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Altitudinal limits of 230 economic crop species in Papua New Guinea

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Introduction

Temperature extremes set limits on the growth of all crop species. In mountainous regions, such as Papua New Guinea (PNG), there is a regular and linear decrease in temperature with increasing altitude. This regularity is known as the lapse rate (McAlpine et al. 1983:92).[1] This relationship is sufficiently precise to enable altitude data to be substituted for temperature data. Furthermore, in regions located at low latitudes, the temperature differences from north to south at a given altitude are small, and similarly, seasonal variation in temperature is very small.[2] This means that estimates of average yearly temperature can be made from altitude with a high degree of precision.

In this paper, I report on the altitudinal limits of 230 crop species based on numerous field observations. It is relatively easy to observe altitudinal limits in PNG because of the rugged topography and the large altitudinal contrasts over short distances. These data were mostly recorded over a three-year period (1980-1982) and the observations were made during extensive driving trips and walking traverses. The main economic product of most of the species (182) is food. The main products of the other species are export commodities (13 species), shade and timber (11), stimulants (6), decoration (6), body covering (6), cover crops, fish poison and weeds (6).

1 This is treated in more detail in Appendix 1 where lapse rates for mean maximum, mean minimum and mean annual temperatures for non-coastal locations in PNG are given.

2 Most of PNG lies in the latitude range 1-9 °S where seasonal temperature differences are very small (typically 1-2°C). A small proportion of the land mass is at 9-12 °S and the wettest part of the year coincides with the Southern Hemisphere winter. There seasonal temperature differences are a little greater (typically 2-3°C) but, even there, the most important environmental influence on temperature is altitude.

The altitudinal limits of crops are of interest for a number of reasons:

1. Agricultural planning. Such data provide basic information for planning and research for agricultural researchers, planners and extension officers.
2. Agricultural technology transfer. Those involved in transferring agricultural information require basic information about where certain crops will grow. For example, an extension officer promoting peanuts, winged bean or pigeon pea as a rotational crop with sweet potato for a particular location must be certain that these species will grow at that location, as sweet potato is grown almost 1000 m higher than the upper altitudinal limit for these three species.
3. Prehistoric agriculture inferences. Information on altitudinal limits is needed to make deductions about prehistoric agriculture, particularly the limits to cultivation before the adoption of sweet potato in the PNG highlands about 300 years ago (Bayliss-Smith 1988; Brookfield 1991; Haberle 1993). These data can also be used to make inferences about species which may have been used for food during the Pleistocene.
4. Assessing climate change. Because of the close relationship between temperature and altitude in PNG, data on crop limits are a surrogate for temperature recordings. Historical data on where crops grow provide a baseline to gauge the impact of temperature changes associated with global climate change.

Altitude, as a surrogate for temperature, also influences the rate of crop development, as well as setting limits to growth. Only a limited amount of information exists on the influence of altitude on crop development and yield in PNG. The available information for five crops is summarised in Appendix 2.

Previous observations

Many villagers in PNG have extensive knowledge about crop altitudinal limits in their territory. This comes from their planting crops in a number of locations in their territory and noting where crops fail to bear, or bear very poorly because of altitude. When a new species is introduced, villagers typically plant it in many environments, including some that are unsuitable because it is too cold, or occasionally, because it is too hot. This experience teaches them the altitudinal range of a species in their territory. This can be illustrated by the introduction of cardamom as a cash crop in the intermediate altitude zone (600-1200 m) and the lower highland valleys (1200-1400 m) in the mid to late 1970s. Some people living in the main highland valleys attempted to grow cardamom over a range of altitudes, many of which were much higher than the upper altitudinal limit recommended by the Department of Agriculture. In the process, villagers discovered that cardamom would bear successfully as high as 1700 m, and occasionally as high as 1890 m, but not above these altitudes.

Knowledge on crop limits is more detailed where altitudinal contrast is greatest; for example, in much of Enga and Simbu provinces in the highlands. This knowledge has not been recorded systematically, although I used it when enquiring about the productivity of species at particular locations. In a number of locations in the highlands, villagers distinguish between 'warmer' and 'colder' zones and this altitudinal break generally coincides with the upper or lower altitudinal limits of a number of important species. This is discussed later.

Researchers working in villages, particularly anthropologists and geographers, commonly report the altitudinal limits of some species for specific communities or localities. For example, some observations on crop altitudinal limits are given for the upper Lai Valley, Enga Province (Meggitt 1958:314-320); Baiyer-Lai valleys, Western Highlands Province (Bulmer 1960:63); Asaro Valley, Eastern Highlands Province (Howlett 1962:81-82, 102); and the Sinasina area of Simbu Province (Hide et al. 1979). In particular, a lower altitudinal limit of 1800-1850 m for *karuka* nut pandanus (*Pandanus jiulianettii* complex) is reported by numerous field workers in the highlands. Papua New Guinea-wide limits for several food crops have been presented by Treide (1967:118-119) and reproduced in a modified form by Brookfield with Hart (1971:171). Bayliss-Smith (1985), French (1986) and Haberle (1993:301) have also given altitudinal limits for various food crops for all of PNG, based in part on my unpublished recordings.

A major data source for crop altitudinal limits in PNG is the collection records and publications of the Division of Botany, Department of Forests in Lae (now Forest Research Institute of the PNG Forest Authority). The collections have been made by Division of Botany staff and by others seeking botanical identification. For example, the altitudinal distribution of various species of grasses, weeds, legumes and nut-bearing plants are given by Henty (1969), Henty and Pritchard (1975), Verdcourt (1979) and Henty (1982) respectively. Some botanists provide data on other species. Hynes (1974), for example, gives the altitudinal range of 13 species of *Nothofagus* in New Guinea, while Smith (1977a, 1977b) presents data on the altitudinal distribution of both food and non-food species in the Mount Wilhelm area. Gardner (2003) gives limits for certain *Piper* species.

However, the published information should be used cautiously, for the following reasons:

1. Before the 1:100,000 map sheets becoming available in the late 1970s and early 1980s, most quoted figures for locations in PNG underestimated the true altitudes. This is because these were derived from altimeter readings when the instrument was zeroed at sea level, generally using aircraft instruments. Because of air-pressure surface flows into the mountains, these instrument readings give systematic errors. This is discussed more fully in Appendix 3.
2. Botanical specimens identified by Division of Botany staff were collected for purposes other than defining limits. Rarely is there an indication that the specimen was collected at or near the species' altitudinal limit. As well, the collection records do not indicate whether the specimen was found within or outside the usual altitudinal range for that species.

Provided these limitations are recognised, the Division of Botany records are a valuable data source. I have incorporated some of their recordings in data presented here, particularly when the Division of Botany records extend the extreme ranges that I recorded.

I have published some of my observations in other papers. These include observations for Enga Province only (Bourke and Lea 1982); citrus species (Bourke and Tarepe 1982); limits of some introduced vegetables (Bull and Bourke 1983); coffee and associated shade species (Bourke 1984); for Gumine District only (Bourke 1988); 22 selected species (Allen and Bourke 2009, Table 1.13.3); fruits and edible nuts (Bourke 2009a); and starchy food species (Bourke In press). Some of the figures presented here differ slightly from those I have published previously. This reflects additional observations made since earlier papers, or reinterpretation of some data.

Methods

Observations on crop altitudinal limits were made during numerous traverses by foot and vehicle throughout PNG (Figure 1). For any given geographical unit, such as a valley, I recorded the altitude at which each species was growing near the previously observed limit of that species. The altitude was recorded with an accurate pocket altimeter (Thommen 2000) and appropriate adjustments were made so the readings were within plus or minus 20 m of the true altitude (see Appendix 3 for details of necessary corrections). The highest recording for a species in any geographical unit was considered the upper altitudinal limit, provided that the species ceased to be grown below the highest point of the traverse. The same technique was used for lower limits. An example of a traverse by car and foot in the Marigl Valley, Gumine District, Simbu Province, over the range 1450-2450 m illustrates the technique. The highest recordings for triploid banana (2310 m), Arabica coffee (2170 m) and guava (2020 m) were taken as upper altitudinal limits for these species in this valley. However, the lower recordings (1450-1500 m) were not taken as the lower limits because observations elsewhere in PNG indicated these species grow below the lowest point of this traverse.

A distinction was made between the 'usual' and 'extreme' altitudinal limits for any species[3]. Most limits were considered as usual, but limits were classed as extreme under the following circumstances:

1. Isolated plantings that were well above or below the usual limit for that species in that location.
2. Plantings that were clearly experimental and were not bearing a product of generally accepted quality.
3. Plantings made under extraordinary conditions, such as in a hothouse.

For example, recordings for pineapple plants at Margarima (2200 m) and Kandep (2380 m) producing tiny fruit and grown well above other pineapple plants in nearby locations (1800-1900 m) were considered as extreme limits. Similarly, a recording for pineapples grown in a glasshouse at Tambul (2320 m) was taken as an extreme value.

The distinction between usual and extreme limits is to some degree subjective, but it is an important one. It is not uncommon for small plantings of a species to be made well outside the usual altitudinal range of that species. These extreme limits are of some interest, but are less important than the usual limits. A distinction between usual and extreme altitudinal limits has also been made by authors working in other countries, although the terminology differs among authors. In Ethiopia, Alkämper (1973) classed altitudinal zones as main cultivation, sporadic cultivation and extreme cultivation. Brush (1976) distinguished between the 'effective' crop limits and 'absolute' limits in Peru, while in Ecuador Stadel (1986) used the terms 'major belt' and 'minor belt' for altitudinal ranges.

Plants of some species grow above (or below) where they produce their main economic product. This is particularly the case for some fruit- and nut-bearing species such as mango, elderberry and coconut. All limits presented here are for plants that are yielding their main economic product. When it was not obvious whether the economic product was being produced, I asked local villagers about the behaviour of individual plants. Responses indicating

3 An alternative term to 'usual limit' is 'optimal limit'. However the altitude at which people usually cease growing a species is often somewhat lower (or higher) than the optimal altitude. For example, the usual altitudinal range of pawpaw (*Carica papaya*) was recorded from sea level (0 m) to 1700 m (n=30; Standard Deviation 100 m for the upper limit). However the altitude range where the best fruit are produced is from sea level to about 1400 m in PNG. The difference between the optimal limit (which was not recorded systematically) and the usual limit (data presented here) varies between species, but is typically about 200 m (equivalent to 1°C temperature difference).

