Nutrient Deficiencies in Export Tree and Food Crops: Literature Review and Field Observations[1]

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Abstract

This paper reviews nutrient deficiencies in agricultural crops of PNG using the literature of agronomic trials and field observations made throughout the country. Nutrient deficiencies have been investigated systematically since the mid-1950s, but research has mainly focused on export tree crops and relatively little information is available on food crops. Literature analysis and field observations showed consistent trends, with deficiencies of boron and phosphorus in large parts of the PNG highlands. The review has been useful in delineating areas where nutrient deficiencies occur and these findings could be used for planning nutrient management research and extension activities in food crops.

THE availability of soil nutrients to plants depends on many factors. Low levels of available nutrients in the soil may be due to low amounts in the parent material from which the soil is derived, fixation and immobilisation of nutrients, or excess losses under high rainfall conditions when nutrients are leached from the soil. Nutrient imbalances in the soil may also cause limited availability of nutrients. Low nutrient levels may also result from cultivation because of removal of nutrients by agricultural crops without subsequent replenishment, leading to accelerated losses compared to natural ecosystems.

In many smallholder agricultural systems in tropical regions, nutrient deficiencies limit food crop production. This effect is enhanced by increasing land pressure. Detailed information on the spatial distribution and seriousness of nutrient deficiencies is needed in order to develop research strategies aimed at alleviating the problems 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 PNG, the information is scattered or unavailable at the national or regional level.

In PNG, subsistence agriculture is practised by more than three-quarters of the population in a wide range of environmental conditions. Annual rainfall varies from 1000 millimetres around Port Moresby to over 8000 millimetres in the mountains of the far west. 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 (Bleeker 1983). Due to the great variety of parent materials, climatic conditions and differences in topography, there are many different

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[1] This paper is an abridged and adapted version of Hartemink and Bourke (2000).

soil types. Agriculture takes place from sea level to 2850 metres above sea level, mostly on young soils like Andisols and Eutropets.

The population of PNG has doubled between 1966 and 1990 (Allen et al. 1995). However, analysis of land-use intensities using aerial photographs from the early 1970s with LandSat^{TM} imagery from 1996 has revealed that the area under cultivation has increased by only 10% (see Land Use and Rural Population Change in PNG: 1975–1996, by J.R. McAlpine et al., in these proceedings). It implies increased land-use intensities and this has mainly occurred in areas already subject to high land-use intensities. The land is cropped more often putting a greater demand on the soil resources, particularly as little or no inorganic fertilisers are being used on food crops. Nutrient deficiencies are likely to increase with higher land-use intensities.

In PNG, research on nutrient deficiencies of agricultural crops started in the 1950s and successive research focused on other export tree crops. Significant research on nutrient deficiencies in food crops started only in the 1970s. In this paper, we have assembled the available information on nutrient deficiencies in agricultural crops of PNG. The information is drawn from about 45 years of literature on nutrient deficiencies and soil and plant analysis in most parts of the country, and field observations on visual symptoms of nutrient deficiency in agricultural and horticultural crops.

Data Collection

Published literature

Soil research in PNG started in the 1950s (Bleeker 1983) and was conducted by two largely independent groups of scientists. At the experiment stations for export tree crops (cash crops), agronomists and soil fertility experts investigated optimum inorganic fertiliser rates and nutrient deficiencies. Here, too, field experiments, greenhouse trials and onfarm experiments were conducted. 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 PNG.

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, that is, 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 in the 1910s, and in the 1950s it was noted that production had drastically decreased with many palms showing stunted growth and leaf chlorosis (Charles 1959). A soil survey was undertaken (van Wijk 1959) and investigations were made into leaf and soil nutrient concentrations. It was concluded that, amongst other agronomic problems, potassium (K) was the main factor limiting coconut production (Baseden and Southern 1959). Subsequent research focused on the use of inorganic fertilisers (Charles and Douglas 1965). 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 PNG (Fahmy 1977). In the 1960s and 1970s, 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 deficiencies of agricultural crops in PNG, although much more is known about export tree crops than about food crops. Most of the research has been published in annual reports of experiment stations and concerns the effects of inorganic fertiliser on crop yield. 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 large sample and seasonal variations. There is also some literature on the deficiency symptoms in plywood forestry nurseries which started in 1953 (Baseden 1960).

