Nutrient deficiencies of agricultural crops in Papua New Guinea

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In Papua New Guinea the population is growing faster than the area under cultivation. As a result, land use is being intensified and soil nutrient depletion may occur, resulting in nutrient deficiencies of agricultural crops. This paper reviews nutrient deficiencies in the agricultural crops of Papua New Guinea using the literature on agronomic trials, expert knowledge and Geographical Information System (GIS) soil fertility databases. One of the aims of this overview is to discuss the spatial distribution of common nutrient deficiencies, which will facilitate the formulation of future strategies on integrated nutrient management research. Nutrient deficiencies have been investigated systematically since the mid-1950s. Research has mainly focused on export tree crops, and relatively little information is available on food crops. Literature analysis and expert knowledge showed consistent trends with deficiencies of B and P in large parts of the highlands. GIS soil fertility databases confirm these observations. The authors' method has been shown to be useful in delineating areas in which nutrient deficiencies occur, and these findings could be used for the planning of nutrient management research and extension activities.

Low levels of available nutrients in the soil may be natural, due to low amounts in the parent material from which the soil is derived, to fixation and immobilization that impair nutrient uptake, or to high rainfall conditions that leach nutrients from the soil. Low nutrient levels may also result from cultivation because of removal by agricultural crops in the absence of nutrient replenishment, and through accelerated losses compared with natural ecosystems. Some soils are resilient and will retain favourable levels of nutrients under cultivation,[1] but in the majority of soils, nutrient levels decrease under permanent cultivation resulting in deficiency syndromes of agricultural crops.

In many smallholder agricultural systems in tropical regions, nutrient deficiencies limit food crop production, which is made worse by increasing land pressure. Detailed information on the spatial distribution and seriousness of nutrient deficiencies is needed to develop research strategies aimed at alleviating the problem and increasing food production. Such information systems are used for planning research on integrated nutrient management in some tropical countries, but in many countries including Papua New Guinea, the information is scattered or unavailable on a national or regional scale.

Papua New Guinea is the largest country in the Pacific region. Subsistence agriculture is practised by more than three-quarters of the population in a wide range of environmental conditions. Annual rainfall varies from 1,000 mm in the area around the capital, Port Moresby, to over

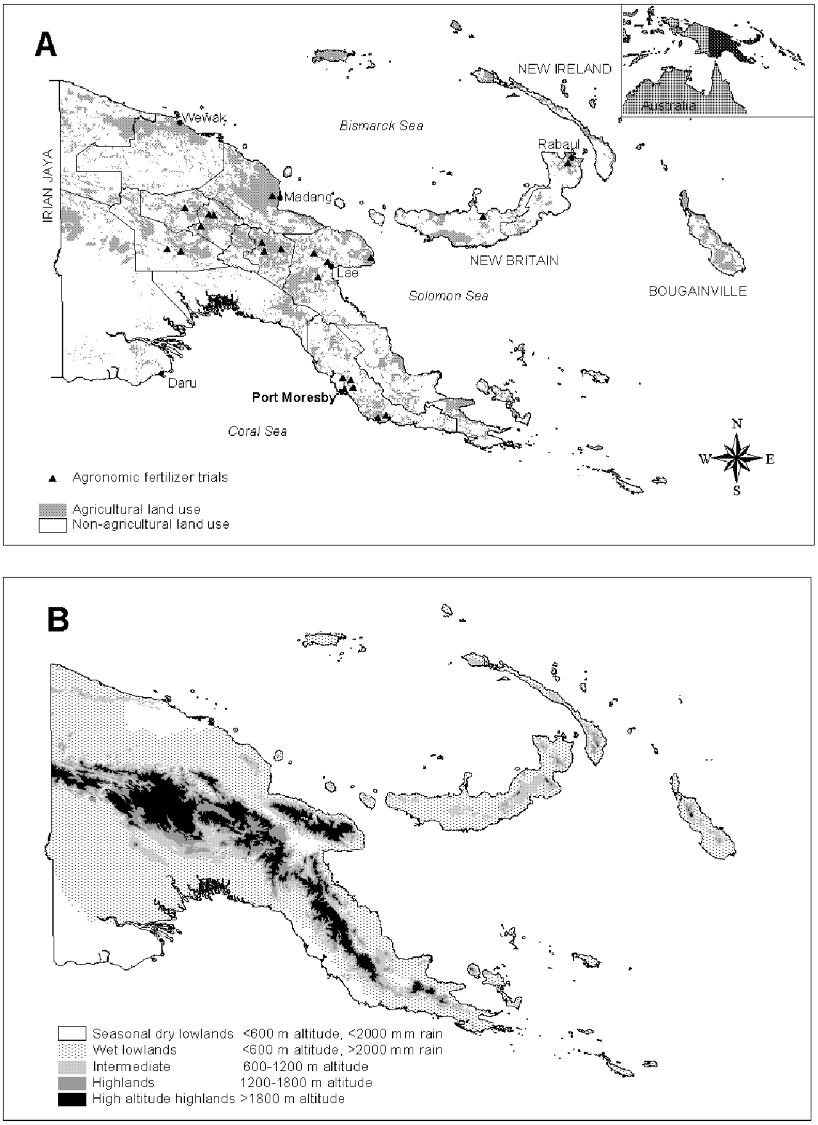

Figure 1. Agricultural land in Papua New Guinea (A), and major agroecological zones based on altitude and annual rainfall (B).