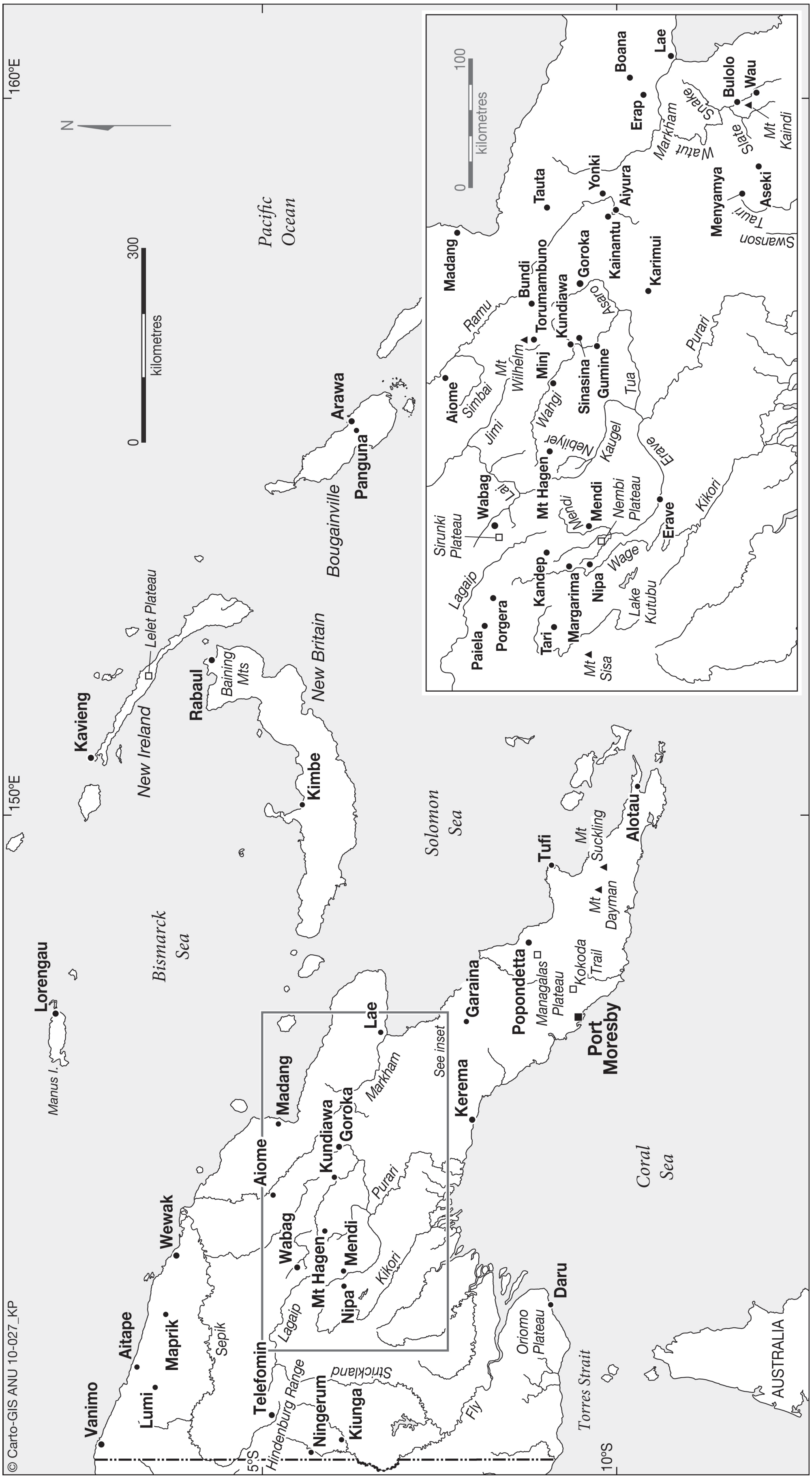

Figure 1. Locations referred to in the text

that a particular plant or group of plants did not bear were taken as indicating that they were outside their usual range. A response indicating that plants bore sparsely or yielded poor quality products was also useful as this suggested that plants were growing near their limit.[4] Similarly, comments by villagers (or my observations) that plants had failed to bear their economic product was a useful indicator that they had been planted above (or below) their altitudinal limit.[5]

Most observations were made over a three-year period (1980-1982). Recordings commenced in mid 1978, but when more accurate topographic maps became available in 1979, I realised that I was systematically underestimating altitude using an altimeter (as others had previously done). I adjusted the 1978 and 1979 observations with more accurate recordings of altitude. Some additional recordings were made between 1983 and 1995, particularly in 1991 when new observations were made at various locations on the Huon Peninsula of Morobe and Madang provinces, including the Nankina Valley, Teptep area, Pindiu area and Kabwum area; and in the Telefomin area of Sandaun Province.

I made most of the observations, but some were made by others (see Acknowledgements). I also examined the collection records for many species held by the Division of Botany in Lae. This was useful in guiding field observations. Where one of the identifications made by Division of Botany staff was from a location with an altitude outside the altitude range that I recorded, this is indicated in the footnotes of the tables.

Observations were made in 18 of the 19 provinces in PNG; the exception was Manus Province, which is a lowland province where people occupy a small altitude range and altitudinal limits are of minor importance. More observations were made in the central highlands than elsewhere in PNG because of the high density of people and agriculture and the good road network. Observations covered all districts of the Highlands region and most districts in the Islands and Momase regions. Traverses were made along virtually all vehicle roads in PNG that extend more than 100 m above sea level. All major mountainous areas were visited. There were numerous lowland areas where recordings were not made; for example, in Western Province, I only made observations in the Kiunga to Ningerum area. The major foot traverses were as follows: Menyamya (Morobe Province) to Swanson River (Gulf); Baining Mountains of New Britain; Nakanai Mountains of New Britain; east coast to west coast of New Ireland, via the Lelet Plateau; Managalas Plateau (Oro) to Kokoda Trail (Central); Chimbu Valley (Simbu) to Ramu Valley via Bundi (Madang); a series of walking traverses on the Huon Peninsula of Morobe and Madang provinces; Golgobip to Olsobip area (Western Province); and Bimin to Oksapmin (Sandaun Province).

The geographical unit used as a sampling framework was usually a valley or plateau, but sometimes it was an administrative one such as a census division. The areas of the units differ and are smaller where population density is greater. For each geographical unit, there are four possible values for any species: the usual upper and lower altitudes, and the extreme upper and lower altitudes. The mean usual limits were derived by averaging the values from the different geographical units. This technique provides an imperfect estimate of mean altitudinal limits. Sources of error are:

1. Erroneous altimeter readings. Such errors were largely eliminated in this study by setting the instrument at a point of known altitude and using a number of corrections where necessary (see Appendix 3 for details).

4 Where plants did not bear, this was recorded as outside the usual and the extreme limits for that location. Recordings of extreme limits are for plants which bore the economic product.

5 Black pepper provides an example of this process (See Footnote 12, Table 6). Pepper is not commonly grown in PNG except at low altitudes, so records of where pepper failed to bear suggest that the usual upper limit is likely to be below 700 m.

2. An inconsistent sampling framework and varying numbers of observations per species. For any particular geographical unit, observations are available only for some species and the mix of locations used to derive mean figures is different for each species. Observations are dictated by where crops are grown and road or walking access to the altitude where they cease to be grown. To overcome this limitation in part, data were gathered on 12 important economic crops at 10 locations between 1600 m and 2500 m; and for five other crops at 15 locations between 700 m and 1400 m.
3. Slope aspects. Cultivation tends to be higher on the east- and north-facing slopes in PNG (Smith 1978). Differences in slope aspect contribute to the error component of these data, but are not considered as great as climatic differences between different locations.
4. Global climate change. Most observations were made over a relatively short period in the early 1980s, but some were made in the late 1980s and early 1990s when temperatures were somewhat higher than in the early 1980s (Bourke et al. 2002).
5. Poorly defined limits. There is a large range in the upper limit for a number of species, particularly green vegetables, as many different species can be grown and villagers are not tempted to grow a species as high as possible. This results in a high error term for some species, particularly green leafy vegetables.

Results and discussion

Data on the usual and extreme altitudinal ranges of 230 crop species and one plant pathogen are presented in Tables 1 to 6. These data are grouped depending on the main economic product, as follows: starchy foods, traditional vegetables, introduced vegetables, fruits, nuts and non-food species. Traditional vegetables are those that were grown, at least in some parts of PNG, before permanent settlement by Europeans (1870 onwards). Introduced vegetables are those introduced into PNG since 1870. For each species the following information is given: botanical family, scientific and common name; mean usual altitudinal range (mean lower and mean upper limits); extreme altitudinal range; number of observations and standard deviation for usual limits. Mean figures for the usual limits are derived from different geographical units and are rounded to the nearest 50 m. Figures for extremes are single observations and are rounded to the nearest 10 m, as are standard deviations. The extreme figures are the highest and lowest obtained for either usual or extreme growing conditions. Common names generally follow French (1986).

Where the usual or extreme lower limit is near sea level (<100 m), this is given as 0 m rather than a mean of actual recordings. Virtually all species that grow below 100 m grow near the ocean, the exception being *marita* pandanus (*Pandanus conoideus*), which is not usually planted near the ocean (Table 4).

Means have been derived for a usual limit where I have a minimum of three observations in different parts of PNG. Means based on three or four observations only must be regarded as approximate. The exception is where the mean upper limit is about 2700 m. This is because the upper limit of arable agriculture in PNG may be taken as 2700 m and food gardens are uncommon above this altitude. Because gardens above 2700 m are planted in a limited number of locations, means for crops that grow up to the limit of agriculture are generally based on only three to five recordings. These crops are potato (Table 1), *Ficus dammaropsis*, *Rorippa schlechteri*, *Rungia klossii*, *Setaria palmifolia* and *Solanum americanum* (Table 2), leek, shallot, spring onion, turnip, carrot, pea and broad bean (Table 3), and pyrethrum and *Eleocharis dulcis* (Table 6). This upper limit of arable agriculture is imposed by the upper limit of sweet potato, the staple food in the highlands. If agriculture was practised at higher altitudes, many of these 15 species would have a higher usual upper limit.

For many vegetables, both traditional and introduced, it is sometimes difficult to define altitudinal limits with much precision, the reason being that many substitute species are available and people tend not to plant a species close to its altitudinal limit. This is reflected in the high standard deviations (>150 m) for the lower limit for many vegetables; for example, *Dicliptera papuana*, *Ficus dammaropsis*, *Oenanthe javanica* (Table 2) and silverbeet (Table 3).

Table 1. The altitudinal range of indigenous and introduced starchy food species in PNG[1]

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Alocasia macrorrhizos[2]	Araceae	Giant taro	0–?	0–400	–	–
Amorphophallus paeoniifolius	Araceae	Elephant-foot yam	0–700	0–1230	–	4/50
**Canna edulis*	Cannaceae	Queensland arrowroot	0–?	0–1620	–	–
Colocasia esculenta[3]	Araceae	Taro	0–2400	0–2760	–	17/150
Dioscorea alata	Dioscoreaceae	Greater yam	0–1900	0–2100	–	15/80
Dioscorea bulbifera	=	Aerial yam	0–1900	0–2110	–	12/110
Dioscorea esculenta[4]	=	Lesser yam	0–1550	0–1670	–	4/120
Dioscorea nummularia	=	Nummularia yam	0–1900	0–2050	–	7/90
Dioscorea pentaphylla	=	Five-leaflet yam	0–1500	0–1620	–	3/40
**Ipomoea batatas*[5]	Convolvulaceae	Sweet potato	0–2700	0–2850	–	10/150
**Manihot esculenta*	Euphorbiaceae	Cassava	0–1800	0–2210	–	32/120
Metroxylon sagu	Arecaceae	Sago	0–1150	0–1250	–	10/60
Musa cvs	Musaceae	Fe'i banana	0–1750	0–2060	–	8/160
Musa cvs	=	Diploid banana	0–1800	0–2030	–	19/70
Musa cvs	=	Triploid banana	0–2150	0–2580	–	30/130
**Oryza sativa*	Poaceae	Rice	0–?	0–2360	–	–
Pueraria lobata	Fabaceae	Pueraria (*kudzu*)	0–2300	0–2740	–	5/180
Saccharum officinarum	Poaceae	Sugar cane	0–2600	0–2760	–	8/160
**Solanum tuberosum*[6]	Solanaceae	Potato	700–2750	0–2850	7/90	4/60
**Xanthosoma sagittifolium*	Araceae	Chinese taro	0–2000	0–2460	–	25/100
**Zea mays*	Poaceae	Maize (corn)	0–2450	0–2680	–	13/130

1. Indigenous species denotes those present in PNG before permanent settlement by Europeans (c. 1870). Introduced species were bought to PNG after 1870 (or after c. 1700 in the case of sweet potato and cassava). Introduced species are denoted by *. The period when food crops were introduced into PNG is given by Bourke (2009b).
2. Native inedible *Alocasia nicolsonii* grows as high as 2640 m, but *Alocasia macrorrhizos* is planted as a food crop only at low altitudes.
3. Stands of *Colocasia* taro are not planted as high as individual plants. The highest observed plot was at 2370 m (Sau Valley, Enga Province) and the mean of six observations was 2250 m (SD 100 m).
4. The lesser yam is not common above 900 m.
5. The usual upper limit of sweet potato (2700 m) is derived from the 10 highest observations, not all observations (Table 7).
6. Potato grown by villagers for subsistence only is usually planted above about 1900 m. Below 1900 m, most crops are intended for both sale and subsistence. Smith (1977a:189) records that he grew potato on Mount Wilhelm at 3580 m.

