-1})	**1,475**	**2,119**	**1,296**	**765**
Nutrients lost in runoff (kg ha^{-1}):				
N	0.71	2.35	0.49	0.71
P	0.084	0.85	0.085	0.33
K	7.87	26.12	6.69	7.89
Dry soil loss (mt ha^{-1})	**4.88**	**9.21**	**3.56**	**1.76**
Nutrients lost in eroded soil (kg ha^{-1}): [2)]				
N	17.09	53.92	11.61	7.61
P	1.94	9.28	1.32	1.50
K	43.54	23.96	31.19	2.66

[1)] Using vetiver grass double hedgerows (1 m width) with mango trees; upland rice in 5 m wide alleys between double hedgerows; [2)]Values correspond to total N, P, and K. Source: Phommasack et al., 1995, 1996.

Nutrient Losses by Leaching and Volatilization

Losses of applied N and K by leaching are expected to be substantial if cassava is grown on light-textured soils and all fertilizers are applied at planting. Losses of N by volatilization may also be substantial if N fertilizers are applied on the soil surface, especially in high pH soils. However, no information is available to quantify these losses in cassava fields.

NUTRIENT INPUTS IN CASSAVA-BASED CROPPING SYSTEMS

Cassava farmers tend to be among the poorest farmers in the world, living generally in marginal areas of steep slopes, low-fertility soils, and with low or unpredictable rainfall. They grow cassava because this crop is very well adapted to these conditions and will produce a reasonable yield even without any external inputs. However, numerous experiments have shown that cassava is highly responsive to fertilizer application, and that continuous production of cassava on the same land without adequate application of chemical fertilizers or manures can lead to nutrient depletion and yield declines (Nguyen Tu Siem, 1992; Sittibusaya, 1993; Tongglum et al., 2001). Cassava farmers, however, may not have the resources to buy the chemical fertilizers needed to maintain high yields, or they may not apply the correct balance of nutrients required by the crop.

Table 8. Effect of two contrasting soil/crop management treatments on runoff and soil loss by erosion, as well as the nutrients lost in runoff and eroded sediments during two years of cropping cassava on 7–13% slope in Santander de Quilichao and on 13–20% slope in Mondomo, Colombia, in 1987/88 and 1988/89.

	Santander de Quilichao				**Mondomo**			
	1987/88		**1987/88**		**1987/88**		**1987/88**	
	T_1[1)]	**T_2**	**T_1**[1]	**T_2**	**T_1**	**T_2**	**T_1**	**T_2**
Runoff (m^3 ha^{-1})	950	1,750	1,400	2,420	340	1,470	540	1,000
Nutrients lost in runoff (kg ha^{-1})								
Total P	0.16	0.33	0.22	0.47	0.08	0.39	0.13	0.26
Total K	1.49	2.79	1.58	3.08	0.61	3.26	1.47	3.96
Total Ca	2.67	3.50	2.96	5.45	1.29	5.11	2.88	7.56
Total Mg	0.43	0.58	0.30	0.75	0.14	1.22	0.20	1.01
Dry soil loss (mt ha^{-1})	3.0	30.4	5.1	68.0	1.5	33.8	2.6	12.6
Nutrients lost in eroded sediments (kg ha^{-1})								
Available P	0.08	0.41	0.07	1.12	0.01	0.44	0.03	0.18
Exchangeable K	0.34	2.73	0.42	5.05	0.17	3.04	0.27	1.11
Exchangeable Ca	4.08	32.83	6.94	73.44	2.58	31.10	4.47	11.59
Exchangeable Mg	0.25	2.92	0.33	7.08	0.10	3.00	0.19	0.61

[1)] T_1 = cassava on contour ridges; T_2 = cassava on up-and-down ridges. Source: adapted from Reining, 1992.

Nutrient Requirements of Cassava

Cassava tolerates high soil acidity and low fertility better than most other crops because of its exceptional tolerance to low pH and high levels of Al in the soil solution (Howeler, 1991b), and low levels of available P (Howeler, 1990). The latter is due to a highly efficient symbiosis between cassava and vesicular-arbuscular (VA) mycorrhizae, which readily colonize the fibrous roots of the crop in almost all natural soils (Howeler et al., 1981; 1987; Sieverding and Howeler, 1985; Howeler, 1990). Due to this symbiosis cassava is able to absorb P from soils with a very low level of P, and the critical level of available soil P for cassava is only 4–10 µg g^{-1}, compared with 10–20 µg g^{-1} for most other crops (Howeler, 2001). Thus, cassava may not respond to the application of P in a soil where upland rice (and other crops) show a very marked response (Figure 5). On the other hand, cassava absorbs and removes from the field considerable amounts of K when only roots are removed and large amounts of N, K, and Ca when all plant parts are removed. Numerous fertilizer trials conducted in Asia indicate that cassava responds mainly to the application of N and K, but less to that of P. There is almost no response to the application of lime (Howeler, 2001) except for the very acid peat soils in Malaysia (Tan and Chan, 1989; Tan, 1992).