Field observations

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

Mainly recorded was the occurrence of leaf deficiency symptoms, but information on stunted growth, defoliation, and dieback was also noted. Nutrient deficiencies were tentatively identified in the field, and slides were taken. In 1996, all slides were shown to experts at the Faculty of Agriculture, The University of Queensland, who confirmed the tentative field identifications. They were also checked with texts on nutrient deficiency (Bennett 1993; O'Sullivan et al. 1996, 1997). If there was doubt as to whether the leaf symptoms were caused by nutrient deficiencies or by pathological, entomological, environmental or genetic causes, the observation was excluded. Several hundred confirmed observations have been made on the deficiency of nine nutrients in 42 crops.

Agricultural Crops of PNG

About a quarter of the total land area in PNG is used for agriculture with varying intensities (Saunders 1993). 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 southwest of Lae extending almost to the south coast; coastal locations in eastern Papua; the islands of Milne Bay; the north coast and northeast of New Britain; the northeast coast of New Ireland, and parts of Bougainville Island.

Export tree crops

Coffee is the main export tree crop and the major source of income for one-third of the population (Harding and Hombunaka 1998). 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 metres above sea level, mostly in Morobe and East Sepik provinces. Research on Arabica coffee commenced in the early 1950s.

Coconuts are grown extensively along the coast and some lowland locations inland. It is estimated that the total area producing coconuts is about 250,000 hectares (Table 1). Copra production is concentrated in the islands region, with most copra coming from East New Britain, Bougainville (North Solomons), New

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

Crop		Extent (ha)[a]	Growing area/province	Soil type
Arabica coffee	*Coffea arabica*	50,000	Highlands, especially Western Highlands, Eastern Highlands and Simbu	Dominantly Andisols
Robusta coffee	*Coffea canephora*	5000	Limited locations, wet lowlands, especially in East Sepik and Morobe	Various
Coconut	*Cocos nucifera*	250,000	Numerous coastal locations, especially in East New Britain, Bougainville and New Ireland, but in all lowland provinces	Various
Cocoa	*Theobroma cacao*	30,000	Certain lowland provinces, especially parts of East New Britain, Bougainville and Madang	Dominantly Andisols
Oil palm	*Elaeis guineensis*	80,000	Parts of West New Britain, New Ireland, Oro and Milne Bay	Dominantly Andisols
Tea	*Camellia sinensis*	3000	Wahgi Valley, Western Highlands only	Histosols and Andisols
Rubber	*Hevea brasiliensis*	5000	Several locations in East Sepik, Central and Western	Various

[a] Extents of export tree crops are estimates based on published literature and figures provided by research stations.
Source: modified from Hartemink and Bourke (2000)

Ireland and West New Britain provinces. Few plantations still produce copra, with most now made by villagers. Systematic research on coconuts commenced in the early 1950s.

Cocoa production is concentrated in the Gazelle Peninsula of East New Britain Province and in Bougainville, East Sepik, Madang, New Ireland and West New Britain provinces. 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 northeast coast of New Ireland, the area near Popondetta in Oro (Northern) Province and an area inland of Milne Bay. Production has expanded rapidly over the past 30 years and continues to expand. Research on 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 1970s.

Food crops

A large number of food crops are grown in PNG for both 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 about 60% of the rural population (Table 2). It dominates agricultural production in the highlands and very high altitude highlands, but it is also significant in many locations in the seasonally dry and wet lowlands. Sago is the staple food for 12% of the villagers, mainly in the East Sepik, Sandaun (West Sepik), Western and Gulf provinces. Banana is the main staple food for 7% of the population, but it is widely grown up to 2200 metres altitude. It is important in the seasonally dry lowlands and in areas with very high rainfall (over 4000 millimetres per year). Other staple foods include yam, taro, Chinese taro, cassava, Irish potato, and maize. There was some research on food crops in the 1930s and again after the Pacific War, but continuous research did not commence until 1970.

Nutrient Deficiencies—Literature Review

Table 3 summarises the information on nutrient deficiencies in export tree crops and food crops, which are discussed in more detail below. 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.

Table 2. Major food crops, their main growing areas and importance in PNG.