Table 2. The altitudinal range of indigenous vegetable species in PNG (Table 2 continues on page 482)

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Abelmoschus manihot	Malvaceae	*Aibika*	0–1900	0–2110	–	20/110
Amaranthus tricolor	Amaranthaceae	Amaranth	0–1950	0–2050	–	11/50
Caryota rumphiana	Arecaceae	Fishtail palm	0–1250	0–1600	–	10/70
Commelina diffusa[1]	Commelinaceae	-	0–?	0–2390	–	–
Cucumis sativus	Cucurbitaceae	Cucumber	0–1950	0–2210	–	19/80
Cyanotis moluccana	Commelinaceae	Cyanotis	0–?	0–2410	–	–
Cymbopogon citratus	Poaceae	Lemon grass	0–?	0–2140	–	–
Desmodium repandum[2]	Fabaceae	–	?–2250	1100–2350	–	6/80
Dicliptera papuana[3]	Acathaceae	Dicliptera	1000–2000	720–2660	6/220	5/170
Erythrina variegata	Fabaceae	Coral tree	0–1550	0–2210	–	9/170
Ficus copiosa	Moraceae	*Kumu musong*	0–2200	0–2450	–	6/140
Ficus dammaropsis	=	Highland *kapiak*	800–2750	0–2820	5/300	3/60
Ficus pungens	=	–	0–1850	0–1900	–	5/60
Ficus wassa[4]	=	–	0–?	0–2520	–	–
Gnetum gnemon[5]	Gnetaceae	*Tulip*	0–1100	0–1330	–	10/150
Graptophyllum pictum	Acanthaceae	Caricature plant	0–?	0–1730	–	–
Ipomoea aquatica	Convolvulaceae	*Kangkong*	0–600	0–760	–	5/100
Lablab purpureus	Fabaceae	Hyacinth bean	0–2000	0–2430	–	15/170
Lagenaria siceraria[6]	Cucurbitaceae	Bottle gourd	0–?	0–2670	–	–
Oenanthe javanica[7]	Apiaceae	Java water dropwort	1050–2700	0–3400	9/220	3/40
Pipturus argenteus	Urticaceae	–	0–1800	0–1950	–	5/90
Polyscias sp.	Araliaceae	*Valangur*	0–1200	0–1230	–	4/30
Psophocarpus tetragonolobus[8]	Fabaceae	Winged bean	0–1900	0–2070	–	28/90
Ricinus communis	Euphorbiaceae	Castor	0–2350	0–2760	–	5/100
Rorippa schlechteri[9]	Brassicaceae	Rorippa	750–2700	180–2850	4/120	4/120
Rungia klossii[10]	Acanthaceae	Rungia	950–2700	0–2760	10/170	4/40
Saccharum edule	Poaceae	Lowland *pitpit*	0–1800	0–2270	–	23/160
Setaria palmifolia[11]	=	Highland *pitpit*	0–2700	0–2760	–	4/40
Solanum americanum	Solanaceae	Nightshade (*karakap*)	0–2550	0–2800	–	6/190
Trichosanthes pulleana	Cucurbitaceae	–	0–2000	0–2200	–	3/80
Zingiber officinale	Zingiberaceae	Ginger	0–1950	0–2200	–	15/80

Table 2. *notes*

1. The extreme upper limit for *Commelina diffusa* is a Division of Botany (now PNG Forest Research Institute) identification from the Kandep area in Enga Province.
2. *Desmodium repandum* has been identified from Mount Wilhelm at 3350 m by staff from the Division of Botany.
3. *Dicliptera papuana* is given as *Hemigraphis* sp. by some authors.
4. The extreme upper limit for *Ficus wassa* is a Division of Botany identification from the Kaugel Valley in Western Highlands Province. There is insufficient data to establish the usual upper altitudinal limit for *F. wassa*, but it is probably about 2200 m.
5. *Gnetum gnemon* produces both edible nuts and leaves over these altitudinal ranges.
6. The extreme upper limit of 2670 m for bottle gourd is from the upper Wage Valley in Enga Province (P. Wohlt, pers comm.). I have not seen bottle gourd at over 2200 m.
7. *Oenanthe* is planted in food gardens up to the altitudinal limit of gardening (c. 2700 m) in Enga and Simbu provinces. Self-sown plants occur as high as 3000 m in Enga Province and 3400 m in Simbu Province. The mean usual lower limit of 1050 m is for locations where *Oenanthe* was traditionally grown. It is now commonly planted in coastal locations by highland migrants.
8. The usual range for all plantings of winged bean is from sea level to 1900 m. This species is planted mainly for tuber production over the range 1200-1900 m.
9. *Rorippa schlechteri* is sometimes given as *Nasturtium schlechteri*.
10. Rungia is planted up to about 2700 m; for example, on the Sirunki Plateau, the Kaugel Valley, the Wage Valley (Bowers 1968:89; Wohlt 1978:132; Allen 1982:112) and in the Chimbu Valley. It is not common above about 2300 m.
11. While highland *pitpit* is grown between sea level and 2700 m, it is more commonly planted above about 500 m.

Table 3. The altitudinal range of introduced vegetable species in PNG (Table 3 continues on pages 483-484)

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Abelmoschus esculentus	Malvaceae	Okra	0–?	0–1600	–	–
Allium ampeloprasum cv. group Leek	Alliaceae	Leek	750–2700	0–2760	5/150	3/70
Allium cepa cv. group Aggregatum	=	Shallot	0–2600	0–2740	–	3/150
Allium cepa cv. group Aggregatum	=	Spring onion	0–2700	0–2850	–	5/60
Allium cepa cv. group Common Onion	=	Bulb onion	?–?	0–2630	–	–
Allium sativum cv. group Common Garlic	=	Garlic	?–?	1520–2760	–	–
Amaranthus caudatus[1]	Amaranthaceae	Amaranth	1600–2400	0–2520	5/90	4/150
Amaranthus cruentus[2]	=	Amaranth	1350–2300	1000–2760	6/230	7/110
Amaranthus dubius	=	Amaranth	0–1800	0–2610	–	4/110
Amaranthus blitum	=	Amaranth	0–2050	0–2320	–	9/140
Apium graveolens var. *dulce*	Apiaceae	Celery	950–2300	870–2800	4/40	8/80
Asparagus officinalis	Asparagaceae	Asparagus	1150–2400	0–2630	4/170	3/220
Basella alba	Basellaceae	Ceylon spinach	0–?	0–1670	–	–
Beta vulgaris cv. group Garden Beet	Amaranthaceae	Beetroot	?–2350	0–2720	–	5/190
Beta vulgaris cv. group Spinach Beet	=	Silverbeet	750–2350	0–2760	4/250	7/140
Brassica oleracea cv. group Broccoli	Brassicaceae	Broccoli	1100–?	0–2760	6/140	–
Brassica oleracea cv. group Brussels Sprouts	=	Brussels sprout	?–?	1620–2630	–	–

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Brassica oleracea cv. group Cauliflower	=	Cauliflower	1100–?	0–2760	4/110	–
Brassica oleracea cv. group Chinese kale	=	Chinese kale	?–?	500–2450	–	–
Brassica oleracea cv. group Kohlrabi	=	Kohlrabi	?–?	0–2630	–	–
Brassica oleracea cv. group White Headed Cabbage[3]	=	Head cabbage	700–2700	0–2850	11/80	5/80
Brassica rapa cv. group Chinese cabbage	=	Chinese cabbage (wong bok)	0–2300	0–2720	–	4/140
Brassica rapa cv.group Pak Choi	=	Chinese cabbage (pak choi)	0–2550	0–2800	–	7/160
Brassica rapa cv. group Vegetable Turnip	=	Turnip	?–2700	720–2790	–	3/80
Cajanus cajan	Fabaceae	Pigeon pea	0–1950	0–2200	–	6/200
Canavalia ensiformis	=	Jack bean	0–?	0–1630	–	–
Canavalia gladiata	=	Sword bean	0–?	0–1780	–	–
Capsicum annuum cv. group Grossum	Solanaceae	Capsicum	0–2300	0–2410	–	4/100
Capsicum annuum cv. group Longum	=	Long cayenne pepper	0–?	0–2380	–	–
Cucurbita moschata[4]	Cucurbitaceae	Pumpkin	0–2350	0–2760	–	14/130
Cucurbita pepo	=	Zucchini	1050–2050	0–2760	3/110	5/180
Daucus carota[5]	Apiaceae	Carrot	0–2650	0–2760	–	4/70
Foeniculum vulgare	=	Fennel	?–?	1410–2240	–	–
Glycine max	Fabaceae	Soya bean	0–2150	0–2600	–	9/110
Lactuca sativa[6]	Asteraceae	Lettuce	700–2350	0–2800	4/40	7/210
Lycopersicon esculentum	Solanaceae	Tomato	0–2250	0–2630	–	13/110
Mentha spicata[7]	Lamiaceae	Mint	0–?	0–3580	–	–
Pastinaca sativa	Apiaceae	Parsnip	?–?	1160–2790	–	–
Petroselinum crispum	Apiaceae	Parsley	0–?	0–2760	–	–
Phaseolus lunatus	Fabaceae	Lima bean	1050–2000	0–2770	8/110	18/170
Phaseolus vulgaris[8]	=	Common bean	0–2350	0–2760	–	12/120
Pisum sativum[9]	=	Pea	900–2700	0–2800	6/310	5/70
Raphanus sativus cv. group Small Radish[10]	Brassicaceae	Radish	0–?	0–2630	–	–
Rheum × cultorum	Polygonaceae	Rhubarb	1000–?	750–2760	4/220	–
Rorippa islandica[11]	Brassicaceae	–	2100–2750	1990–2850	4/100	4/20

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Rorippa nasturtium-aquaticum	=	Watercress	0–2900	0–3580	–	3/70
Sechium edule	Cucurbitaceae	Choko	0–2300	0–2680	–	16/120
Solanum melongena cv. group Common Eggplant	Solanaceae	Eggplant	0–1800	0–2260	–	7/100
Spinacia oleracea	Amaranthaceae	Spinach	1000–?	870–2630	4/130	–
Symphytum asperrimum	Boraginaceae	Russian comfrey	0–2350	0–2630	–	5/170
Talinum triangulare	Portulacaceae	–	0–?	0–1600	–	–
Vicia faba	Fabaceae	Broad bean	2050–2650	1620–2760	4/90	4/80
Vigna radiata	=	Mung bean	0–?	0–1620	–	–
Vigna umbellata	=	Rice bean	0–?	0–2070	–	–
Vigna unguiculata cv. group Sesquipedalis	=	Snake bean	0–1600	0–1890	–	10/200
Vigna unguiculata cv. group Unguiculata	=	Cowpea	0–1750	0–1840	–	6/70

1. *Amaranthus caudatus* was recorded by Peekel (1984:164) as growing near sea level on New Ireland Province. It is rarely seen in the lowlands, but I have seen it near Angoram in East Sepik Province at 60 m.
2. *Amaranthus cruentus* has been recorded by Peekel (1984:164) from near sea level on New Ireland Province and identified by Division of Botany staff from specimens from Malalau (3 m) and Maprik (200 m). The lowest altitude I have seen plants growing was at 1000 m at Bomai in Simbu Province.
3. Cabbage grown by villagers for subsistence only is usually planted above about 1700 m. Smith (1977a:189) records that he grew cabbage on Mount Wilhelm at 3580 m.
4. Records for pumpkin are for plants producing both fruit and leaves. I have seen another species of pumpkin (*C. pepo*?) growing at 2680 m on the Sirunki Plateau in Enga Province.
5. Carrot generally produces better-quality roots at 400 m and above.
6. Lettuce can be grown at sea level in PNG, but the quality is often poor. Acceptable quality lettuce is grown at 700 m and above.
7. Mint is grown at about 2600 m in Simbu and Enga provinces, and this is probably the usual upper limit.
8. Common bean grows poorly at sea level and is usually grown above 400 m.
9. Peas grown by villagers for subsistence only are usually planted above about 1700 m.
10. Radish was grown by Smith (1977a:189) at 3580 m on Mount Wilhelm.
11. *Rorippa islandica* has been identified by Division of Botany staff from specimens at lower altitudes in the Baliem Valley, Papua (West New Guinea) (1600 m) and in south Simbu Province (1680 m).