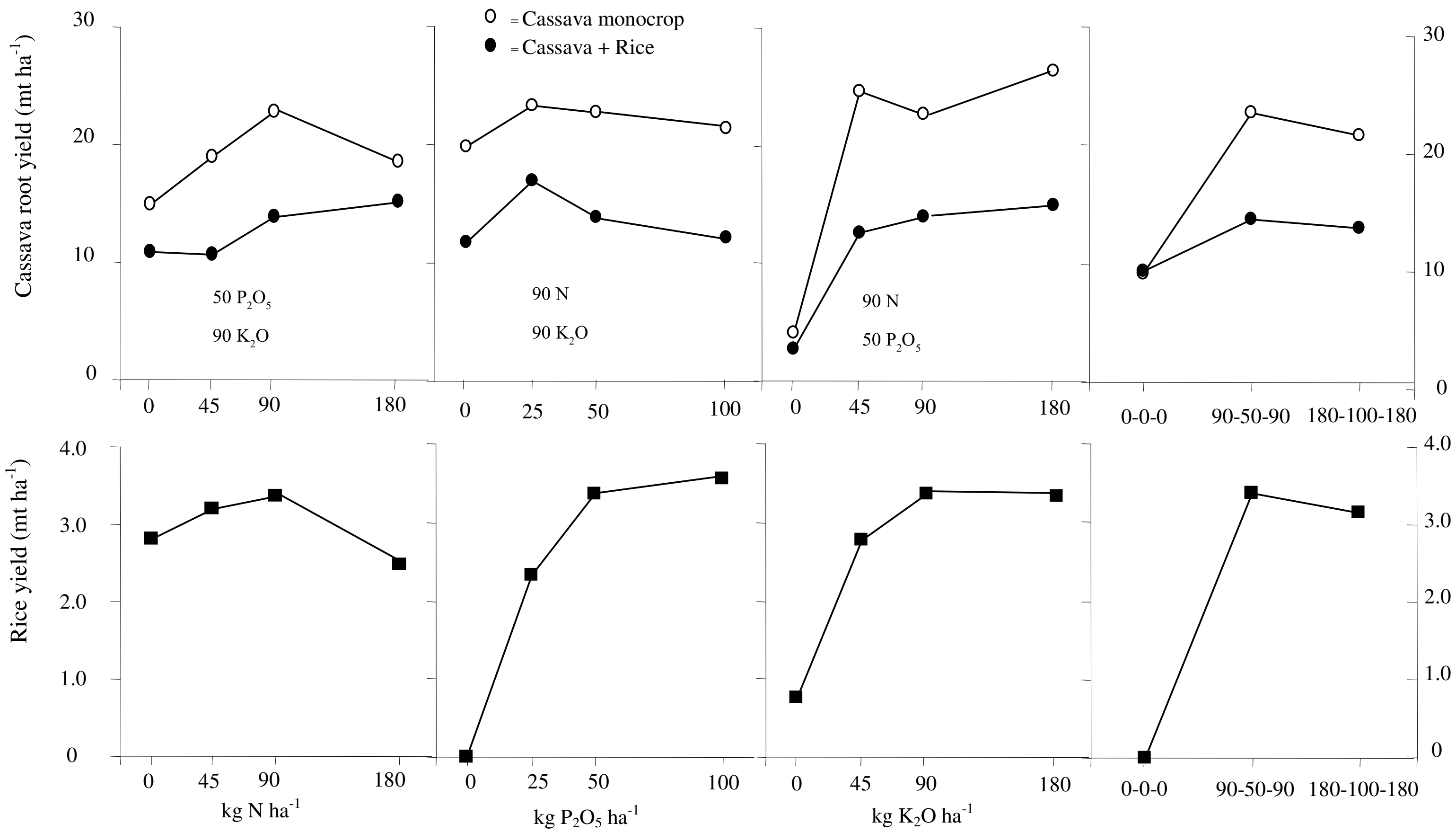

Figure 5. Effect of annual applications of various levels of N, P and K on the yields of cassava (both monocropped and intercropped with rice and upland rice during the 9th consecutive cropping cycle in Tamanbogo, Lampung, Indonesia (1999/2000).