Crop		Main growing area	Importance[a]
Sweet potato	*Ipomoea batatas*	Throughout the country in all rainfall and altitude zones, up to 2700 metres above sea level	61
Sago	*Metroxylon sagu*	Wet lowlands in locations subject to inundation	12
Banana	*Musa* cultivars	Lowlands under wide range of rainfall conditions (1000–6000 mm per year)	7
Yam	*Dioscoraea* spp.	Seasonal dry lowlands	5
Taro	*Colocasia esculenta*	Wet lowlands	4
Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands	2
Cassava	*Manihot esculenta*	A number of lowland locations under wide range of rainfall conditions (1000–6000 mm per year)	1
No dominant staple			8

[a]Percentage of the rural population for whom this is the dominant staple, i.e. the crop occupying more than one-third of the garden area.
Source: based on Mapping Agricultural Systems of PNG data (Allen et al. 1995)

Table 3. Nutrient deficiencies reported in export tree crops and food crops in PNG.

		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	3	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	–	–	–	–

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

Source: based on reconciliation of published literature 1955–98 (Hartemink and Bourke 2000)

Macronutrients

In PNG, it was found that the nitrogen content of soils is generally higher at higher altitudes, and is also higher in Andisols where organic matter forms complexes with allophane and aluminium oxides which retard organic matter decomposition (Bleeker 1983). Poor drainage hindering decomposition also results in higher organic matter, and hence higher nitrogen, content of the soil (Bleeker 1983).

Nitrogen

Nitrogen (N) deficiencies have been reported for Arabica coffee grown under conditions of low shade intensity or where inorganic fertilisers high in sulfur have been applied. Deficiency in N has been widely reported for cocoa except when it is shaded. Under coconuts, N deficiency has been reported from an Andisol that had been frequently burned inducing N losses. Nitrogen responses have been reported for various crops, including sorghum on Vertisols, oil palm on Andisols, taro on Andisols in the lowlands, and broccoli on Andisols in the highlands. Nitrogen was the key element for sweet potato on Andisols in the wet lowlands and highlands but Hartemink et al. (2000) reported a negative yield response of sweet potato to N fertiliser on alluvial soils with low native N levels.

Phosphorus

Phosphorus (P) 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. Highly weathered soils and acid soils are not common in PNG. Soils derived from predominantly Quaternary volcanic ash (Andisols) are common, particularly in the highlands where they cover large areas. Andisols have a large pH charge dependency and adsorb P strongly at low soil pH. In these soils P availability is strongly dependent on pH and clay mineralogy. The decomposition of organic matter supplies the bulk of the P crop requirement (Kanua 1995). Phosphorus deficiency was only recognised as a problem in food crops in the 1970s; until then, research was mainly focused on tree crops, which have a low inherent P requirement.

Available P is low where coconuts are grown on soils derived from limestone but, because of the low P requirements of coconuts, it is not likely to be a limiting nutrient. Also, mature Arabica coffee is able to extract sufficient P even from soils low in P and so yield responses to P fertilisers are rare (Harding and Hombunaka 1998). For sweet potato, it was shown that yields slightly increased by applying P fertilisers on an Andisol in the highlands (D'Souza and Bourke 1986; Floyd et al. 1988). On Andisols in the lowlands, no response to P fertiliser was recorded for taro, although a positive response was obtained for maize. Bourke (1977) reported infrequent small increases in sweet potato yield to P on an Andisol in the wet lowlands. Favourable responses to P fertiliser were also obtained on alluvial soils (Vertisols, Fluvents) in the lowlands, whereas sheep manure and inorganic P fertiliser dramatically increased sweet potato yields on Andisols in the highlands.

Potassium

The distribution of soil potassium (K) generally follows a pattern that is related to rock type and the degree of weathering of the soils (Bleeker 1983). 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 calcium (Ca) and magnesium (Mg) levels in the soil may result in K deficiency and this has been reported to occur in very acid soils, and in soils along the coast derived from limestone.