8,000 mm in the mountains of the far western part (see Figure 1: B). The rugged mainland and the surrounding islands form part of a highly mobile zone of the earth's crust where volcanic activity occurs. Many areas have been covered by volcanic deposits, while weathering and denudation of the steeply sloping mountains have caused the deposition of extensive alluvial plains.[2] Due to the great variety of parent materials, climatic conditions and differences in topography, there are many different soil types. Relatively more agriculture is found on young soils such as Andisols and Eutropepts. Agriculture takes place from sea level to 2,850 metres above sea level.

The population of Papua New Guinea doubled between 1966 and 1990.[3] Analysis of land-use intensities using aerial photographs from the early 1970s with LandSat™ imagery from 1996 revealed, however, that the area under cultivation had increased by only 7% over a 24-year period.[4] This implies increased land-use intensities, which have mainly occurred in areas that had already had high land-use intensities in the past. The land is cropped more often and that puts a greater demand on the soil resource, particularly as few or no inorganic fertilizers are being used on food crops. Nutrient deficiencies are likely to increase with higher land-use intensities.

Research on nutrient deficiencies of agricultural crops started in Papua New Guinea in the 1950s, and successive research projects focused on export tree crops. Significant research on nutrient deficiencies in food crops started only in the 1970s. Earlier reviews[5] had revealed that macro- and micronutrient deficiencies were occurring locally in some agricultural crops. In this paper, we have assembled the available information on nutrient deficiencies in the agricultural crops of Papua New Guinea. The information is drawn from three sources:

(i) about 45 years of literature on nutrient deficiencies and soil and plant analysis in most parts of Papua New Guinea;
(ii) field observations throughout PNG on visual symptoms of nutrient deficiency in agricultural and horticultural crops;
(iii) data held in a GIS-based natural resource and agricultural systems databases.

Data collection

Existing literature

Soil research in Papua New Guinea started in the 1950s,[6] and was conducted by two almost independently working groups of scientists. At the experiment stations for export tree crops (cash crops), agronomists and soil fertility experts investigated optimum inorganic fertilizer rates and nutrient deficiencies using field experiments, greenhouse trials and on-farm experiments. Figure 1: A gives an overview of where fertilizer trials have been conducted in the past decades. The second group were pedologists and soil surveyors who used broad-scale mapping techniques to map the soils of large parts of the country. This yielded spatial information on soil chemical properties in many parts of Papua New Guinea.

Much of the early agronomic research was focused on the establishment and development of export tree crops, particularly coconuts, coffee and tea. Research occurred on an *ad hoc* basis, ie when a problem was observed at the plantation. A clear example is the research on coconut plantations in New Ireland, which started in the mid-1950s. The plantations were established by the Germans between 1910 and 1920, and in the 1950s it was noted that production had drastically decreased, with many palms showing stunted growth and leaf chlorosis.[7] A soil survey was undertaken[8] and investigations were carried out on leaf nutrient content and soil nutrient levels. It was concluded that, amongst other agronomic problems, K was the main factor limiting coconut production.[9] Subsequent research focused on the use of inorganic fertilizers.[10] The success of the approach used in New Ireland in clearly defining the nutritional disorder established the value of chemical techniques for plant nutrition diagnosis, as well as guidelines for future plant nutrition research in Papua New Guinea.[11] In the 1960s and 70s, research focused on the establishment and development of new plantations, following the developments in soil survey and land evaluation techniques. This yielded information on nutrient deficiencies in new export tree crops, particularly oil palm and cocoa.

Overall there is a fair body of literature on nutrient deficiency of agricultural crops in Papua New Guinea, although much more is known about export tree crops than about food crops. Most of the research has been published in annual reports of experimental stations, and concerns the effects of inorganic fertilizer on crop yields, which gives insights into the limiting nutrients. See Figures 2 and 3. Information on nutrient deficiencies in crops was usually obtained through foliar analysis, but it has been more successful in some crops than others, mainly because of sample size and seasonal variations. There is also some literature on deficiency symptoms in plywood forestry nurseries that started in 1953.[12]

Figure 2. Factorial fertilizer trials with sweet potato (*Ipomoea batatas*) at the experimental farm of the University of Technology in Lae, 65 m above sea level.

Figure 3. Pot trials in the greenhouse have been used to identify nutrient disorders at the University of Technology in Lae.

Field observations

Field observations of visual symptoms of nutrient deficiency in agricultural and horticultural crops were made by R.M. Bourke, who has visited every Papua New Guinean district over the past 30 years. These observations were usually done while surveying village agriculture, crop altitudinal limits and crop seasonality. As the field observations were not made systematically, but incidentally to other survey work, the coverage of observations across the country is uneven.

The occurrence of leaf deficiency symptoms has mainly been recorded, but information on stunted growth, defoliation and die-back was also noted. Nutrient deficiencies were tentatively identified in the field, and slides were taken. In 1996, all slides were shown to experts in the Faculty of Agriculture, University of Queensland, who confirmed the tentative field identifications. They were also checked with texts on nutrient deficiency.[13] In cases in which there was doubt as to whether the leaf symptoms were caused by nutrient deficiencies or by pathological, entomological, environmental or genetic causes, these observations were excluded. Several hundred

Figure 4. The multipurpose planted tree species *Casuarina oligodon* showing stunted growth caused by severe boron deficiency, Nembi Plateau, 1,700 m asl.

confirmed observations have been made on the deficiency of nine nutrients in 42 crops. See Figure 4.