In many countries in Asia cassava farmers apply 5–10 mt ha^{-1} of animal manures, mostly from pigs, cattle or chickens, but few experiments have been conducted to determine the response to different types and rates of animal manures. In Latin America good responses to up to 6 mt ha^{-1} of farmyard manure were obtained in Paraiba state of Brazil (Silva, 1970) and up to 4.3 mt ha^{-1} of chicken manure in Mondomo, Colombia (Howeler, 1985a). The chicken manure was about twice as effective as cattle manure applied at equivalent levels of P. Farmers in Mondomo, Colombia, claim to get much better yields with the application of chicken manure than with chemical fertilizers; the exact reason for this is not clear.

Nutrient Inputs from Chemical Fertilizers, Manures, and Compost

Nutrient inputs from the application of chemical fertilizers, manures or compost naturally depend on the rates applied and the chemical composition of each compound. The nutrient compositions of chemical fertilizers are generally well-defined. Those of the most commonly used fertilizers are shown in Table 9. The composition of animal manures and compost, however, is highly variable, depending largely on their moisture content and the degree of composting or leaching that they have been subjected to. Moreover many manures are composted together with straw, rice husks or lime, changing their nutrient composition markedly. Table 10 shows values reported in the literature. Using the average values for cattle, pig, and chicken manure in Table 10, one can calculate that 1 mt of wet manure contains approximately the following nutrients:

Cattle manure (32% DM):	5.9 kg N, 2.6 kg P and 5.4 kg K
Pig manure (40% DM):	8.2 kg N, 5.5 kg P and 5.5 kg K
Chicken manure (57% DM):	16.6 kg N, 7.8 kg P and 8.8 kg K

This compares with the nutrient content of one bag (50 kg) of 15-15-15 fertilizer which contains 7.5 kg N, 3.3 kg P, and 6.2 kg K, respectively. Thus, while manures tend to be cheap, their cost of transport and application may be 10 to 20 times higher than that of a compound fertilizer like 15-15-15 on an equivalent nutrient content basis. However, in addition to N, P, and K, manures also supply Ca, Mg, S, and micronutrients, and they may improve the organic matter content and physical conditions of the soil. The composition of composts of municipal garbage, rice straw, and peanut residues, as well as that of wood ash are shown in Table 10. These tend to be quite low in nutrients except for wood ash, which contains considerable amounts of K, Ca, and Mg.

Incorporation of green manures can supply large amounts of nutrients to the following crop (Tongglum et al., 1992; Howeler et al., 1999). However, most of these nutrients are merely recycled within the system, except for N, some of which may have been derived from biological N-fixation.

Table 9. Nutrient content (%) of commonly used inorganic fertilizers.

	N	P	K	Ca	Mg	S
Ammonium nitrate	33	-	-	-	-	-
Mono-ammonium phosphate	11	23	-	-	-	-
Di-ammonium phosphate	18	20	-	-	-	-
Ammonium sulfate	20.5	-	-	-	-	23
Calcium ammonium nitrate	20.5	-	-	7-14	-	-
Calcium nitrate	15.5	-	-	20	-	-
Potassium nitrate	13	-	37	-	-	-
Sodium nitrate	16	-	-	-	-	-
Urea	45	-	-	-	-	-
Urea formaldehyde	38	-	-	-	-	-
Simple superphosphate	-	8-9	-	17-22	-	12
Triple superphosphate	-	20	-	12-16	-	-
Basic slag	-	6.5	-	32-35	1-3	0.2
Rhenia phosphate	-	12.7	-	29	0.6	0.4
Potassium chloride	-	-	50	-	-	-
Potassium sulfate	-	-	42	-	-	18
Potassium magnesium sulfate	-	-	18	-	11	22
Magnesium sulfate	-	-	-	-	10	13
Magnesium oxide	-	-	-	-	32	-

Source: adapted from Jacob and Uexküll, 1973.

Nutrient Inputs from N-fixation and from Atmospheric and Soil Sediment Deposits

N-fixation

Not being a legume, it is unlikely that cassava fixes substantial amounts of N. Endophytic N_2-fixation by soil bacteria such as *Acetobacter diazotripicus* was found to be minimal in cassava, intermediate in sugarcane, and quite significant in pineapple (Ando et al., 1999). However, experiments on successive cuttings of cassava top growth for forage production in Colombia showed that about 350 kg N ha^{-1} was removed in the crop harvest, 25 kg in the roots, and 326 kg in four cuttings of tops, while only 100 kg N ha^{-1} had been applied as fertilizer. N-mineralization from soil OM could have accounted for about 175 kg N, while the remaining 75 kg of N might have come from atmospheric deposition or N-fixation (CIAT, 1988). Whether N-fixation by association with N-fixing bacteria is indeed significant in cassava needs further investigation.