Table 4. The altitudinal range of indigenous and introduced fruit species in PNG[1] (Table 4 continues on page 486)

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
**Ananas comosus*[2]	Bromeliaceae	Pineapple	0–1800	0–2380	–	25/110
**Annona cherimolia*	Annonaceae	Cherimoya	?–?	750–2200	–	–
**Annona muricata*	=	Soursop	0–1000	0–1460	–	7/100
**Annona reticulata*	=	Bullock's heart	0–?	0–1210	–	–
**Annona squamosa*	=	Custard apple (sweetsop)	0–?	0–1210	–	–
**Artocarpus heterophyllus*	Moraceae	Jackfruit	0–?	0–1230	–	–
**Averrhoa bilimbi*	Oxalidaceae	Tree cucumber	0–?	0–750	–	–
**Averrhoa carambola*	=	Five corner (carambola)	0–1300	0–1430	–	4/120
Burckella obovata	Sapotaceae	*Bukabuk*	0–?	0–390	–	–
**Carica pubescens*	Anacardiaceae	Mountain pawpaw	?–?	1750–2760	–	–
**Carica papaya*	=	Pawpaw	0–1700	0–1950	–	30/100
**Citrullus lanatus*[3]	Cucurbitaceae	Watermelon	0–1700	0–1980	–	6/180
**Citrus aurantifolia*	Rutaceae	Lime	0–1800	0–2260	–	5/80
**Citrus limon*[4]	=	Lemon	0–2150	0–2240	–	6/90
**Citrus maxima*	=	Pomelo	0–1300	0–1640	–	4/70
**Citrus paradisi*	=	Grapefruit	0–1800	0–1980	–	6/100
**Citrus paradisi × Citrus reticulata?*	=	*Ugli*	0–1800	0–1830	–	3/50
**Citrus reticulata*	=	Mandarin	0–1800	0–2260	–	9/50
**Citrus sinensis*	=	Orange	0–1800	0–2280	–	12/80
**Cucumis melo*	Cucurbitaceae	Rockmelon	0–?	0–2180	–	–
**Cyphomandra betacea*	Solanaceae	Tree tomato (tamarillo)	1050–2300	0–2600	8/160	7/170
**Durio zibethinus*[5]	Malvaceae	Durian	0–?	0–?	–	–
**Eriobotrya japonica*	Rosaceae	Loquat	850–1800	0–2410	3/170	6/70
**Eugenia uniflora*	Myrtaceae	Brazil cherry	0–1750	0–1880	–	3/140
**Fortunella japonica*[6]	Rutaceae	Cumquat	0–?	0–1160	–	–
**Fragaria* sp.	Rosaceae	Strawberry	800–2450	660–2800	7/100	5/240
**Fragaria vesca*	=	Alpine strawberry	?–?	1740–3580	–	–
**Garcinia mangostana*[7]	Clusiaceae	Mangosteen	0–?	0–?	–	–
**Hibiscus sabdariffa*	Malvaceae	Rosella	0–1700	0–2220	–	8/160
**Malus domestica*	=	Apple	?–?	600–2670	–	–
**Mangifera indica*[8]	Anacardiaceae	Mango	0–1600	0–1820	–	13/110
Mangifera minor	=	Traditional mango	0–1750	0–1900	–	6/100
**Monstera deliciosa*	Araceae	Ceriman	?–2200	0–2330	–	3/180
**Morus nigra*	Moraceae	Mulberry	800–2200	0–2760	6/100	8/150
**Nephelium lappaceum*	Sapindaceae	Rambutan	0–?	0–750	–	–
Pandanus conoideus[9]	Pandanaceae	*Marita*	0–1700	0–1980	–	37/90
**Passiflora edulis* f. *edulis*	Passifloraceae	Purple passionfruit	800–2300	700–2520	7/90	13/90

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
**Passiflora edulis* f. *flavicarpa*	=	Lowland yellow passionfruit	0–850	0–960	–	5/80
**Passiflora ligularis*	=	*Suga prut* (highland yellow passionfruit)	1350–2350	1300–2460	3/80	4/140
**Passiflora mollissima*[10]	=	Banana passionfruit	1850–2800	1640–2920	7/110	5/100
**Passiflora quadrangularis*	=	Granadilla	0–1000	0–1520	–	10/300
**Persea americana*	Lauraceae	Avocado	0–2050	0–2430	–	16/160
**Physalis peruviana*	Solanaceae	Cape gooseberry	950–2800	750–2870	5/190	6/60
Pometia pinnata[11]	Sapindaceae	*Ton* (*taun*)	0–800	0–1120	–	7/160
**Prunus* sp.	Rosaceae	Plum	?–?	1590–2600	–	–
**Psidium cattleianum*	Myrtaceae	Cherry guava	0–1850	0–1900	–	3/90
**Psidium guajava*	=	Guava	0–1850	0–2020	–	19/110
**Punica granatum*	Rosaceae	Pomegranate	0–?	0–1620	–	–
**Rubus lasiocarpus*	=	Black raspberry	950–2250	760–2830	5/150	11/180
Rubus moluccanus	=	Red raspberry	0–2150	0–2250	–	3/120
Rubus rosifolius[12]	=	Red raspberry	950–2800	700–2900	8/180	5/60
**Sambucus nigra*[13]	Adoxaceae	Elderberry	450–1900	0–2150	3/110	11/140
Spondias cytherea	Anacardiaceae	Golden apple	0–950	0–1070	–	4/110
**Syzygium aqueum*	Myrtaceae	Watery rose apple	0–1600	0–1640	–	3/50
Syzygium malaccense	=	Malay apple	0–850	0–1580	–	5/80

1. Indigenous species denotes those present in PNG before permanent settlement by Europeans (c. 1870). Introduced species were bought to PNG after 1870. Introduced species are denoted by *. The period when food crops were introduced into PNG is given by Bourke (2009b).
2. Smooth-leaf and rough-leaf pineapple have the same usual upper altitudinal limit (1800 m). The rough leaf is less common above about 1500 m and produces better-quality fruit between about 400 m and 1200 m.
3. Watermelon is not common above about 1200 m, but is grown up to a mean usual upper limit of 1700 m.
4. Lemon grows better above about 400 m. For a fuller discussion on the optimum altitudinal range for citrus species in PNG, see Bourke and Tarepe (1982).
5. Durian has failed to establish at Bulolo (750 m) (Simpson and Arentz 1982), suggesting that its upper limit may be below 750 m.
6. Cumquat would almost certainly bear at higher altitudes in PNG as it is cold tolerant, but it has not been recorded growing above 1160 m.
7. Mangosteen failed to bear fruit at 550 m on the Managalas Plateau, suggesting that its upper limit may be below this.
8. Mango fruit quality is poor above about 1200 m and bearing is irregular above 1600 m.
9. *Marita* pandanus is not usually planted near the ocean, but it is grown inland at altitudes below 100 m; for example, near Kiunga, Popondetta, Gogol Valley and Aitape. It is more commonly planted above about 500 m.
10. Banana passionfruit plants grow as high as 3580 m, but the highest that I recorded fruit was at 2920 m (Chimbu Valley) and 2850 m (Sirunki Plateau). Self-sown plants are not common below about 2000 m, although planted vines bear as low as 1640 m (Aiyura).
11. *Pometia pinnata* bears edible fruit up to a mean upper limit of 800 m, but the tree grows at higher altitudes. It has been recorded at about 1700 m in the Nipa area by Sillitoe (1983:115).
12. Peekel (1984:202) implies that *Rubus rosifolius* has been recorded as low as 300 m in New Ireland and New Britain. The Division of Botany has one identification from 200 m (Tufi), but all other specimens in their collections come from over 1000 m. My observations are of a mean minimum of 950 m (eight recordings).
13. Elderberry grows up to about 2650 m, but does not usually bear fruit above a mean of 1900 m.

Table 5. The altitudinal range of indigenous and introduced edible nut species in PNG[1]

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation	
					Usual min.	Usual max.
Aleurites moluccana	Euphorbiaceae	Candle nut	0–1800	0–2160	–	9/140
**Arachis hypogaea*	Fabaceae	Peanut	0–1850	0–1940	–	21/70
Artocarpus altilis	Moraceae	Breadfruit	0–1250	0–1450	–	23/130
**Anacardium occidentale*	Anacardiaceae	Cashew	0–?	0–1400	–	–
Barringtonia procera	Barringtoniaceae	*Pao*	0–500	0–620	–	4/90
Canarium indicum	Burseraceae	*Galip*	0–700	0–930	–	5/160
*Carya illinoensis		Pecan	?–?	1390–1640	–	–
Castanopsis acuminatissima[2]	Fagaceae	Castanopsis	700–2350	570–2440	6/80	8/110
Cocos nucifera[3]	Arecaceae	Coconut	0–950	0–1310	–	20/190
Finschia chloroxantha[4]		Finschia	0–1850	0–2000	–	4/110
Inocarpus fagifer	Fabaceae	Polynesian chestnut (*aila*)	0–400	0–870	–	4/90
**Macadamia integrifolia/ *M. tetraphylla*[5]	Proteaceae	Macadamia	0–1750	0–1810	–	3/60
Pandanus antaresensis	Pandanaceae	Wild *karuka*	1000–2350	850–2460	4/110	9/90
Pandanus brosimos	=	Wild *karuka*	2400–3100	1800–3300	20/150	6/60
Pandanus jiulianettii	=	Planted *karuka*	1800–2600	1450–2800	50/110	18/100
Pangium edule		*Sis* (*solomon*)	0–1050	0–1380	–	11/120
Terminalia catappa	Combretaceae	Sea almond (*talis*)	0–300	0–460	–	4/100
Terminalia impediens	=	*Okari*	0–1000	0–1100	–	3/110
Terminalia kaernbachii	=	*Okari*	0–1100	0–1260	–	11/90

1. Data for tulip nuts (*Gnetum gnemon*) are given in Table 2. Indigenous species denotes those present in PNG before permanent settlement by Europeans (c. 1870). Introduced species were bought to PNG after 1870. Introduced species are denoted by *. The period when food crops were introduced into PNG is given by Bourke (2009b).
2. Self-sown castanopsis is more common above about 1100 m, although the usual mean lower limit is 700 m.
3. Coconut palms grow as high as 1760 m, but the highest palms that bore nuts in the period 1980-1982 were at Yonki, EHP (1310 m) and the Baiyer Valley, WHP (1220 m). By 1999, coconuts were bearing as high as 1370 m (Benabena Valley, EHP), 1420 m (Korofeigu, EHP) and 1450 m (Wahgi Valley, WHP). By mid-2009, coconut palms were bearing as high as 1560 m (near Goroka, EHP).
4. The highest recording for finschia (2000 m) is a Division of Botany record from Aseki in Morobe Province.
5. In their natural range in Australia, *Macadamia tetraphylla* occurs in a slightly cooler climate than *M. integrifolia*. *M. tetraphylla* has also proven more cold tolerant than *M. integrifolia* in California (Cull and Trochoulias 1982). The limited numbers of observations from PNG do not indicate a separate range for the two species; both species bear from sea level up to 1700-1800 m.