Geographical databases

Soil mapping started in Papua New Guinea in the 1950s, applying the land-system approach developed in Australia in the late 1940s.[14] As part of the surveys, soil samples were taken for chemical characterization of mapping units. The soil survey work was later used to develop Papua New Guinea Resource Information Systems (PNGRIS). PNGRIS is a natural resource database for the whole of Papua New Guinea at a scale of 1:0.5 million.[15] It contains 4,852 resource mapping units (RMU), which are differentiated by three physical resource attributes: landform, geology (rock type) and altitude. For each RMU there is information on soil physical and chemical properties. The soil chemical database in PNGRIS includes information on a range of soil fertility parameters including pH, total N, available P and exchangeable bases.

In the 1990s, PNGRIS was used to develop the Mapping Agricultural System Project (MASP) which mapped the agricultural systems of Papua New Guinea at a scale of 1:0.5 million.[16] MASP contains information on a wide range of agricultural practices, including the dominance and extent of food crops and the significance of export tree crops in all agricultural systems. PNGRIS and MASP were used to map soil chemical properties of agricultural land areas in Papua New Guinea.

Agricultural crops of Papua New Guinea

About a quarter of the total land area in Papua New Guinea is used for agriculture, with varying intensities. Figure 1: A shows the agricultural land based on aerial photograph information.[17] The largest areas of agricultural land are in a series of valleys and basins in the central highlands; in the mountains and foothills inland of Wewak; along much of the north coast of the main island; land south-west of Lae extending almost to the south coast; in coastal locations in eastern Papua; the islands of Milne Bay; the north coast and north-east of New Britain; the north-east coast of New Ireland, and parts of Bougainville Island (Figure 1: A).

Figure 1: B shows the distribution pattern of the five major ecological zones based on altitude and rainfall. Most of the lowlands (< 600 m asl) are wet with annual rainfall exceeding 2,000 mm. In the south-west, part of the Sepik plain and around the capital, Port Moresby, there are extensive areas that are seasonally dry with rainfall as low as 1,000 mm per year. The valleys and basins in the central highlands are located at over 1,200 m asl and high concentrations of people live between 1,500 and 2,000 m asl. Extensive parts of the highlands are over 1,800 m asl with a significant number of people living and farming at higher altitudes up to 2,800 m asl.

Export tree crops

Coffee is the main export tree crop in Papua New Guinea and the major source of income for one-third of the population.[18] A few plantations were established during the 1930s, but a rapid expansion of the industry started in the early 1950s. Smallholders produce about 70% of the total production. Arabica coffee accounts for about 95% of production, and is grown in the Central Highlands and mountainous parts of Morobe province. Some Robusta coffee is grown below 600 m asl, mostly in Morobe and East Sepik provinces. Research on Arabica coffee began in the early 1950s.

Coconuts are grown extensively along the coast and in some inland lowland locations. It is estimated that the total area under coconuts is about 250,000 ha (Table 1). Copra production is concentrated in the Islands region, with most copra coming from East New Britain, Bougainville, New Ireland and West New Britain provinces. Most production is done by villagers and few plantations still produce copra. Systematic research on coconuts commenced in the early 1950s.

Cocoa production is concentrated in the Gazelle Peninsula of East New Britain, Bougainville, East Sepik, Madang, New Ireland and West New Britain. About 65% of cocoa is grown by smallholders, and research commenced in the early 1950s.

Oil palm is grown by estates, settlers and villagers, and production is limited to the north coast of West New Britain, the north-east coast of New Ireland, the area near Popondetta in Oro province, and an area inland of Milne Bay. Production has expanded rapidly over the past 30 years, and continues to do so. Research on the oil palm started in the mid-1960s.

Tea production started in the late 1940s, but is now restricted to several estates in the Wahgi Valley of the Western Highlands. Smallholder production ceased in the late 1970s. Research was conducted between the late 1960s and the mid-1980s.

Rubber is produced by several estates and smallholders in a limited number of locations in Central, Western and East Sepik provinces. A limited amount of research was conducted during the 1960s and 70s.

Food crops

Large numbers of food crops are grown in Papua New Guinea, both for subsistence consumption and for sale at local markets. The most important are root crops, sago, banana, maize and green vegetables. Sweet potato is the major food crop and is the staple food for over 60% of the rural population (Table 2). It dominates agricultural production in the highlands and very high altitude

Table 1. Extent and growing areas of major export tree crops in Papua New Guinea.

Crop	Botanical name	Extent (ha) [1]	Growing area
Arabica coffee	*Coffea arabica*	50,000	Highlands, predominantly Andisols
Robusta coffee	*Coffea canephora*	5,000	Wet lowlands, various soil types
Coconuts	*Cocos nucifera*	250,000	Wet and seasonal dry lowlands, various soil types
Cocoa	*Theobroma cacao*	30,000	Wet lowlands, mainly Andisols
Oil palm	*Elais guineensis*	80,000	Wet lowlands, mainly Andisols
Tea	*Camellia sinensis*	3,000	Highlands, Histosols and Andisols
Rubber	*Hevea brasiliensis*	5,000	Seasonal dry and wet lowlands, various soil types

[1] Extents of export tree crops are estimates based on published literature and figures provided by research stations.

Table 2. Major food crops, their main growing areas and importance in Papua New Guinea. Based on data in MASP (Allen *et al*, 1995).