Atmospheric Deposits

The deposition of nutrients in rainwater is highly variable and not well quantified. Near industrialized areas this may contribute significant amounts of S, while those of N are usually less than 20–30 kg ha^{-1}.

Soil Sediment Deposits

These are of major significance in lowland rice paddies that undergo regular flooding. In the uplands, where cassava is generally grown, they may be significant at the lower end of slopes where soil eroded from the upper slopes is deposited. This can contribute substantial amounts of nutrients from the eroded soil as well as from washed-out crop residues, ash, manures, and fertilizers.

Table 10. Nutrient content of animal manures and composts, as reported in the literature.

Source of manure/compost	**% Moisture**	**(% of dry material)**						
		C	**N**	**P**	**K**	**Ca**	**Mg**	**S**
Buffalo manure [1)]	60.4	17.4	0.97	0.58	1.28	-	-	-
Dairy cattle manure [2)]	79.0	-	2.66	0.48	2.38	1.33	0.52	0.23
Fattening cattle manure [2)]	80.0	-	3.50	1.00	2.25	0.60	0.50	0.43
Cattle manure [1)]	46.4	16.9	1.11	0.44	1.56	-	-	-
Cattle manure [3)]	-	-	2.00	0.65	1.67	2.86	0.60	0.20
Cattle manure (Dampit, Indonesia) [4)]	-	-	1.43	2.96	1.60	2.13	0.96	-
Cattle manure (Indonesia) [5)]	-	39.1	1.87	0.56	1.09	0.57	0.23	-
Cattle manure (Costa Rica) [6)]	-	-	2.23	0.77	2.25	1.77	0.89	-
Cattle manure [8)]	75.0	-	2.40	0.61	2.67	-	-	-
Cattle manure [9)]	-	-	0.35	0.06	0.16	-	-	-
Average cattle manure	**68.2**	**-**	**1.85**	**0.81**	**1.69**	**1.54**	**0.62**	**0.29**
Pig manure [1)]	29.9	19.0	1.32	2.37	0.96	-	-	-
Pig manure [2)]	75.0	-	2.00	0.56	1.52	2.28	0.32	0.54
Pig manure [8)]	75.0	-	2.80	1.22	1.67	-	-	-
Average pig manure	**60.0**	**-**	**2.04**	**1.38**	**1.38**	**-**	**-**	**-**
Chicken manure [3)]	-	-	5.00	1.31	1.25	2.86	0.60	0.80
Chicken manure (Blitar, Indonesia) [4)]	-	-	1.75	0.23	0.77	6.82	1.46	-
Chicken manure (Blitar, Indonesia) [4)]	-	-	0.43	0.67	0.39	4.93	1.43	-
Chicken manure (Khaw Hin Sorn, Thailand) [4)]	-	-	1.25	0.43	1.27	1.31	0.37	-
Chicken manure (Costa Rica) [6)]	-	-	1.68	2.58	1.19	6.90	0.66	-
Chicken manure (Pescador, Colombia) [7)]	-	-	4.96	1.95	2.27	4.53	0.48	-
Chicken manure (layer) [8)]	70	-	5.00	1.89	2.50	-	-	-
Chicken manure (broiler) [8)]	40	-	4.83	1.82	2.50	-	-	-
Chicken dropping [9)]	-	-	2.80	1.33	1.04	-	-	-