Table 6. The altitudinal range of some indigenous and introduced non-food species in PNG[1] (Table 6 continues on page 489)

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation		Main uses[2]
					Usual min.	Usual max.	
Albizia chinensis	Fabaceae	Albizia	0–1900	0–2060	–	15/110	S
Araucaria cunninghamii[3]	Araucariaceae	Hoop pine	0–?	0–2140	–	–	T
Araucaria hunsteinii	=	Klinki pine	0–?	0–2140	–	–	T
Areca catechu	Arecaceae	Betel nut	0–1100	0–1390	–	17/140	N
Areca macrocalyx	=	Highland betel nut	1100–1950	770–2120	8/160	14/110	N
**Bixa orellana*	Bixaceae	Bixa	0–1650	0–1910	–	12/140	B
Broussonetia papyrifera	Moraceae	Paper mulberry	?–?	0–2440	–	–	B
**Camellia sinensis*[4]	Theaceae	Tea	?–?	1210–2670	–	–	E
Campnosperma brevipetiolata[5]	Anacardiaceae	*Tigaso* oil tree	0–850	0–?	–	–	B
**Cannabis sativa*	Cannabaceae	Marijuana	0–?	0–2570	–	–	N
**Capsicum frutescens*	Solanaceae	Birdseye chilli	0–1800	0–2420	–	10/110	E
Casuarina oligodon	Casuarinaceae	Casuarina	700–2600	120–2820	8/100	10/150	TS
**Ceiba pentandra*	Malvaceae	Kapok	0–1250	0–1550	–	6/200	E
**Chrysanthemum cinerariaefolium*	Asteraceae	Pyrethrum	2400–2800	1630–2850	8/20	5/50	E
**Codiaeum variegatum*	Euborbiaceae	Croton	0–1700	0–1920	–	16/100	D
Coix lachryma-jobi	Poaceae	Job's tears	0–?	0–2460	–	–	B
**Coffea arabica*[6]	Rubiaceae	Arabica coffee	700–2050	80–2380	15/150	30/90	E
**Coffea canephora* var. *robusta*	=	Robusta coffee	0–550	0–1700	–	5/50	E
Cordyline fruticosa[7]	Laxmanniaceae	Tanget	0–3100	0–3250	–	4/180	BD
**Crotalaria lunata*	Fabaceae	Crotalaria	1450–2400	1300–2740	4/100	10/140	S
**Crotalaria micans*	=	Crotalaria	0–1850	0–2090	4/100	10/90	S
Derris sp.	=	Derris	0–?	0–1110	–	–	F
**Elaeis guineensis*	Arecaceae	Oil palm	0–?	0–920	–	–	E
Eleocharis dulcis	Cyperaceae	Reeds	0–2750	0–2820	–	3/80	B
**Elettaria cardamomum*	Zingiberaceae	Cardamom	550–1700	0–1890	4/110	11/140	E
**Flemingia macrophylla*	Fabaceae	Flemingia	0–1850	0–2140	–	9/130	D
Gymnostoma papuanum	Casuarinaceae	Casuarina	0–2000	0–2260	–	13/130	T
**Helianthus annuus*	Asteraceae	Sunflower	0–2200	0–2630	–	5/120	E
**Hevea brasiliensis*	Euphorbiaceae	Rubber (para)	0–?	0–700	–	–	E
**Hibiscus rosa-sinensis*	Malvaceae	Hibiscus	0–?	0–2360	–	–	D

Scientific name	Family name	Common name	Mean usual altitudinal range (m)	Extreme altitudinal range (m)	Number of observations/ standard deviation		Main uses[2]
					Usual min.	Usual max.	
**Lantana camara*	Verbenaceae	Lantana	0–2100	0–2200	–	5/100	DW
**Leucaena leucocephala*	Fabaceae	Leucaena	0–1800	0–1890	–	15/70	ST
**Lupinus* cv. *Russell Hybrid*[8]	=	Blue lupin	1850–?	1530–2920	8/80	–	D
**Mimosa invisa*	=	Mimosa	0–1650	0–1770	–	5/90	W
Mucuna novo-guineensis	=	–	0–1500	0–1890	–	4/270	D
**Mucuna pruriens*	=	Velvet bean	0–?	0–1620	–	–	C
Musa ingens	Musaceae	Wild banana	1300–1850	1150–1930	4/130	6/70	D
**Nicotiana tabacum*[9]	Solanaceae	Tobacco	0–2400	0–2790	–	14/200	N
**Phytophthora colocasiae*[10]	Phythiaceae	Taro blight	0–1300	0–1620	–	11/180	P
**Piper aduncum*	Piperaceae	–	0–1850	0–1920	–	4/90	W
Piper betle	=	Lowland betel pepper	0–1000	0–1140	–	7/90	N
Piper gibbilimbum[11]	=	Highland betel pepper	1150–2300	780–2580	4/260	10/110	N
**Piper nigrum*[12]	=	Black pepper	0–?	0–1080	–	–	E
Ptychococcus sp.	Arecaceae	Black palm	?–1900	?–1990	–	4/90	T
**Spathodea campanulata*	Bignoniaceae	West African tulip	0–?	0–1600	–	–	T
**Stylosanthes humilis*	Fabaceae	Townsville stylo	0–?	0–1620	–	–	C
**Tephrosia vogelii*	=	Tephrosia	1050–1950	0–2540	3/100	20/130	S
**Theobroma cacao*	Malvaceae	Cocoa	0–800	0–1390	–	7/140	E
**Vanilla planifolia*	Orchidaceae	Vanilla	0–1000	0–1080	–	4/100	E

1. Indigenous species denotes those present in PNG before permanent settlement by Europeans (c. 1870). Introduced species were bought to PNG after 1870 (or after c. 1700 in the case of tobacco and bixa). Introduced species are denoted by *. The period when stimulants were introduced into PNG is given by Bourke (2009b).
2. The main use of these species in PNG is as follows:
   B. Body covering (*Cordyline fruticosa* and *Eleocharis dulcis*), a dye (*Bixa*), a source of beads (Job's tears), tapa cloth (*Broussonetia papyrifera*) or body oil (*tigaso* tree)
   C. Cover or pasture crop
   D. Decorative plant
   E. Export crop (or potential one)
   F. Fish poison
   N. Stimulant or used with a stimulant (betel pepper)
   P. Plant pathogen
   S. Shade for export crop
   T. Timber source
   W. Weed
3. Natural stands of hoop pine occur as high as 2800 m on Mount Suckling and Mount Dayman according to Whitmore (1984:212).
4. Plantation tea is grown over a range of 1210-1960 m in Western Highlands Province. It grows at about 750 m in the Garaina area in Morobe Province.
5. The upper limit for *tigaso* oil tree is based on the distribution in Southern Highlands Province (C. Ballard, pers comm. 1994).
6. Plantation Arabica coffee occurs over a range of 930 m (Wau area) to 1820 m (Asaro Valley and Wahgi Valley). For a fuller discussion on the distribution of coffee see Bourke (1984).
7. *Cordyline fruticosa* has been recorded on Mount Wilhelm at 3580 m by Smith (1977a:192).
8. The mean usual lower limit of 1850 m for blue lupin is for self-sown plants.
9. Tobacco is commonly grown under the eves of houses towards the top of its altitudinal range. However, the range for tobacco grown in the open and under shelter is the same and observations on plants grown in all situations have been combined.
10. All specimens of the fungus that causes taro blight were identified by Department of Primary Industry plant pathologists.
11. The Division of Botany has two records for highland betel pepper from about 200 m (at Aitape and Maprik), indicating that the extreme lower limit is less than the 780 m that I recorded. Gardner (2003) records that *P. gibbilimbum* grows to about 3000 m.
12. Black pepper does not bear at Bulolo (750 m), Garaina (760 m) or Boana (920 m), although it has borne at Pindiu (930 m) and at Erave (1080 m). Thus, the mean usual upper limit is likely to be less than 700 m.

Usual altitudinal ranges

Considerable variation exists in the usual altitudinal ranges of different species. The ranges may be classed as small (<1000 m), medium (1000-2000 m), and large (2000-3000 m). This is illustrated with data on 22 crop species (Figure 2).

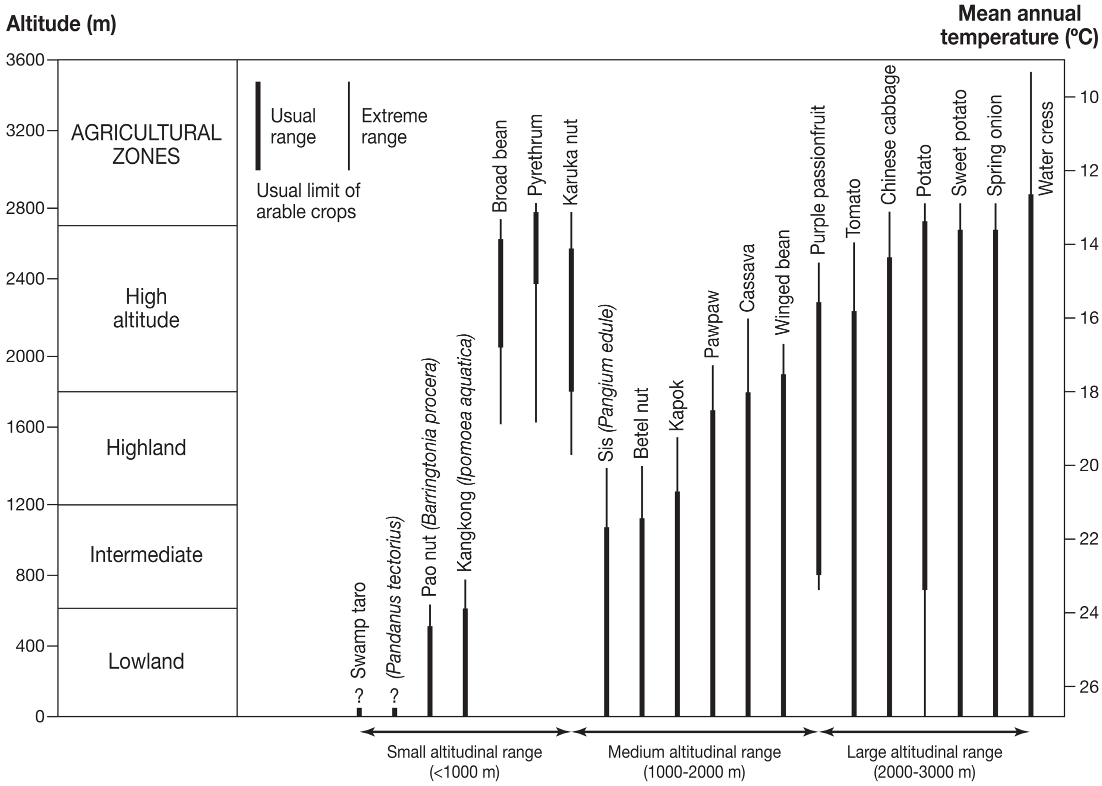

Figure 2. The usual and extreme altitudinal ranges of 22 crop species in PNG

Small range (<1000 m). A number of crops are grown from sea level to altitudes not above 100 m. These include swamp taro (*Cyrtosperma chamissonis*), lotus (*Nelumbo nucifera*), water lily (*Nymphaea pubescens*) and *Pandanus tectorius*.[6] It is likely that the upper limit of these species is determined by factors other than temperature.