Crop	Botanical name	Main growing area	Importance [1]
Sweet potato	*Ipomoea batatas*	Throughout the country, except in seasonal dry lowlands	61
Sago	*Metroxylon sagu*	Wet lowlands	12
Banana	*Musa* cultivars	Seasonal dry lowlands	7
Yam	*Dioscorea* spp.	Seasonal dry lowlands	5
Taro	*Colocasia esculenta*	Wet lowlands	4
Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands	2
Cassava	*Manihot esculenta*	Seasonal dry lowlands	1
No dominant staple			8

[1] Percentage of the rural population for whom this is the dominant staple, that is the crop occupying more than one-third of the garden area.

highlands, but it is also significant in the wet lowlands. Sago is the staple food for 12% of villagers, mainly in the East Sepik, West Sepik, Western and Gulf provinces. Banana is the main staple food for 7% of the population, and is widely grown up to 2,200 m altitude. It is important in the seasonally dry lowlands and in areas with very high rainfall (> 4,000 mm y1). Other staple foods include yam, taro, Chinese taro, cassava, Irish potato and maize. Some research on food crops was conducted in the 1930s and again after the Pacific War, but continuous research began only in 1970.

Nutrient deficiencies — literature

Macronutrients

Nitrogen is commonly deficient and limiting to crop production in cultivated soils of the tropics.[19] Soil nitrogen levels depend largely on the agroecological conditions and soil management practices, causing a large spatial and temporal variability. In general, N levels increase with decreasing temperatures — which lower decomposition rates, and increased rainfall — which favours biomass production.[20] In Papua New Guinea, it was found that the N content of soils was generally higher at higher altitudes, and in Andisols where organic matter forms complexes with allophane and aluminium oxides, which retard organic matter decomposition.[21] Poor drainage, hindering decomposition, also results in higher organic matter content and hence higher nitrogen content of the soil.[22]

Nitrogen deficiencies have been reported under Arabica coffee in conditions of low shade intensity, or when inorganic fertilizers high in S are applied.[23] Nitrogen deficiency has been widely reported in cocoa except when it is shaded. Under coconuts, N deficiency has been reported from an Andisol that had been frequently burned, inducing N losses.[24] Nitrogen responses have been reported for various crops, including sorghum on Vertisols,[25] oil palm on Andisols,[26] taro on Andisols in the lowlands,[27] and broccoli on Andisols in the highlands.[28] Nitrogen was the key element for sweet potato on Andisols in the wet lowlands and highlands,[29] but Hartemink *et al*[30] reported a negative yield response of sweet potato to N fertilizer on alluvial soils with low native N levels.

Phosphorus deficiency is common in highly weathered and acid soils in which the mineral fraction is dominated by kaolinite and sesquioxides, and in Andisols consisting of allophane and its weathering products.[31] Highly weathered soils are not common in Papua New Guinea,[32] nor are very acid soils.[33] Soils derived from predominantly Quaternary volcanic ash (Andisols) are common, particularly in the highlands where they cover large areas.[34] Andisols have a large pH charge dependency, and adsorb P strongly at low soil pH, and the P availability strongly depends on pH and clay mineralogy. The decomposition of organic matter supplies the bulk of the P crop requirement.[35] The deficiency of P was recognized as a problem in food crops only in the 1970s, because until then research had been mainly focused on tree crops, which have a low inherent P requirement.

Available P is low in soils derived from limestone under coconuts, but because of the low P requirements it is not likely to be a seriously limiting nutrient for coconuts.[36] Mature Arabica coffee is able to extract sufficient P from soils low in P[37] and yield responses to P fertilizers are rare.[38] D'Souza and Bourke[39] and Floyd *et al*[40] showed that sweet potato yields were slightly increased by applying P fertilizers on an Andisol in the highlands. On Andisols in the lowlands, no response to P fertilizer was recorded for taro,[41] although a positive (see Figure 5) response was obtained for maize.[42] Bourke[43] reported infrequent small increases in sweet potato yield in response to P on an Andisol in the wet lowlands. Favourable responses to P fertilizer were also obtained by

Figure 5. On-farm field trials to determine optimum inorganic fertilizer rates at Hobu, (Morobe province), 405 metres above sea level. The maize (*Zea mays*) in the foreground received no fertilizer whereas the maize in the background received 100 kg N and 50 kg P/ha^{-1}.

Figure 6. Massive response by edible lupins (*Lupinus* sp.) to applied phosphate fertilizer at Tambul at 2,300 metres above sea level. Treated lupins on the left; control on the right.

Aburu[44] and Parfitt and Williams[45] on alluvial soils (Vertisols, Fluvents) in the lowlands. Sivasupiramaniam *et al*[46] showed that sheep manure and P inorganic fertilizer dramatically increased sweet potato yields on Andisols in the highlands. Figure 6 shows the response of edible lupins to applied phosphate fertilizer at Tambul, 2,300 m above sea level.

The distribution of soil K generally follows a pattern that is related to rock type and the degree of weathering of the soils.[47] Deficiency of K is more often found in highly weathered and leached soils that have limited amounts of mineral reserves remaining. Soils developed in volcanic ashes commonly have high K levels because of their high levels of primary minerals (eg feldspars). High Ca and Mg levels in the soil may result in K deficiency, which has been reported to occur in very acid soils, and in soils along the coast derived from limestone.

Baseden and Southern[48] reported K deficiency in coconuts on soils developed over coral limestone, because of an imbalance in cations and the considerable amounts of K that are removed with the husks and nuts. On these soils, coconuts showed a dramatic response to K applications,[49] which was also found in soils with high Mg/K ratios.[50] Many coffee plantations have soils deficient in K.[51] Applications of K are generally favourable, although negative interaction with Ca and Mg can occur.[52] Root crops are large K consumers,[53] but K deficiencies in Papua New Guinea have been only partially documented. On Andisols in the wet lowlands, Bourke[54] reported large yield responses to applied and residual K. D'Souza and Bourke[55] demonstrated a marked increase in sweet potato yield following K fertilizer applications on Andisols in the highlands. Taro showed no response to K application on Andisols in the lowlands.[56]