Table 10 Continued								
Chicken manure [9]	-	-	2.87	1.27	1.83	-	-	-
Broiler chicken manure [10]	25.0	-	2.26	1.08	1.67	-	-	-
Hen manure [10]	37.0	-	2.06	1.90	1.81	-	-	-
Average chicken manure	**43.0**	**-**	**2.91**	**1.37**	**1.54**	**4.56**	**0.83**	**-**
Horse manure [2]	60.0	-	1.72	0.25	1.50	1.96	0.35	0.17
Duck manure [1]	22.2	21.4	1.02	1.38	0.90	-	-	-
Sheep manure [3]	-	-	2.00	0.65	2.50	1.78	1.20	0.60
Sheep manure [2]	65.0	-	4.00	0.60	2.86	1.67	0.53	0.26
Average sheep manure	**-**	**-**	**3.00**	**0.62**	**2.68**	**1.72**	**0.86**	**0.43**
Human manure [9]	-	-	1.20	0.06	0.21	-	-	-
City garbage compost (Bangkok)[1]	28.8	17.3	0.97	0.46	0.86	-	-	-
City compost [9]	-	-	1.75	0.44	1.25	-	-	-
Rural compost [9]	-	-	0.75	0.20	0.60	-	-	-
Average city/rural compost			**1.16**	**0.37**	**0.90**	**-**	**-**	**-**
Rice straw compost [1]	73.7	33.8	1.07	0.19	0.69	-	-	-
Rice straw [9]	-	-	0.40	0.10	0.40		-	-
Rice husk [9]	-	-	0.62	0.08	1.25	-	-	-
Peanut stems + leaf compost [1]	58.6	11.6	0.81	0.10	0.38	-	-	-
Water hyacinth [1]	-	-	2.00	1.00	2.30	-	-	-
Ash (rice husks) [4]	-	-	0.03	0.40	1.06	0.47	0.22	-
Fly ash (Nanning, China) [4]	-	-	0.09	<0.10	1.20	4.14	1.14	-
Wood ash (Trivandrum, India) [11]	-	-	-	-	8.70	20.8	1.90	-
Wood ash [3]	-	-	-	0.87	4.17	23.2	2.10	0.40

[1] Suzuki et al., 1988 ; [2] Loehr, 1968; [3] Jacob and Uexkull, 1973; [4] Howeler (unpublished); [5] Rachman Sutanto et al., 1993; [6] Don Kass (personal communication); [7] Amezquita et al., 1998; [8] Scaife and Bar-Yosef, 1995; [9] FADINAP; [10] Perkins et al., 1964; [11] Kabeerathumma et al., 1990

NUTRIENT BALANCES—EXAMPLES FROM VIETNAM AND THAILAND

Nutrient balances should consider all nutrient inputs and outflows. However, quantitative data on nutrient losses due to erosion are highly site- and time-specific, while nutrient inputs from N-fixation, and atmospheric and eroded soil deposits are also very site specific and data are generally not available. While not negating the potential importance of these factors especially that of erosion, nutrient balances in this section are calculated only on the basis of nutrient inputs from manure and fertilizers, and nutrient outflows through crop removal, which can be estimated more easily.

Vietnam

In 1990/1991 a formal survey was conducted in all major cassava-producing areas of Vietnam. A total of 1,117 farmers were interviewed in 45 districts of 20 provinces (out of 43 provinces) in six agro-ecological regions. Among many questions, farmers were asked about fertilizers and manure inputs as well as yields obtained (Pham Van Bien et al., 1996; Pham Thanh Binh et al., 1996). Table 11 shows the average amounts of organic manures and chemical fertilizers applied in each of the agro-ecological regions; from this the total average, inputs of N, P, and K could be calculated. Table 12 shows the average fresh root yields obtained in each region (according to the interviewed farmers), and the nutrient removal in those roots as well as the corresponding tops, assuming that farmers in Vietnam remove both roots and tops from the field. From these data on nutrient outflows and the data on nutrient inputs (from Table 11), the nutrient balance was calculated for each region, for north and south Vietnam, as well as for Vietnam as a whole. It can be seen that the N balance was negative in three of the six regions, the P balance was highly positive in most regions but negative in one region, while the K balance was highly positive in one region but negative in three regions. The nutrient balances were positive for all three nutrients in the Red River Delta, and in the North and South Central Coasts where farmers tend to apply large amounts of manure. In comparison, nutrient balances were negative for all three nutrients in the Central Highlands where farmers apply very little manure and almost no chemical fertilizers. For Vietnam as a whole, as well as for both north and south Vietnam, the balance was positive for P and negative for both N and K. This indicates that cassava farmers in Vietnam, especially in the north, apply too much P (because it is cheap), but not enough N and K to satisfy the requirements of cassava. Many fertilizer trials conducted in Vietnam, both on experiment stations (Nguyen Huu Hy et al., 1998) and by farmers on their own fields (Nguyen The Dang et al., 1998), show mainly a response of cassava to N and K, but little response to P.

Studying the long-term effect of the cultivation of four crops—rubber, sugarcane, cashew, and cassava—in comparison with native forest on soil chemical and physical properties, Cong Doan Sat and Deturck, (1998) reported that after long-term cropping of Ultisols in southeastern Vietnam, soils under rubber and cassava had actually accumulated available P, but those under cassava had the lowest levels of total N and exchangeable Mg, and the second lowest levels of exchangeable K (Table 13). For this reason they concluded that cassava production under currently used practices is unsustainable, leading to soil degradation.