A number of other species have restricted altitudinal ranges (400-600 m). These either grow near the lower limit of agriculture in PNG, that is, near sea level, or near the upper limit (2700 m). Species that grow at low altitudes only include kangkong (*Ipomea aquatica*) (Table 2), durian (*Durio zibethinus*), mangosteen (*Garcinia mangostana*) (Table 4) and *pao* nut (*Barringtonia procera*) (Table 5). Presumably these species would grow in warmer conditions than those in PNG if other environmental conditions were favourable. At the other extreme are cold-tolerant species that grow only near the upper altitudinal agricultural limit in PNG. These include *Rorippa islandica*, broad bean (*Vicia faba*) (Table 3) and pyrethrum (*Chrysanthemum cinerariaefolium*) (Table 6). One species with a restricted altitudinal range does not grow near sea level, nor at the usual upper limit of agriculture. This is the cultivated karuka nut (*Pandanus jiulianettii*), which grows over a usual range of 800 m (Figure 2).

Medium range (1000-2000 m). Species that have a usual range of 1000-2000 m mostly fall into two groups. The first are tree species that bear over an altitudinal range of 1000-1250 m; for example, sago (*Metroxylon sagu*) (Table 1), breadfruit (*Artocarpus altilis*), *sis* nut (*Pangium edule*), *okari* nut (*Terminalia kaernbachii*) (Table 5) and kapok (*Ceiba pentandra*) (Table 6).

6 The limits for these four species are not presented in the tables as they range in altitude from sea level to less than 100 m altitude.

The second group contains many species and these have a usual range from sea level to 1700-1900 m. They include three yam species (*Dioscorea alata*, *D. bulbifera* and *D. nummularia*), cassava (*Manihot esculenta*) (Table 1), cucumber (*Cucumis sativus*), winged bean (*Psophocarpus tetragonolobus*) (Table 2), pawpaw (*Carica papaya*) and five citrus species (Table 4).

Large range (2000-3000 m). Again, there are two main groups of species in this category, although the grouping is not as marked as for the medium-range species. The first group contains species that grow from sea level up to 2200-2400 m, such as pumpkin (*Cucurbita moschata*), Chinese cabbage (*Brassica rapa* cv. group Chinese cabbage) and tomato (*Lycopersicon esculentum*) (Table 3). The upper limit of this group coincides with the altitude above which frosts are common (c. 2200 m) and their upper limit is probably determined by annual frosts. Species in the other group have a usual range of about 2700 m because they grow from sea level to the usual limit of agriculture. These include sweet potato (*Ipomoea batatas*) (Table 1), highland *pitpit* (*Setaria palmifolia*) (Table 2), spring onion (*Allium cepa* cv. group Aggregatum), carrot (*Daucus carota*) (Table 3) and reed (*Eleocharis dulcis*) (Table 6).

Several species have an even larger range. Watercress (*Rorippa nasturtium-aquaticum*) grows from sea level to 2900 m (Table 3, Figure 3). It was not possible to define the usual upper limit of mint (*Mentha spicata*), but it has an extreme range of about 3600 m (Table 3).

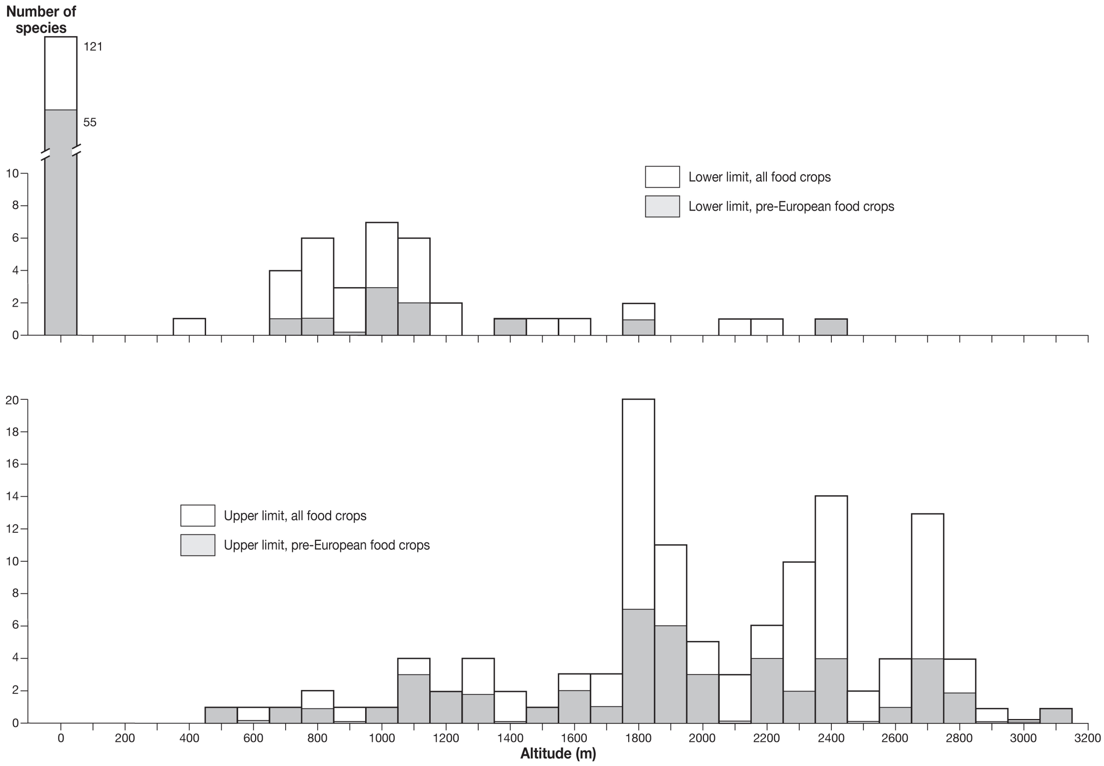

Figure 3. Distribution of the upper and lower altitudinal limits of 160 food crops in PNG

Distribution of crop limits

The distribution of the upper and lower usual altitudinal limits of 160 food crops by 100 m altitudinal classes is plotted in Figure 3. This plot illustrates the grouping of limits within a number of relatively narrow bands.

The most common single altitudinal limit is sea level, as 76 per cent (121 species) of food crops for which observations are available have their usual lower limit at sea level. A number of species have their usual lower limit between 650 m and 1150 m (28 species). Upper altitudinal limits are concentrated in three bands: 1750-1900 m, 2250-2350 m and at about 2700 m (Figure 3).

The concentration of crop altitudinal limits provides a basis for the altitudinal zones frequently recognised in PNG. These are the lowlands (0-600 m), the intermediate zone (600-1200 m), the highlands (1200-1800 m) and the high altitude zone (1800-2700 m) (Figure 2). The lower altitudinal limits of many cold-tolerant species and the upper limits of a number of important lowland tree species occur in the intermediate zone. The large number of species with an upper altitudinal limit of 1750-1900 m defines the upper limit of the highland zone (Figure 3).

The distinction is made in Figure-3 between food crops that pre-date European settlement in PNG in the 1870s and those that post-date European settlement. The same general pattern applies to both pre-European and post-European species (Figure 3). However, before 1870, only a limited number of food crops had a usual lower limit other than sea level. The increase in the number of species with lower limits other than sea level reflects the adoption of cold-tolerant species for use in the highlands. These originated in both Asia and Europe (for example, cabbage, silverbeet and mulberry), and in America (for example, potato and purple passionfruit).

Usual upper limit of food gardens

Near the upper limit of agriculture in PNG, sweet-potato gardens interplanted with other food crops constitute the major agricultural activity. Sweet-potato gardens are not common above about 2700 m and this may be taken as the usual upper limit of arable agriculture. Nevertheless, in parts of the highlands, some food gardens are planted at a higher altitude. The highest garden in PNG was observed between the Sirunki Plateau and the Lagaip Valley in Enga at 2850 m (Table 7). Persistent cloud cover and atmospheric saturations rather than low temperatures probably limit cultivation in parts of the highlands, particularly on the outer faces of the main mountain ranges (Brookfield 1964). Thus, the upper limit of food gardens in parts of the region occurs below 2700 m (Table 7).

Table 7. Highest subsistence sweet-potato (*Ipomoea batatas*) gardens observed in PNG[1, 2]

Location	Altitude (m)
Sirunki Plateau, Enga	2850
Upper Wage Valley, Enga	2840
Upper Lagaip Valley, Enga	2830
Tambul Basin, Western Highlands	2800
Chimbu Valley, Simbu	2770
Lai-Ambum Valleys divide, Enga	2750
Nebilyer Valley, Western Highlands	2570
Teptep area, Morobe	2560
Minyamb Valley, Enga	2500
Mendi Valley, Southern Highlands	2490
Gumine area, Simbu	2460
Margarima area, Southern Highlands	2460
Sinasina area, Simbu	2370
Asaro Valley, Eastern Highlands	2300
Porgera area, Enga[3]	2300
Bundi area, Madang	2200
Paiela area, Enga	2200

1. Houses and cleared land (and presumably food gardens) are shown at somewhat higher altitudes on the 1:100 000 map sheets. For example, they occur as high as 2640 m in the Margarima area in Southern Highlands Province. The highest dwelling and cleared land is shown at about 2900 m on the divide between the Lai and Ambum valleys in Enga Province.
2. The highest sweet-potato gardens recorded in Papua (West New Guinea) are at Kwiyawagi (4° 04' S, 138° 10' E) at c. 2800 m in the West Baliem Valley. There are higher gardens in the East Baliem Valley at Iniuni at c. 2900 m, where cabbage and *Solanum* potato, but not sweet potato, are grown (G. Hope, pers comm. 2009).
3. The highest food gardens observed in the Porgera area in Enga Province in 1980-1981 were at 2300 m. By 1993, sweet-potato gardens were being planted as high as 2650 m (G. Banks, pers comm. 1993).

Based on observations in the early 1960s, Brookfield (1964:30-31) reported on the limits to cultivation in several parts of the highlands. After correcting for systematic underestimation of altitudes, the figures reported by Brookfield are similar to the upper limits that I observed. For example, Brookfield noted abandoned gardens at 9000 feet (2880 m corrected figure) in the Chimbu Valley and upper Wage Valley (Wage-Kandep uplands) of Enga Province. This is similar to my observations in the early 1980s from these locations (Table 7).

In many parts of the highlands, two main types of food gardens may be distinguished. These are sweet-potato gardens and mixed gardens. The latter contain numerous species of food crops planted in a mixed arrangement. Sweet potato is unusual in these gardens. Cropping intensity is low and they are located on more fertile sites. I made 12 observations on the usual upper limit of mixed gardens. The mean was 2050 m (n = 12, SD = 130 m). The highest garden seen was in the Minyamb Valley at 2480 m. Some mixed gardens are also planted as high as 2500 m in the Chimbu Valley (Wohlt and Goie 1986:35-39). The mean upper limit of this garden type coincides with the upper limit of most of the supplementary food crops that are planted in mixed gardens (Figure 3).

The upper altitudinal limit of *Colocasia* taro is of particular interest because it was probably the main staple food for high-altitude dwellers before the adoption of sweet potato about 300 years ago. The mean usual upper limit for all taro planting was 2400 m (Table 1). The mean upper limit for monospecific taro planting is lower, at 2250 m. Thus, the mean upper limit of arable agriculture before the introduction of sweet potato into the highlands was probably about 2200 m, assuming climatic conditions were similar to those prevailing today. Triploid banana cultivars had a mean usual limit almost as high, at 2150 m, in the early 1980s (Table 1). As banana is likely to have been an important supplementary food to taro, this reinforces the suggestion that the upper limit for agriculture before the adoption of sweet potato was about 2200 m.