There have been only few reports on Mg deficiencies, which mostly result from a cation imbalance. Deficiency of Mg is common in Arabica coffee,[57] but no yield responses have been obtained in fertilizer trials due to the low K status of most soils that favours Mg uptake.[58] Deficiency of Mg occurs in Andisols under oil palm, and is aggravated by high N fertilizer applications.[59] Recent investigations confirm the widespread deficiency of Mg in oil palm on Andisols.[60]

Sulphur deficiency has been reported from very different soils and appears to be fairly common, although the occurrence is more likely to be ecological than pedological.[61] Contributing factors are high rainfall and leaching, frequent burning of vegetation by which S is lost, the lack of inorganic fertilizer use, and competition with other plants, notably *Imperata cylindrica*. It was found that S deficiencies were common in coconuts on soils derived from limestone.[62] Sulphur deficiencies in coconut were also observed on Andisols and Fluvents on which vegetation burning was common,[63] and on soils derived from limestone when K deficiency was corrected.[64] Sulphur deficiencies occur in the Arabica coffee growing areas,[65] particularly when high N fertilizer rates are applied.[66] Hill[67] showed a marked response of peanuts to S fertilizers on alluvial soils. There have been no reports of S deficiency in rubber, sweet potato or other staple root crops, but sulphur deficiency has been reported for rice (*Oryza sativa*) grown on alluvial soils,[68] and also for tea, sorghum and pasture crops.[69]

Micronutrients

Until 1965, research focused on macronutrients, partly because problems associated with macronutrients were more obvious, but also because facilities were not available for research into micronutrients.[70] Investigations in micronutrients began in 1966 after routine methods, mainly using atomic absorption, became possible. This review on micronutrient deficiency is largely based on the work of Southern and Dick,[71] who surveyed export tree crops across the whole of Papua New Guinea in the 1960s, and on the work of Bourke[72] who reviewed the literature up to the beginning of the 1980s. The information on micronutrients is based mainly on foliar analysis, as there is virtually no information about minor elements in the soils of PNG.[73]

Boron deficiency has been reported for Arabica coffee in the highlands,[74] and dramatic yield increases following B applications occur. In Robusta coffee and rubber, no symptoms of B deficiency have been recorded, but B toxicity is common in some acid coastal soils where rubber is grown.[75] No serious B deficiency has been found in coconuts or cocoa.[76] Casuarina and pinus trees are both susceptible to B deficiency, and casuarina trees have been reported to respond vigorously to B applications, particularly in soils with low organic matter contents.[77] Although B deficiency is widespread in certain tree crops, relatively little information is available on the food crops.[78] Bang[79] showed that Irish potato yields increased after applications of both B and P on Andisols in the highlands, but D'Souza and Bourke[80] found a yield reduction in sweet potato after applying B fertilizers. Application of B fertilizer to peanuts, cowpea and winged beans had no effect,[81] but in the high altitude highlands, favourable responses of B applications to pyrethrum have been found.[82] Figure 7 shows severe boron deficiency symptoms on tomato foliage.

Research on Zn deficiency in Papua New Guinea started after it was identified in Netherlands New Guinea.[83] In Papua New Guinea, Zn deficiency occurs in Arabica coffee throughout the highlands and is usually more severe in unshaded coffee,[84] although seasonal variation is considerable.[85] In Robusta coffee, Zn deficiency commonly occurs in conjunction with Mn deficiency in alkaline soils.[86] Zinc deficiency is a problem in tea on drained Histosols in the highlands, but no serious Zn deficiency has been reported for coconuts. In cocoa, Zn deficiency ('sickle leaf') is common, particularly when grown on alkaline soils. Little is known about Zn deficiency in food crops, and the only reports available are for Zn deficiency in rice and peanuts grown on alluvial soils (Fluvents).[87]

Investigations into Mn nutrition have been concentrated on alkaline alluvial soils, neutral to alkaline soils of the coast and atolls, and soils developed in volcanic ash.[88] In general, Mn levels in Arabica coffee leaves are high,[89] and no symptoms of Mn toxicity have been observed. There is evidence that Mn contents have increased following the use of acidifying N fertilizers. In cocoa, low Mn levels were found in plants on neutral to slightly alkaline soils, but there is no evidence that Mn applications increase growth or cocoa production. In rubber, Mn deficiency may occur on soils high in exchangeable Mg,[90] and deficiency of Mn was observed in yams grown on soils derived from coral limestone.[91] On a young Andisol in the wet lowlands, Mn deficiency symptoms on pomelo (*Citrus grandis*) and other citrus species disappeared after foliar applications of both Zn and Mn, whereas the sole applications of Zn or Mn had no effect.[92] Sweet potato showed no response to Mn in a field trial on an Andisol in the wet lowlands.[93]

Figure 7. Severe boron deficiency symptoms on tomato foliage at Aiyura, 1,600 m above sea level.

Slight symptoms of Fe deficiency in Arabica coffee are common throughout the highlands, particularly on pruned trees.[94] The deficiency of Fe is not a serious problem in Arabica coffee and no corrective measures are necessary.[95] In cocoa, Fe deficiency is fairly common, particularly on soils derived from coral limestone. No symptoms of Fe deficiency have been recorded for rubber, but Fe deficiency was reported in high pH soils of forestry nurseries.[96]

There are no records of Cu deficiency in Arabica coffee and fertilizer effects have not been observed in Papua New Guinea.[97] Tentative values indicated that Robusta coffee leaves had locally low Cu levels. Copper deficiency has not been observed in cocoa, but low Cu values were found in trees growing on Andisols.[98] Cu deficiency is unlikely to occur in rubber, except in nurseries.