Table 11. Nutrient application for cassava production in various regions of Vietnam according to farm level surveys of 1, 117 households in 20 provinces in 1990/91.

	Organic (kg ha^{-1})	Chemical (kg ha^{-1})					N applied [1] (kg ha^{-1})					P [2] applied (kg ha^{-1})				K [2] applied (kg ha^{-1})			
		Urea	**SA**	**SSP**	**KCl**	**NPK**	**Organic**	**Urea**	**SA**	**NPK**	**Total**	**Organic**	**SSP**	**NPK**	**Total**	**Organic**	**KCl**	**NPK**	**Total**
Total Vietnam	**3,400**	**27**	**19**	**30**	**24**	**3**	**31.3**	**12.1**	**3.9**	**0.4**	**47.7**	**28.9**	**2.2**	**0.2**	**31.3**	**22.8**	**12.0**	**0.4**	**35.2**
North Vietnam	*4,426*	*21*	*0*	*61*	*35*	*0*	*40.7*	*9.4*	*0*	*0*	*50.1*	*37.6*	*4.5*	*0*	*42.1*	*29.7*	*17.5*	*0*	*47.2*
-North Mountainous Region	2,389	15	0	37	15	0	22.0	6.7	0	0	28.7	20.3	2.7	0	23.0	16.0	7.5	0	23.5
-Red River Delta	7,452	40	0	79	93	0	68.6	18.0	0	0	86.6	63.3	5.8	0	69.1	49.9	46.5	0	96.4
-North Central Coast.	7,288	22	0	112	36	0	67.0	9.9	0	0	76.9	61.9	8.3	0	70.2	48.8	18.0	0	66.8
South Vietnam	*2,543*	*31*	*36*	*4*	*15*	*5*	*23.4*	*13.9*	*7.4*	*0.7*	*45.4*	*21.6*	*0.3*	*0.3*	*22.2*	*17.0*	*7.5*	*0.6*	*25.1*
-South Central Coast	4,690	33	55	2	20	1	43.1	14.8	11.3	0.1	69.3	39.8	0.1	0.1	40.0	31.4	10.0	0.1	41.5
-Central Highlands	172	8	0	0	0	0	1.6	3.6	0	0	5.2	1.4	0	0	1.4	1.2	0	0	1.2
-Southeastern Region	850	40	27	9	16	14	7.8	18.0	5.5	2.1	33.4	7.2	0.7	0.9	8.8	5.7	8.0	1.8	15.5

[1] Assuming urea to contain 45% N; ammonium sulfate 20.5% N; NPK 15% each of N, P_2O_5 and K_2O; SSP 17% P_2O_5 and KCl 60% K_2O, and that "organic" refers to wet pig manure, which may have a composition (wet weight basis) of : 50% moisture, 0.92% N, 0.85% P and 0.67% K. [2] P and K in elemental form. Source: Pham Van Bien et al., 1996.

Table 12. Nutrient balance as a result of nutrient removal and application in the production of cassava in various regions of Vietnam in 1991/92.

	Cassava root yield (mt ha^{-1})	Nutrient removal (kg ha^{-1}) [1]			Nutrients applied (kg ha^{-1}) [2]			Nutrient balance (kg ha^{-1}) [3]		
		N	P [4]	K [4]	N	P [4]	K [4]	N	P [4]	K [4]
Total Vietnam	**12.36**	**62**	**7.0**	**40**	**48**	**31.3**	**35**	**-14**	**24.3**	**-5**
North Vietnam	*14.54*	*80*	*8.8*	*49*	*50*	*42.1*	*47*	*-30*	*33.3*	*-2*
-North Mountainous Region	16.26	85	10.0	51	29	23.0	23	-56	13.0	-28
-Red River Delta	11.47	58	6.5	39	87	69.1	96	29	62.6	57
-North Central Coast	12.45	65	7.1	41	77	70.2	67	12	63.1	26
South Vietnam	*10.61*	*57*	*6.0*	*36*	*45*	*22.2*	*25*	*-12*	*16.2*	*-11*
-South Central Coast	9.95	48	5.2	32	69	40.0	41	21	34.8	9
-Central Highlands	8.54	43	4.8	29	5	1.4	1	-38	-3.4	-28
-Southeastern Region	12.37	63	7.0	40	33	8.8	15	-30	1.8	-25

[1] Assuming all plant parts are removed from the field and nutrient removal is read off the curves presented in Figure 3; [2] Nutrients applied as organic manures and chemical fertilizers (see Table 11); [3] Nutrient balance = nutrients applied nutrients removed in harvested products; [4] P and K in elemental form.