Potassium deficiency has been reported in coconuts grown on soils developed over coral limestone. This is due to an imbalance of cations in the soil and the fact that considerable amounts of K are removed with the husks and nuts of the coconuts. On these soils, coconuts showed a dramatic response to K applications. This response was also found in soils with high Mg/K ratios. Many coffee plantations have soils deficient in K but applications of K are generally favourable, although negative interaction with Ca and Mg can occur (Harding and Hombunaka 1998). Root crops are large K consumers, but K deficiencies in PNG soils have been only partly documented. On Andisols in the wet lowlands, large yield responses have been reported for applied and residual K, whereas on Andisols in the highlands, a marked increase was found in sweet potato yield following K fertiliser applications. Taro showed no response to K application on Andisols in the lowlands.

Magnesium

There have been few reports on magnesium (Mg) deficiencies, which mostly result from a cation imbalance in the soil. Deficiency of Mg is common in Arabica coffee but no yield responses have been obtained in fertiliser trials, as most soils are low in K, and therefore favour Mg uptake. Recent investigations have confirmed the widespread deficiency of Mg in oil palm on Andisols (I. Orrell, Oil Palm Research Association, pers. comm. 1999), a problem that is aggravated by high applications of N fertiliser.

Sulfur

Sulfur (S) deficiency has been reported for a wide range of soils and appears to be fairly common, although the occurrence is more likely to be ecological than pedological (Southern 1967). Contributing factors are high rainfall and leaching, loss of S by frequent burning of vegetation, the lack of inorganic fertiliser use, and competition with other plants, notably *Imperata cylindrica*. It was found that S deficiencies are common in coconuts on soils derived from limestone. Sulfur deficiencies in coconut were also observed on Andisols and Fluvents where burning of vegetation was common, and on soils derived from limestone when K deficiency was corrected (Sumbak 1971). Sulfur deficiencies occur in the Arabica coffee growing areas, particularly when high rates of N fertiliser are applied. There have been no reports of S deficiency in rubber, sweet potato or other staple root crops but S deficiency has been reported for rice (*Oryza sativa*) grown on alluvial soils, and for tea, sorghum and pasture crops (Vance et al. 1983).

Micronutrients

Until 1965, research focused on macronutrients, partly because problems associated with macronutrients were more obvious and because facilities were not available for research into micronutrients (Southern and Dick 1969). Investigations into micronutrients began in 1966 after routine methods, mainly using atomic absorption, became available. This review on micronutrient deficiency is largely based on the work of Southern and Dick (1969) who surveyed export tree crops across the whole of PNG in the 1960s, and on the work by Bourke (1983) who reviewed the literature up to the beginning of the 1980s. The information on micronutrients is mainly based on foliar analysis as there is virtually no information about minor elements in the soils of PNG (Bleeker 1983).

Boron

Boron (B) deficiency has been reported for Arabica coffee in the highlands, 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 rubber in some acid coastal soils. No serious B deficiency has been found in coconuts and cocoa. 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. Although B deficiency is widespread in certain tree crops, relatively little information is available on the food crops. Bang (1995) showed that the yield of Irish potato increased after applications of both B and P on Andisols in the highlands, whereas a yield reduction was found for sweet potato after applying B fertilisers (D'Souza and Bourke 1986). Application of B fertiliser to peanuts, cowpea, and winged beans had no effect, but in the high altitude highlands, favourable responses to B applications have been found for pyrethrum.

Zinc

Zinc (Zn) deficiency occurs in Arabica coffee throughout the highlands and is usually more severe in unshaded coffee, although seasonal variations are considerable. In Robusta coffee, Zn deficiency commonly occurs in conjunction with manganese (Mn) deficiency in alkaline soils. Zinc deficiency is a problem in tea plants grown 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, with only some data available for rice and peanuts grown on alluvial soils (Fluvents).

Manganese

Investigations into Mn nutrition have been concentrated on alkaline alluvial soils, neutral to alkaline soils of the coast and atolls, and soils developed from volcanic ash soils. In general, Mn levels in Arabica coffee leaves are high, and no symptoms of Mn toxicity have been observed. There is evidence that Mn contents have increased following the use of acidifying N fertilisers. In cocoa, low Mn levels were found in plants on neutral to slightly alkaline soils but there are no references that Mn applications increase growth or cocoa production. In rubber, Mn deficiency may occur on soils high in exchangeable Mg and deficiency of Mn was observed in yams grown on soils derived from coral limestone. 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 application of Zn or Mn alone had no effect. Sweet potato showed no response to application of Mn in a field trial on an Andisol in the wet lowlands.