Variation between locations

These data on crop altitudinal limits confirm earlier studies on temperature and vegetation boundaries (McAlpine et al. 1983:94) that indicate that the mass mountain heating effect operates in PNG. This is the phenomenon, also known as Massenerhebung, whereby large mountains and the central parts of large ranges are warmer at a given elevation than small mountains and outlying spurs (Van Steenis 1961; Whitmore 1984:253).

Data on the usual altitudinal limits for 12 crop species at 10 locations in the central highlands between 1500 m and 2500 m are presented in Table 8. The usual upper limits for five crop species at 15 locations between 700 m and 1400 m are given in Table 9. The same data for selected species and locations are given in Figures 4 and 5. Within the central highlands, the usual limits for these species do not vary greatly among locations. Upper limits are lower for most species at the two locations in Southern Highlands Province. The same phenomenon occurs throughout that province and probably reflects high cloud cover and infertile soils.[7] The upper limits for most species are particularly high in the upper Chimbu Valley (Table 8) and many of the extreme upper altitudinal figures in Tables 1-6 were observed in this valley.

7 This suggests that there is an interaction between certain environmental factors, such as temperature and soil fertility, with a good value in one factor able to compensate to some degree for a poor value in another.

Table 8. The usual altitudinal limit of 12 crops at 10 locations between 1600 m and 2500 m in PNG[1]

Scientific name	Common name	PNG mean[2]	NAN	KTU	ASA	SIN	GUM	U/S	HGN	LAI	MEN	NEM
Arachis hypogaea	Peanut	1840	1750	1940	1880	1760	1770	1920	1800	1870	1810	1810
Carica papaya	Pawpaw	1700	1690	1730	1730	1790	1770	1790	1740	1780	1790	1750
Coffea arabica	Arabica coffee	2070	2280	2080	2050	2060	2170	2390	2080	2150	2030	1990
Manihot esculenta	Cassava	1820	1800	1830	2030	1950	2010	2000	1990	1900	1880	1700
Musa cvs	Banana	2160	2370	2120	2010	2260	2310	2460	2280	2220	2260	2280
Pandanus conoideus	*Marita* pandanus	1720	1800	1670	1780	1870	1830	1940	1820	1780	1640	1670
Pandanus jiulianettii	*Karuka* pandanus	1780	2020	1690	1850	1730	1870	1960	1820	1860	1700	1820
Persea americana	Avocado	2060	2280	2090	1900	1960	2190	2430	2010	2260	2030	1920
Psidium guajava	Guava	1840	1800	1780	1730	1940	2020	1930	1820	1900	1790	1700
Psophocarpus tetragonolobus	Winged bean	1910	2050	2040	2020	1870	2020	2050	2000	1910	1810	1810
Saccharum edule	Lowland *pitpit*	1810	1750	1840	1670	1920	2120	1920	1910	1870	1790	1710
Xanthosoma sagittifolium	Chinese taro	2020	2040	2150	2050	1970	2060	2130	2130	2000	2030	1980
Mean		1890	1970	1910	1890	1920	2010	2080	1950	1960	1880	1850

1. Locations are: Nankina Valley and Teptep area, Huon Peninsula, Madang and Morobe provinces; Kainantu area, Eastern Highlands Province; Asaro Valley, Eastern Highlands Province; Sinasina area, Simbu Province; Gumine area, Simbu Province; upper Chimbu Valley, Simbu Province; Mount Hagen and Bukapena areas, Western Highlands Province; Lai Valley, Enga Province; Mendi Valley, Southern Highlands Province; Nembi Plateau and Nipa area, Southern Highlands Province.
2. The PNG mean is the mean usual limit, with means rounded to 10 m, not 50 m as in Tables 1 to 6. Figures for *Pandanus jiulianettii* are the usual lower limit. Figures for the other species are the usual upper limit.

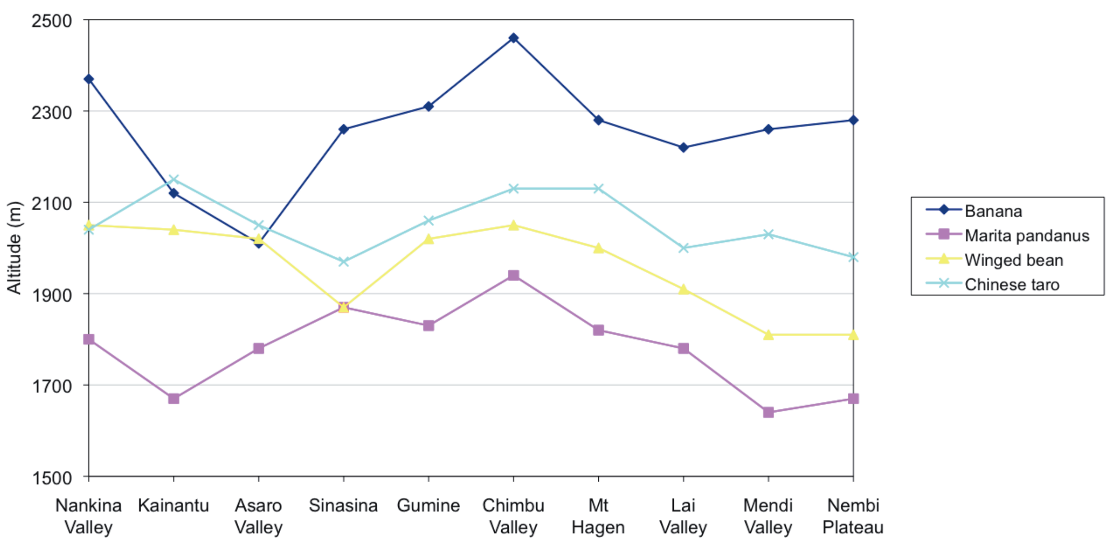

Figure 4. The usual upper altitudinal limits of four food crops at 10 locations in PNG

Table 9. The usual upper altitudinal limit of five crops at 15 locations between 700 m and 1400 m in PNG

Scientific name	Areca catechu	Artocarpus altilis	Cocos nucifera	Pangium edule	Terminalia kaernbachii
Common name	Betel nut	Breadfruit	Coconut	*Sis*	*Okari*
PNG mean[1]	1080	1240	960	1060	1080
Bougainville Island	–	–	730	–	–
Baining Mts, ENB	840	–	750	–	–
Lelet Plateau, NIP[2]	960	–	<960	–	–
Managalas Plateau, ORO	940	–	920	890	980
Kokoda Trail, CEN	–	970	830	970	–
Pindiu area, MOR	1190	1300	1190	–	1020
Kabwum area, MOR	1180	1180	970	–	–
Snake Valley, MOR	1000	1020	1020	–	950
Wau area, MOR	1160	1210	1160	–	1000
Slate Creek Valley, MOR	1170	1280	1130	1230	1260
Tauri Valley, GUL	930	1330	<1200	1180	1130
Tauta, MAD	1110	1110	1010	1040	<1060
Bundi area, MAD	1390	1390	1250	1380	–
Erave area, SHP	1080	1250	1080	–	1110
Elip Valley, SAN	1270	1310	<1270	–	–

1. The PNG mean is the mean usual upper limit given in Tables 1, 5 and 6, rounded to 10 m, not 50 m.
2. Data from the Lelet Plateau differ from those from other locations because observations there are only from the narrow altitudinal range where hamlets and food gardens are located (950-970 m). Thus, betel nut bears at 960 m on Lelet Plateau, but it would possibly bear if planted at a higher altitude. Coconut bears only infrequently at 960 m there, thus the usual altitudinal limit is given as less than 960 m. For the other locations, observations were made over a range of altitudes greater than the local limits for these crops. However, settlement and food gardens are less dense here than in the central highlands of PNG and this is why the limits for any locality for these crops often tend to be grouped in a more restricted range in this dataset compared with locations in Table 8.

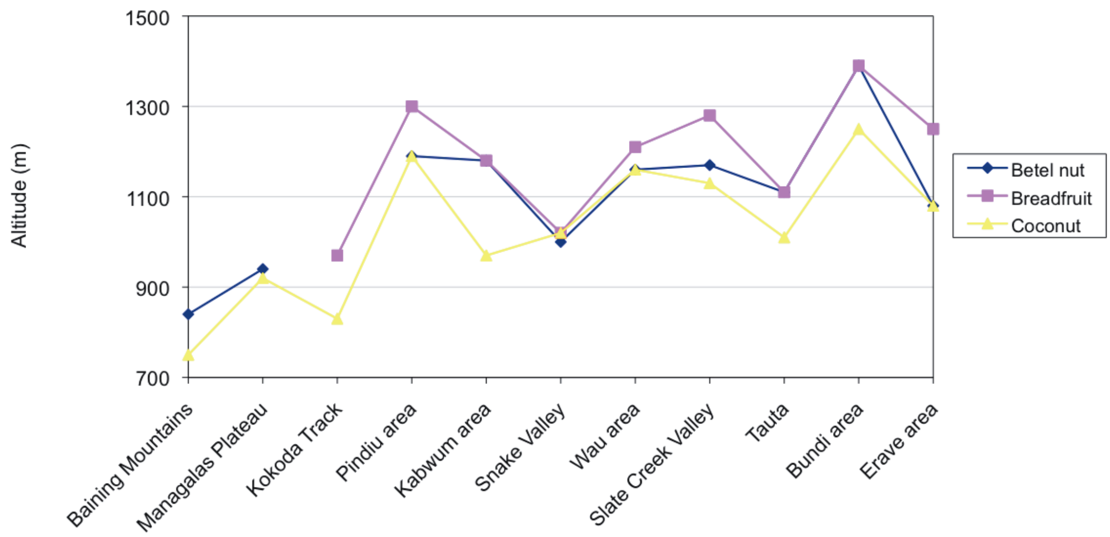

Figure 5. The usual upper altitudinal limits of three crops at 11 locations in PNG

There is a greater difference in usual upper altitudinal limits among locations on smaller island ranges and the main ranges of New Guinea (Table 9, Figure 5). On the small islands of Bougainville, New Britain and New Ireland, the limits are lower than on the large island of New Guinea. Limits are also lower on the Managalas Plateau and Kokoda Trail. This probably reflects the fact that these two places are further south (about 9° S) and thus experience somewhat lower temperatures in the middle of the year.

The comparison between altitudinal limits in the Snake Valley, Wau area and Slate Creek Valley illustrates microclimatic differences. These locations are close to one another (Figure 1). The Slate Creek Valley and Wau area are broad valleys, with predominantly grasslands on the valley floor. In contrast, Snake Valley is narrower and the dominant vegetation is forest. The upper altitudinal limits for crops are generally lower in Snake Valley than in the other two (Table 9, Figure 5). Presumably, the broader grassland valleys have a slightly higher maximum temperature than the narrower forested valley and this is reflected in the crop limits.

Influence of cultivars on species limits

Data presented here are generally at the species level. It is implicit that these observations are for the cultivars presently grown in PNG. However, other cultivars may have somewhat different limits, as it is well established that cultivars do not have the same tolerance of temperature extremes. See, for example, Laing et al. (1983:243) on common bean (*Phaseolus vulgaris*) and Wu et al. (1974) on sweet potato. Data presented here give some indication of cultivar-temperature interactions in PNG. For example, triploid bananas grow to a mean of 350 m higher than diploid cultivars (Table 1).

Recognition of altitudinal divisions

For a number of locations in the highlands and highlands fringe, it has been documented that villagers distinguish with separate terms 'warmer' and 'cooler' zones, based in part on crop altitudinal limits. Some examples of these breaks are: in the Karimui area of Simbu Province, where people recognise a break at about 1100 m (Hide et al. 1984:17, 211); in the Bundi area on the other side of the main ranges, where a break is known at 1450 m (author's field work, 1984); in the Marigl Valley of Simbu Province, where people speak of a break at about 1850 m (author's field work, 1988); in the Lai Valley in Enga Province, where villagers recognise an ecological break also at 1850 m (Meggitt 1958:314); and in the Sinasina area of Simbu Province, where the villagers note an ecological break at about 2100 m (Hide et al. 1979:5).