Table 13. Chemical properties of various horizons of Haplic Acrisols that have been under different land use in southeastern Vietnam.

	Forest	Rubber	Sugarcane	Cashew	Cassava	CV (%)
Organic C (%)	1.032 a	0.839 ab	0.796 ab	0.579 ab	0.496 b	44.7
Total N (%)	0.058 a	0.054 ab	0.040 abc	0.032 bc	0.022 c	36.7
Available P (Bray 2) (µg g^{-1})						
-1st horizon	5.21 b	20.90 a	20.68 a	4.85 b	15.33 ab	37.5
-2nd horizon	2.48 b	7.03 a	7.92 a	3.19 b	5.31 ab	32.6
-3rd horizon	1.57 b	2.83 ab	3.82 a	1.08 ab	3.82 a	44.6
CEC (meq $100g^{-1}$)	3.43 a	2.94 a	3.24 a	2.39 ab	1.53 b	27.1
Exch. K (meq $100g^{-1}$)						
-1st horizon	0.132 a	0.127 a	0.051 b	0.070 ab	0.060 b	66.3
-2nd horizon	0.073 a	0.046 ab	0.022 b	0.031 ab	0.021 b	75.1
Exch. Mg (meq $100g^{-1}$)	0.145 a	0.157 a	0.055 ab	0.046 ab	0.036 b	89.1

Values are average of 6–10 profiles per cropping system. Within rows data followed by the same letter are not significantly different at the 5% level by Tukey's Studentized Range Test. Source: Cong Doan Sat and Deturck, 1998.

Thailand

In Thailand cassava has been cultivated very extensively and almost continuously for the past 25 years in many areas of the east and northeast. Cassava fields are seldom rotated with other crops, because few other crops can tolerate the poor sandy soils and unpredictable rainfall of those regions. However, since farm size in Thailand is relatively large, farmers may leave some fields under fallow for several years before returning the field to cassava cultivation. A survey conducted in 1990/1991 (DOAE, 1992) indicated that about 50 percent of cassava farmers applied some chemical fertilizers to the crop, usually between 10 and 50 kg of 15-15-15/rai (60–300 kg/ha). Farmers are well aware that cassava yields will decrease if no fertilizers are applied, but often lack the financial resources to buy fertilizers, especially in those years that cassava prices are very low. Thai farmers almost never apply animal manures or compost to cassava fields, and seldom practice green manuring, intercropping or crop rotations. According to data from the Office of Agricultural Economics (1998), cassava farmers spend "on average" 427 baht ha^{-1} on fertilizers, which corresponds to about 70 kg 15-15-15 ha^{-1}. In this case, they would be applying 10.5 kg N, 4.6 kg P, and 8.7 kg K ha^{-1}. Assuming an average yield of 15 mt ha^{-1} and that only roots are harvested and removed (parts of the stems are used as planting material, but as such are also returned to the field), we can estimate an annual nutrient outflow in the root harvest (from the curves in Figure 2) of 30 kg N, 3.5 kg P, and 20 kg K ha^{-1}. This would result in an "average" nutrient balance of –19.5 kg N, 1.1 kg P, and –11.3 kg K ha^{-1}. As in the case of Vietnam, the balance in Thailand is positive for P but negative for N and K, i.e. farmers apply too much P and not enough N and K.

Fertilizer trials have usually shown a response mainly to K and N, with less response to P (Nakviroj and Paisancharoen, personal communication; Tongglum et al., 2001). For this reason, the Departments of Agriculture (DOA) and Agricultural Extension (DOAE) are now recommending the application of 25–50 kg rai^{-1} (150–300 kg ha^{-1}) of 15-7-18, which better corresponds to the nutritional requirements of the crop.

In 1999 Thailand exported 4.34 million mt of cassava pellets and 0.93 million mt of starch, corresponding to about 9.76 and 4.42 million mt of fresh roots, respectively (TTTA, 2000). We may assume that nutrients are exported only in the chips but not in the starch. Each tonne of fresh roots contains about 2.00 kg N, 0.233 kg P, and 1.333 kg K (from Figure 2, assuming an average yield of 15 mt ha^{-1}). Thus, with the export of 4.34 mt of chips, Thailand exported also 19,520 mt of N, 2,270 mt of P, and 13,010 mt of K, with a total value in terms of fertilizers of 581 million baht. The total value of pellet exports was 12,446 million baht (TTTA, 2000). Thus, about 4.7 percent of the export value corresponds to the value of lost nutrients. These nutrients end up mainly in the form of pig manure in the Netherlands, causing a serious environmental problem there, while cassava soils in Thailand become more and more degraded. A shift towards greater use of cassava pellets for domestic animal feeding would help to alleviate this problem, while the export of meat would add value to cassava products, to the benefit of farmers and the country as a whole.