Iron

Slight symptoms of iron (Fe) deficiency in Arabica coffee are common throughout the highlands, particularly in pruned trees. This deficiency is not a serious problem and no corrective measures are necessary. 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.

Copper

There are no records of copper (Cu) deficiency in Arabica coffee and fertiliser effects have not been observed in PNG, although 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. In rubber, Cu deficiency is not likely to occur, except in nurseries.

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, are good indicator plants of P deficiency. Symptoms are more severe at altitudes over 2000 metres above sea level throughout the highlands and dramatic responses to P have been observed for potato, lupins and soybean at the High Altitude Experiment Station at Tambul at 2300 metres above sea level. Deficiency symptoms of K are uncommon in agricultural crops in PNG, 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 for 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 summarises the field observations on macronutrient deficiencies.

Symptoms of B deficiency are widespread on casuarina, pine trees and, 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 zone and highlands in PNG. 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 the Lowlands Agricultural Experiment Station 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.

Discussion

Nitrogen deficiencies have been commonly observed in the field in PNG and in literature data, and most crops respond favourably to N fertiliser. About one-third of the soils in PNG have low available P based on PNG Resource Information System data, which is consistent with information from fertiliser 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 deficiencies, as well as P fertiliser responses, are less likely to occur in tree crops. However, the most important food crop is sweet potato, which is an efficient P scavenger. It is unlikely that sweet potato would have dominated highland agriculture the way that it does unless this were so, 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 corresponds to areas shown by the geographical information system (GIS) map as having soils low in exchangeable K (Hartemink and Bourke 2000). Calcium nutrition has been poorly investigated in the soils of PNG, possibly because very acid soils are not widespread. Magnesium deficiency has been reported very locally, which is in accordance with the pattern of soil reaction and moderate to high base status of the soils. Field observations on micronutrient deficiencies in the highlands corresponded fairly well with the literature of agronomic trials but the GIS databases contain no soil micronutrient information. In large parts of the highlands, soils are deficient in Zn and its application has been effective. Boron fertiliser 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 to be effective in delineating major areas of nutrient deficiencies, but there are some limitations that deserve mentioning. In the agronomic literature, results from various plant and soil analytical studies are not always consistent and this can hinder extrapolation of the results. This emphasises 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 are low 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 alkaline soils.

Currently, much of the agronomic work in PNG 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, giving an overview of the nutrient deficiencies reported in the literature, could be the basis 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 Angoram area of East Sepik Province, Mg problems in the Wau–Bulolo area and on the north coast of New Britain and boron deficiencies on 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 fertilisers are not being used. There is a need to monitor the development of nutrient deficiencies and for proper identification through pot-trials and soil and foliar analysis. Comprehensive fertiliser trials could be designed to diagnose minor element deficiencies, and nutrient budgets could be used to study inputs and outputs of cropping systems in different agroecological zones.

Table 4. Field observations on macronutrient deficiencies in PNG.