Table 3 summarizes the information on nutrient deficiencies in export tree crops and food crops, as discussed in the previous sections. The table shows that nutrient deficiencies in export tree crops have been more widely reported as they have received more research attention than food crops. Nutrient deficiencies in Arabica coffee have been researched more than in any other crop.

Nutrient deficiencies — field observations

Nitrogen deficiency is common in arable crops, especially in areas where soil fertility has declined through extended cropping periods. However, symptoms have not been recorded systematically in the field. The deficiency symptoms of P are widespread throughout the highlands on a wide range of crops. Maize and the weed, Cobbler's Pegs (*Bidens pilosa*) are good indicator plants of P deficiency. Symptoms are more severe at altitudes over 2,000 m asl throughout the highlands, and dramatic responses have been observed to P on potato, lupins and soybean at an experimental station 2,300 m asl. Deficiency symptoms of

Table 3. Nutrient deficiencies reported in export tree crops and food crops in Papua New Guinea, based on reconciliation of published literature 1955–98.

		Macronutrients					Micronutrients				
		N	*P*	*K*	*Mg*	*S*	*B*	*Zn*	*Fe*	*Cu*	*Mn*
Export tree crops	Arabica coffee	2	3	1	2	2	1	1	1	4	4
	Robusta coffee	–	–	–	–	–	4	3	–	2	2
	Cocoa	1	–	–	–	–	4	2	2	3	3
	Coconuts	2	3	2	–	2	4	4	–	–	–
	Oil palm	2	–	–	2	–	–	–	–	–	–
	Rubber	–	–	–	–	4	4	–	4	4	3
	Tea	–	–	–	–	2	–	3	–	–	–
Food crops	Sweet potato	1	2	2	4	4	2	4	4	4	
	Taro	1	3	2	–	4	–	–	–	–	–
	Irish potato	–	3	–	–	–	3	–	–	–	–
	Citrus spp.	–	–	–	–	–	–	1	–	–	3
	Maize	–	2	–	–	3	–	–	–	–	–
	Rice	–	–	–	–	2	–	3	–	–	–
	Peanuts	–	–	–	–	2	4	3	–	–	–
	Pyrethrum	–	–	–	–	–	3	–	–	–	–

1 = common in many parts of the country
2 = locally
3 = very locally
4 = investigated, but no deficiency present
– = not investigated.

K are uncommon in agricultural crops in Papua New Guinea, but they have been observed on a number of crops on alluvial soils in the Sepik plain and on alluvial soils in coastal Central province. Mild Mg deficiency symptoms occur on a number of crops on volcanic ash soils in East New Britain and on similar soils on the north coast of New Britain. Symptoms are very common on a range of crops in the Bulolo and Wau areas of Morobe province. Symptoms of S deficiency have been noted on citrus at two locations in the highlands. Table 4 summarizes the observations on macronutrient deficiencies as observed in the field.

Symptoms of B deficiency are widespread on casuarina and pine trees and on brassicas in the highlands. They have been noted on a number of other crops, including sweet potato (Table 5). Symptoms of Zn deficiency are universal wherever citrus are grown in the lowlands, intermediate altitude zones and highlands in Papua New Guinea (Figure 1). They are also common on Arabica coffee in the highlands, but have not been noted on other crops. Manganese deficiency was proven on pomelo at Keravat, together with Zn deficiency, but otherwise there are no observations on Mn deficiency. Symptoms of Fe deficiency have been noted on a number of crops on soils derived from coral limestone, but the area is small and the deficiency is of minor economic significance.

Figure 8 shows the approximate distribution of macro- and micronutrient deficiencies in agricultural crops of Papua New Guinea, based on field observations by R.M. Bourke.

Nutrient deficiencies — GIS databases

Soil fertility information was derived from the Papua New Guinea Resource Information System (PNGRIS) and plotted for the areas currently under village agriculture. Soil chemical fertility information for each mapping unit includes: total N, exchangeable K, available P, anion fixation, soil reaction (pH), and base saturation. Maps were derived from the database using ArcView GIS software and small areas were excluded from the map to improve its readability (Figure 9).

Despite the great variation in climatic and soil conditions, the following pattern emerges. The majority of soils in the coastal areas of Papua New Guinea have low to moderate content of N. Many soils in the central highlands have N contents exceeding 5 g/kg soil, which is caused by slower decomposition than occurs in the lowlands. The status of available K is generally favourable in most soils of Papua New Guinea. Most soils have a slightly acid to neutral soil reaction, and alkaline soils occur along the coast and locally in the highlands. Base saturation is moderate to high in most soils, although soils in the highlands have low base saturation. The maps also clearly show that P fixation and low P availability are common problems in the central highlands and on the volcanic active islands, including the northern part of New Britain and Bougainville island.

By overlaying the agricultural systems map on the PNGRIS map it was possible to calculate how much of the agricultural land had soils low in total N. This was calculated for the four major soil chemical properties (N,P,K and base saturation) and the results are presented in Table 6. The analysis shows that about 25% of the soils under agriculture have high total N levels, whereas 15% of the land has low to very low N content. About one-third of the agricultural land in Papua New Guinea has soils with low available P, and almost 90% of the land has low to moderate available P levels. Three-quarters of the agricultural land has soils with moderate K levels, and in 82% of the soils base saturation is moderate or high.

Table 4. Field observations on macronutrient deficiencies in Papua New Guinea.