SOURCES OF UNCERTAINTIES AND ERRORS IN THE USE OF NUTRIENT BALANCES

Nutrient balances have been used to determine whether a particular nutrient is accumulating or is being depleted. However, as mentioned above, major errors in calculation can occur because:

1. Nutrient removal in the harvested product is usually calculated from the average nutrient content per tone of product. However, nutrient concentrations in the product tend to increase with increasing yield. This results in the nutrient content not being linearly related to yield, and nutrient removal being overestimated when yields are low.
2. In many crops it is often uncertain which part of the plant is being removed from the field—only the harvested grain (or roots) or also the straw (or other crop residues)?
3. Incorporation of green manures, *in-situ* mulches, and intercrop residues may contribute nutrients to the following crop, but most of these nutrients have merely been recycled and thus cannot be considered as a nutrient input to the system. In fact, the harvest of intercrops is likely to result in a nutrient outflow, unless these intercrops have been adequately fertilized.
4. Nutrient inputs from N-fixation, atmospheric deposits, as well as nutrient losses by leaching and volatilization are very difficult to estimate and are therefore usually ignored.
5. Nutrient losses in eroded soil sediments and runoff, and nutrient inputs from the deposition of eroded sediments are very site-specific and extremely variable over time, making it almost impossible to arrive at meaningful estimates from these sources.
6. Nutrient losses in eroded sediments are often calculated from the analyses of “available” P and “exchangeable” cations in the eroded sediments. However, the loss of total N, total P, and total K in the sediments should be determined to get a more accurate estimate of nutrient losses; these losses can be 5 to 10 times greater than the “available” fraction generally determined.
7. Nutrient inputs from animal manures, compost, ash etc are uncertain due to the variable moisture content and composition of these products.

CONCLUSIONS

1. Nutrient balances, i.e. the difference between nutrient inputs and outflows, are often used to determine whether a particular nutrient is accumulating or is being depleted. In the latter case it may be concluded that the cropping system being used is unsustainable. While this is correct in principle, there are major difficulties in accurately determining all nutrient inputs and outflows. For this reason, nutrient balances are generally “partial” balances, which ignore those sources that are either of minor importance or are difficult to quantify. Thus, care should be taken in the interpretation of results.

2. In the case of cassava, nutrient removal in the harvested roots is generally lower than that in the harvested products of other crops. When cassava yields are high the nutrient contents of the roots are K>N>P, but when yields are low (<30 mt ha^{-1}) nutrient removal is N>K>P. When all plant parts are removed from the field at harvest, the removal of N, Ca, and Mg is greatly increased and nutrient removal is generally N>K>P.

3. Cassava causes more erosion than most other crops, but erosion can be markedly reduced by the use of better management practices. Total nutrients in both eroded sediments and runoff tend to be high in K and N, but low in P. These losses can be as high as, or higher than, losses of nutrients in the harvested products. However, these losses are not uniform over time or space, and therefore are very difficult to estimate.

4. Partial nutrient balances of nutrient inputs in fertilizers and manures, and outflows in harvest products in Vietnam and Thailand indicate that the balances for N and K are usually negative, while those for P are positive. Especially in Vietnam, cassava farmers tend to apply too much P and not enough N and K to the crop. Experiments on farmers' fields generally show that farmers can increase yields and net income by reducing the amounts of FYM and P applied and increasing the application of K in the form of chemical fertilizers. In Thailand, farmers have been applying mainly compound 15-15-15 fertilizers to cassava. With this type of fertilizer farmers apply too much P and not enough N and K. With an average yield of 15 mt ha^{-1} of fresh roots, farmers should apply at least 200 kg ha^{-1} (32 kg rai^{-1}) of 15-7-18 fertilizers to maintain a positive balance for all three major nutrients.

5. Nutrient balances in Thailand indicate that with the annual export of over four million mt of cassava pellets, the country also exports nearly 20,000 mt of N, over 2,000 mt of P, and 13,000 mt of K with a value of about 580 million baht. Unless these nutrients are returned to the soil in the form of chemical fertilizers, there is no doubt that cassava soils will be depleted in nutrients and cassava production may not be sustainable in the long term.

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