Macro-nutrient	Crop	Botanical name	Location/province	Soil type[a]
Nitrogen	Pineapple	*Ananas comosus*	Gazelle Peninsula, East New Britain	Andisols
	Arabica coffee	*Coffea arabica*	Various highland locations, including Aiyura	Andisols
	Coconuts	*Cocos nucifera*	Gazelle Peninsula, East New Britain	Andisols
	Taro	*Colocasia esculenta*	Various locations in both highlands and lowlands	
	Sweet potato	*Ipomoea batatas*	Various locations in both highlands and lowlands	
	Avocado	*Persea americana*	Aiyura, Eastern Highlands	Andisols
Phosphorus	Cobbler's pegs	*Bidens pilosa*	Widespread in the highlands	
	Cabbage	*Brassica oleracea*	Widespread in the highlands	
	Soybean	*Glycina max*	Tambul, Western Highlands	Andisols
	Sweet potato	*Ipomoea batatas*	Widespread in the highlands	
	Lupins	*Lupinus* sp.	Tambul, Western Highlands	Andisols
	Irish potato	*Solanum tuberosum*	Tambul, Western Highlands	Andisols
	Maize	*Zea mays*	Widespread in the highlands	
Potassium	Aibika	*Abelmoschus manihot*	Angoram, East Sepik	Fluvents
	Coconuts	*Cocos nucifera*	Angoram, East Sepik	Fluvents
	Pumpkin	*Cucurbita moschata*	Angoram, East Sepik	Fluvents
	Soybean	*Glycine max*	Oksapmin, Sandaun (West Sepik)	
	Taun	*Pometia pinnata*	Angoram, East Sepik,	Fluvents
	Pueraria	*Pueraria lobata*	Angoram, East Sepik	Fluvents
	Cocoa	*Theobroma cacao*	Angoram, East Sepik	Fluvents
	Chinese taro	*Xanthosoma sagittifolium*	Cape Rodney, Central Cape Hoskins, West New Britain Angoram, East Sepik	Fluvents Andisol Fluvents
	Maize	*Zea mays*	Angoram, East Sepik	Fluvents
Magnesium	Aibika	*Abelmoschus manihot*	Bulolo area, Morobe	
	Betel nut	*Areca catechu*	Wau area, Morobe	
	Arabica coffee	*Coffea arabica*	Marawaka area, Eastern Highlands	
	Robusta coffee	*Coffea canephora*	Gazelle Peninsula, East New Britain	Andisols
	Taro	*Colocasia esculenta*	Wau area, Morobe	
	Loquat	*Eriobotrya japonica*	Bulolo area, Morobe	
	Sweet potato	*Ipomoea batatas*	North coast New Britain	Andisols

Continued on next page

Table 4 (cont'd). Field observations on macronutrient deficiencies in PNG.

Macro-nutrient	Crop	Botanical name	Location/province	Soil type[a]
Magnesium (cont'd)	Lantana	*Lantana camara*	Mendi Valley, Southern Highlands	Andisols
	Cassava	*Manihot esculenta*	North coast of New Britain	Andisols
	Yam bean	*Pachyrhizus erosus*	Gazelle Peninsula, East New Britain	Andisols
	Avocado	*Persea americana*	Nembi Plateau, Southern Highlands Bulolo area, Morobe	Andisols
	Pepper	*Piper nigrum*	Gazelle Peninsula, East New Britain	Andisols
	Winged beans	*Psophocarpus tetragonolobus*	Wau area, Morobe	
	Chinese taro	*Xanthosoma sagittifolium*	Wau area, Morobe	
	Legumes		Marawaka area, Eastern Highlands	
Sulfur	Orange	*Citrus sinensis*	Aiyura, Eastern Highlands Wahgi Valley, Western Highlands	Andisols Histosols

[a]Spaces in this column indicate either a range of soil types or unknown.
Source: modified from Hartemink and Bourke (2000)

Table 5. Field observations on micronutrient deficiencies in PNG.

Micro-nutrient	Crop	Botanical name	Location/province	Soil type[a]
Boron	Brassicas	*Brassica oleracea*	Widespread throughout the highlands	
	Casuarina	*Casuarina oligodon*	Widespread throughout the highlands	
	Sweet potato	*Ipomoea batatas*	Aiyura, Eastern Highlands Nembi Plateau, Southern Highlands	Andisols
	Tomato	*Lycopersicon esculentum*	Aiyura, Eastern Highlands	Andisols
	Cape gooseberry	*Physalis peruviana*	Aiyura, Eastern Highlands	Andisols
	Pine trees	*Pinus* sp.	Widespread throughout the highlands	
Zinc	Orange, lemon, mandarin, pomelo, lime, grapefruit	*Citrus* spp.	Widespread in all altitude zones in PNG	
	Arabica coffee	*Coffea arabica*	Widespread throughout the highlands	

Continued on next page

Table 5. Field observations on micronutrient deficiencies in PNG.

Micro-nutrient	Crop	Botanical name	Location/province	Soil type[a]
Manganese	Pomelo	*Citrus maxima*	Keravat, East New Britain	Andisols
Iron	Cocoa	*Theobroma cacao*	East coast, New Ireland	Soils derived from limestone
	Snake bean	*Vigna uniguiculata*	East coast, New Ireland	Soils derived from limestone
	Chinese taro	*Xanthosoma sagittifolium*	Vanimo, Sandaun (West Sepik)	Soils derived from limestone

[a]Spaces in this column indicate either a range of soil types or unknown.
Source: modified from Hartemink and Bourke (2000)

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