Nutrient	Crop	Botanical name	Location and soil type
N	Arabica coffee	*Coffea arabica*	Highlands, Andisol
	Coconuts	*Cocos nucifera*	Wet lowlands, Andisol
	Sweet potato	*Ipomoea batatas*	Various locations in both highlands and lowlands
	Avocado	*Persea americana*	Highlands, Andisol
	Taro	*Colocasia esculenta*	Various locations in both highlands and lowlands
	Pineapple	*Ananas comosus*	Wet lowlands, Andisol
P	Maize	*Zea mays*	Widespread in the highlands
	Sweet potato	*Ipomoea batatas*	Widespread in the highlands
	Cobbler's pegs	*Bidens pilosa*	Widespread in the highlands
	Cabbage	*Brassica oleracea*	Widespread in the highlands
	Lupins	*Lupinus* sp.	High altitude highlands, Andisols
	Irish Potato	*Solanum tuberosum*	High altitude highlands, Andisols
	Soybean	*Glycine max*	High altitude highlands, Andisols
	Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands, soils on limestone
K	Cocoa	*Theobroma cacao*	Wet lowlands, Fluvents
	Coconuts	*Cocos nucifera*	Wet lowlands, Fluvents
	Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands, Andisol, Fluvents
	Maize	*Zea mays*	Wet lowlands, Fluvents
	Aibika	*Abelmoscus manihot*	Wet lowlands, Fluvents
	Soybean	*Glycine max*	Highlands
	Pueraria	*Pueraria lobata*	Wet lowlands Fluvents
	Pumpkin	*Cucurbita moschata*	Wet lowlands, Fluvents
	Taun	*Pometia pinnata*	Wet lowlands, Fluvents
Mg	Arabica coffee	*Coffea arabica*	Highlands, Andisol
	Robusta coffee	*Coffea canephora*	Wet lowlands, Andisol
	Avocado	*Persea americana*	Intermediate altitude, highlands, Andisol
	Loquat	*Eriobotrya japonica*	Intermediate altitude
	Betel nut	*Areca catechu*	Intermediate altitude
	Sweet potato	*Ipomoea batatas*	Wet lowlands, Andisol
	Taro	*Colocasia esculenta*	Intermediate altitude
	Chinese taro	*Xanthosoma sagittifolium*	Intermediate altitude
	Cassava	*Manihot esculenta*	Wet lowlands, Andisol
	Yam bean	*Pachyrhizus erosus*	Wet lowlands, Andisol
	Aibika	*Abelmoschus manihot*	Intermediate altitude
	Pepper	*Piper nigrum*	Wet lowlands, Andisol
	Winged beans	*Psophocarpus tetragonolobus*	Intermediate altitude
	Legumes		Highlands, Andisol
	Lantana	*Lantana camara*	Highlands, Andisol
S	Orange	*Citrus sinensis*	Highlands, Andisol, Histosol

Table 5. Field observations on micronutrient deficiencies in Papua New Guinea.

Nutrient	Crop	Botanical name	Location and soil type
B	Casuarina	*Casuarina oligodon*	Widespread throughout the highlands
	Pine trees	*Pinus* sp.	Widespread throughout the highlands
	Sweet potato	*Ipomoea batatas*	Highlands, Andisols
	Cape gooseberry	*Physalis peruviana*	Highlands, Andisols
	Tomato	*Lycopersicon esculentum*	Highlands, Andisols
	Brassicas	*Brassica oleracea*	Widespread throughout the highlands
Zn	Arabica coffee	*Coffea arabica*	Widespread throughout the highlands
	Orange, lemon, mandarin, pomelo, limes, grapefruit	*Citrus* spp.	Widespread throughout the country
Mn	Pomelo	*Citrus maxima*	Wet lowlands, Andisols
Fe	Cocoa	*Theobroma cacao*	Wet Lowlands, soils derived from limestone
	Snake bean	*Vigna uniguiculata*	Wet lowlands, soils derived from limestone
	Chinese taro	*Xanthosoma sagittifolium*	Wet Lowlands, soils derived from limestone

Discussion

In this paper we have reviewed nutrient deficiencies of agricultural crops in Papua New Guinea using literature, field observations and GIS soil fertility databases. In the discussion we will focus on the integration of this information and how it can be used.

Nitrogen deficiencies have been commonly observed in the field and in literature data, and most crops respond favourably to N fertilizer. The GIS map showed that high soil N contents were found in the highlands and on volcanic soils on Bougainville island. Despite these high N contents, fertilizer responses were also common in these areas, and the GIS map does not fully depict the likely occurrence of N deficiencies. The P and anion fixation map showed that about one-third of the soils had low available P, which is consistent with information from fertilizer trials and field observations. There is, however, a difference between food crops and export tree crops in their susceptibility to P deficiency. In general, tree crops are better P scavengers than annual crops, and both deficiencies and P fertilizer responses are less likely to occur in tree crops. However, the most important food crop in PNG is sweet potato, which is an efficient P scavenger. It is unlikely that sweet potato would have dominated highland agriculture in the way that it does without this ability, given the widespread P problems in highland ash soils.

Potassium deficiency has been reported for coffee in the highlands and for coconuts in the coastal areas, which roughly correspond to areas delineated by the GIS map with soils low in exchangeable K. Calcium nutrition has been poorly investigated in the soils of Papua New Guinea, possibly as very acid soils are not very widespread. Magnesium deficiency has been reported very locally, which accords with the pattern of soil reaction and moderate to high base status of the soils. Field observations on micronutrient deficiencies in the highlands correspond fairly well with the literature of agronomic trials, but the GIS database contains no soil micronutrient information. In large parts of the highlands, Zn is deficient and Zn

Figure 8. Macro- and micronutrient deficiencies in agricultural crops of Papua New Guinea based on field observations and expert knowledge.

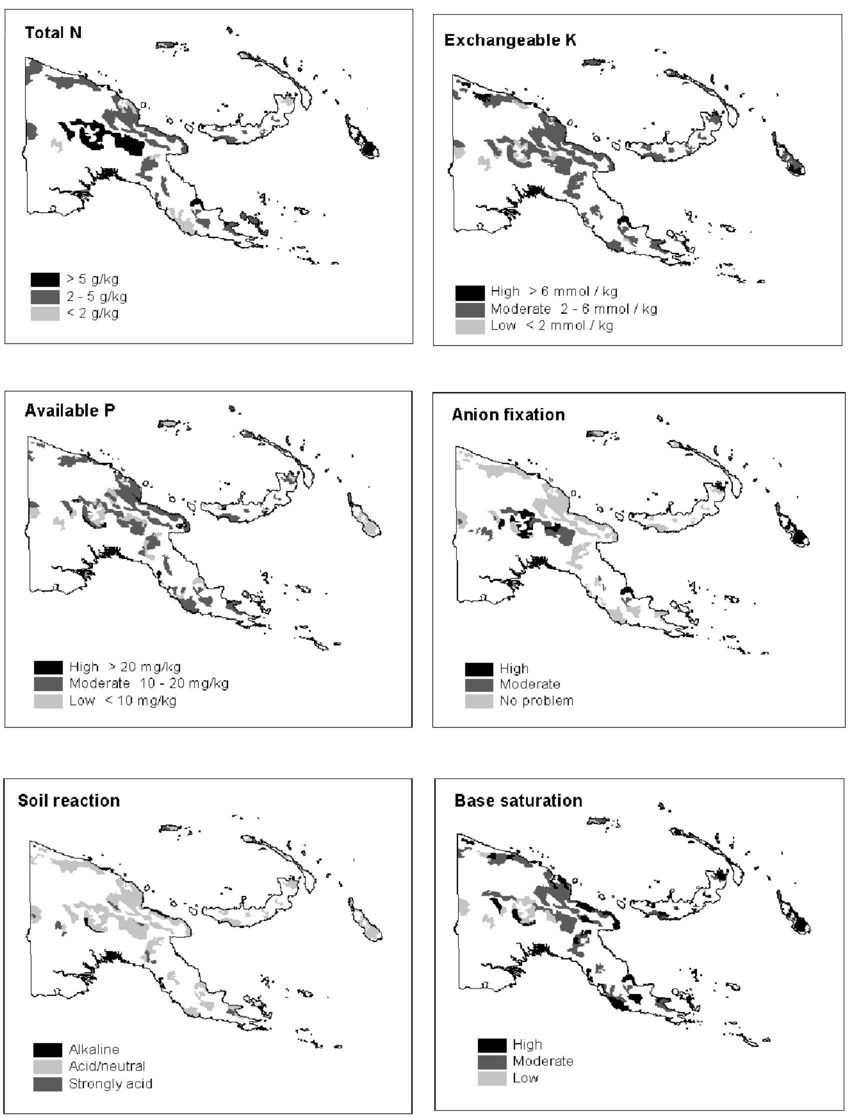

Figure 9. Soil fertility status of agricultural soils in Papua New Guinea based on the Papua New Guinea Resource Information System (PNGRIS). *Source:* J.A. Bellamy and J.R. McAlpine, *Papua New Guinea Inventory of Natural Resources, Population Distribution and Land Use: Handbook*, Australian Agency for International Development, Canberra, 1995.

application has been shown to be effective. Boron fertilizer is routinely applied to pine trees managed by the Forest Authority, and B applications are recommended for commercial vegetable growers in the highlands.

This review has shown the effectiveness of delineating major areas of nutrient deficiencies, but there are some limitations that deserve to be mentioned. In the agronomic literature, results from various plant and soil analytical studies have been shown not always to be consistent, which hinders extrapolation of the results. This emphasizes the need for detailed and accurate soil and site descriptions. Although the information in the GIS soil fertility databases presents an overview of areas where nutrient contents in the soils and deficiencies may be expected, the information is too scarce to allow spatial correlation with the agronomic literature. Much of the literature on micronutrients is based on foliar analysis, and there is hardly any information on micronutrient levels in the soils. Such studies might be of interest, particularly B in relation to volcanic ash soils, and Zn and Mn on soils with alkaline reactions.

Currently, much of the agronomic work in Papua New Guinea focuses on crop cultivars and entomology. These are important research areas to sustain and increase agricultural production, but very little research is conducted on nutrient management strategies and nutrient deficiencies This applies to both export tree crops and food crops. Table 3, which gives an overview of the nutrient deficiencies reported in the literature, could be the base for such research. This review has indicated some of the locations where particular problems, which so far have received little attention, require further investigation. These include K deficiencies in the inland Sepik area; Mg problems in the Wau-Bulolo area and on the north coast of New Britain; and boron deficiencies in many crops in the highlands. Further intensification of land use will affect soil fertility, and nutrient deficiencies are therefore likely to increase, particularly in food crops where inorganic fertilizers are not being used. There is a need to monitor the development of nutrient deficiencies, as well as to ensure

Table 6. Extent of soil fertility classes as percentages of agricultural land area in Papua New Guinea.

Class	Total N	Available P	Exchangeable K	Base saturation
Low	15	31	13	18
Moderate	60	57	76	40
High	25	12	12	42

Source: PNGRIS.

proper identification through pot trials and soil and foliar analysis. Comprehensive fertilizer trials could be designed to diagnose minor elements, and nutrient budgets could be used to study inputs and outputs of cropping systems in different agroecological zones.

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