It is likely that this perception of a warmer and cooler zone dichotomy based on crop performance and altitudinal limits is widespread within the PNG highlands and that the actual altitude of the ecological break varies between locations. Such breaks are probably more commonly recognised where a number of important species have usual upper or lower limits in a narrow range, particularly at about 1800 m (Figure 3).

Crop altitudinal limits in PNG and some other equatorial countries

It is difficult to compare altitudinal limits between an equatorial location, such as PNG, and a non-equatorial location because of the confounding influence of latitude on temperature and crop growth. However, cautious comparisons are possible with other equatorial locations; for example, maize and sweet potato (Table 10) and a number of crop species that are common to both PNG and Indonesia (Table 11).[8]

8 Sources for data from Indonesia do not indicate where the data comes from, but it is almost certainly not from Papua (Indonesian New Guinea).

Table 10. The usual and extreme upper altitudinal limits of maize and sweet potato in a number of countries

Country		Maize		Sweet potato	Source
	Usual	Extreme	Usual	Extreme	
Kenya[1]	1850	2450	1850	–	Morgan (1968:274)
Rwanda	2000	–	–	–	Ford (1990:45)
Ethiopia	2100	2400	–	–	Alkämper (1973:30)
East Africa[2]	–	–	2100	2400	Jana (1982:68)
Papua New Guinea	2450	2700	2700	2850	This paper
Peru	3100	>3100	–	–	Brush (1976:158)
Ecuador	3200	–	–	–	Stadel (1986:57)
Bolivia[1,3]	2450	3650	2750	>2750	Yen (1974:151)
Tibet Plateau, China	3200	–	–	–	Yu and Sun (1981)

1. Figures given by Morgan (1968) and Yen (1974) were in thousands of feet.
2. Jana's discussion covers Kenya, Tanzania and Uganda.
3. The extreme altitudinal limit for maize given by Yen (1974) is for Bolivia and Peru. His extreme limit for sweet potato is for Bolivia and Ecuador.

Table 11. The usual altitudinal range of eight crops in Indonesia and PNG

Scientific name	Common name	Usual altitudinal range (m)		Indonesian source
		Indonesia	PNG	
Dioscorea alata	Greater yam	0–800	0–1900	IBPGR (1981a:53) Ochse and Brink (1977:231)
Artocarpus altilis	Breadfruit	0–1000	0–1250	IBPGR (1980:21)
Psidium guajava	Guava	0–1200	0–1850	IBPGR (1980:109)
Leucaena leucocephala	Leucaena	0–1500	0–1800	Ochse and Brink (1977:393)
Psophocarpus tetragonolobus	Winged bean	0–1500	0–1900	IBPGR (1981b:89)
Cyphomandra betacea	Tree tomato	250–1700	1050–2300	IPBGR (1980:53)
Zingiber officinale	Ginger	0–1700	0–1950	IBPGR (1981a:101)
Vicia faba	Broad bean	>1300	2050–2650	IBPGR (1981b:111)

For maize, sweet potato and some other crops for which data are available (such as cassava), altitudinal limits are generally higher in PNG than in East African locations. The PNG limits are generally lower than those in the Andes of South America (Table 10). Limits are generally much higher in PNG than in Indonesia (Table 11). These differences are again a likely reflection of the mass mountain heating effect. The mountains of the Andes are more massive than the New Guinea mountains, which in turn are larger than the ranges of the Indonesian islands. This is consistent with observations from within PNG, where altitudinal limits are higher on the island of New Guinea than on the smaller islands of Bougainville, New Britain and New Ireland (Table 9).

Impact of climate change on crop limits

Most observations reported here were made in the early 1980s. Thus, they provide baseline data on crop growth that can be used in the future to assess the impact of increasing temperature associated with global climate change.

An analysis of changes in temperatures up to 1999 was made for nine coastal stations by Bourke et al. (2002). They found that maximum, mean and minimum temperatures increased in the PNG lowlands by a mean of 0.6°C between 1970 and 1999; that is 0.2°C per decade. Datasets that covered a longer period, from 1904 in the case of Port Moresby, indicated that increases in temperature had been greater from the mid 1970s onwards, which is consistent with the global pattern. The only highland station for which good quality long-term data were available was Aiyura (1640 m) in Eastern Highlands Province. There, the maximum temperature increased by 0.75°C over the period 1977-2001, a rate of 0.3°C per decade.

In the period 1980-1982, coconut palms grew at altitudes as high as 1760 m, but the highest palms that bore nuts were at 1310 m. By 1999, coconut palms were bearing as high as 1450 m.[9] The increase in the altitude at which coconuts bore nuts was 140 m over a 20-year period, which suggests that temperatures increased by about 0.7°C over this period. This is consistent with the recorded increase in temperature at Aiyura between 1977 and 2001. By mid-2009, coconut palms were bearing small nuts near Goroka, at 1560 m. This was 110 m higher than the highest recorded bearing palms 10 years earlier. Presuming this difference was caused by increasing temperatures, and this is the most likely explanation, this implies a temperature increase of 0.57°C in 10 years – an extremely high rate of increase. This suggestion needs to be checked against long-term temperature data, which are available from Aiyura.

The recorded increase in the altitude at which coconut palms bear is also consistent with observations by many villagers that coconut, betel nut, breadfruit and other tree crops were bearing at higher altitudes in the 1990s and 2000s than in the 1970s and 1980s. At Nokopo village on the Huon Peninsula in Morobe Province, people claim that the climate warmed during the 1980s. They cite the facts that they could plant *marita* pandanus (*Pandanus conoideus* complex) in this period for the first time; that certain species of birds occupied higher-altitude locations; and that there had been an increase in altitude at which a certain palm could be grown (Kocher Schmid 1991:27).

Bananas also provide evidence of the impact of increasing temperature in the highlands. Up to the end of 1978, bananas were not grown at Tambul (2300 m) in Western Highlands Province. From the mid-1980s onwards, people started to plant bananas, which bore fruit in that area (M. Gunter pers comm. 2001).

These limited observations indicate increasing temperature in the New Guinea highlands. As temperatures continue to increase in the coming decades, the observations reported here, particularly the detailed observations at named locations, can be used to assess the rate of increase (Tables 8 and 9).

Acknowledgements

Most of the observations reported here were made while I was employed by the PNG Department of Primary Industry (1978-1983). Some were made while I was supported by the Department of Human Geography in the Research School of Pacific Studies at the Australian National University. This Department provided support for compilation of the work.

Many villagers shared their often extensive knowledge of where plants grow. A number of agriculturalists and other observers also gave information on the distribution of crop plants, particularly Bruce French, Robin Hide and Tevo Tarepe. Others who assisted were Will Akus,

9 See Footnote 3, Table 5 for more detail.

Chris Ballard, Vern Berley, Bruce Carrad, Euclid D'Souza, Geoff Hope, Ger Reesink, Jack Simpson, Clement Tumana and Steve Woodhouse. David Evesson of the National Weather Bureau in Port Moresby advised on air pressure in PNG. Staff of the Division of Botany in Lae gave access to altitude data in their collection records and were unfailingly helpful, particularly Jim Croft, Ted Henty and Karl Kerenga, in identifying plants. Diseased specimens were identified by plant pathologists of the Department of Primary Industry. Robin Hide and Geoff Humphreys commented on an earlier draft, and two referees offered helpful suggestions. Tracy Harwood and Sandra Davenport edited the paper. It is a pleasure to acknowledge the assistance of all those named above.

Appendix 1. Lapse rates in Papua New Guinea

Temperature in PNG declines with increasing altitude (McAlpine et al. 1983:92). The rate of decline is termed the lapse rate. A number of authors have calculated lapse rates for PNG. I have recalculated them here because more accurate information is now available on the altitude of weather stations. (Earlier figures underestimated true altitudes by up to 100 m.) As well, more long-term data has became available for some stations, particularly in the altitude range of 2000-3000 m.

Previously published information on lapse rates for PNG is firstly summarised. Fitzpatrick (1965) and McAlpine (1970) quoted a general lapse rate of 5.5°C per 1000 m. McAlpine et al. (1983:91-95) gave a lapse rate of 6.7°C for mean maximum temperature and 5.4°C for mean minimum temperature for stations above 500 m altitude. The altitudes used by these authors were generally too low. Humphreys (1981a), using corrected altitude figures, calculated 36 lapse rates for non-coastal locations of mainland PNG. In a later publication, he gave lapse rates for a narrow strip that covers Simbu Province (Humphreys 1984:26-30). Researchers at the Centre for Resource and Environmental Studies at the Australian National University devised a computer program that generates lapse rate surfaces for all of the island of New Guinea. This provides estimates of maximum and minimum temperatures as a function of latitude, longitude and altitude (H. Nix, pers comm. 1988).

Humphreys (1981b) calculated a theoretical lapse rate for soil at 50 cm depth in PNG. Dronia (1983) recorded soil temperatures at various depths and altitudes in three regions of PNG. He gave the lapse rate at a depth of 50 cm as 4.6°C per 1000 m between sea level and 2600 m and commented that this value is probably one of the lowest soil lapse rates on earth.

Temperature data covering a minimum of three years are available from 31 non-coastal locations in PNG. All except Panguna are located in the eastern half of the island of New Guinea and are a minimum of 20 km from the ocean. The 30 stations on New Guinea lie between latitudes of 3°30' S and 8°40' S and between longitudes of 141°40' E and 148°20' E. Mean temperatures for these non-coastal stations are presented in Table A1.

The relationship between altitude and mean maximum/minimum temperature is shown in Figure A1. The moderating influence of the ocean is apparent for coastal locations. The mean maximum temperatures for coastal locations are less than those for non-coastal low-altitude locations. The mean minimum temperatures are greater than those for non-coastal low-altitude locations. For non-coastal locations, there is a regular linear decline in temperature with increasing altitude. This decline in temperature may be expressed as a series of equations, as follows:

$$Y_{max.} = 32.67 - 0.0052\,x \qquad r = 0.958^{***}$$

$$Y_{ann.} = 27.32 - 0.0052\,x \qquad r = 0.983^{***}$$

$$Y_{min.} = 22.08 - 0.0052\,x \qquad r = 0.979^{***}$$

where: $Y_{max.}$, $Y_{ann.}$ and $Y_{min.}$ are mean maximum, mean annual and mean minimum air temperatures (°C) respectively (31 locations)
x is the altitude in metres
r is the regression coefficient.

All three regressions are highly significant ($P<0.001$) and explain between 92 and 97 per cent of the variation. These regressions are similar to those derived by Humphreys (1981a). The lapse rates are 5.2°C per 1000 m. This is somewhat lower than many other locations on the globe, as the mean global lapse rate is about 6°C per 1000 m (Giddings 1980:17).

For the two non-coastal stations located in either coastal ranges (Lumi in Sandaun Province) or on an island range (Panguna on Bougainville Island), the mean maximum temperature is lower than for locations on the fringe of the central highlands of New Guinea (Figure A1). McAlpine et al. (1983:94) suggested that data from these two locations indicate that maximum (but not minimum) temperatures are depressed in isolated coastal and island ranges. However, observations on crop altitudinal limits from locations on the northern side of the mountainous Huon Peninsula, including the Nankina Valley and Teptep area, suggest that temperatures are high for the altitude in those locations (Table 8). Thus the observations from the Huon Peninsula contradict the hypothesis of McAlpine et al. (1983). Observations made on crop altitudinal limits in island ranges on New Britain, New Ireland and Bougainville islands indicate that temperatures are lower at any given altitude than on the island of New Guinea, and this is consistent with the temperature recordings from Panguna (Table 9).

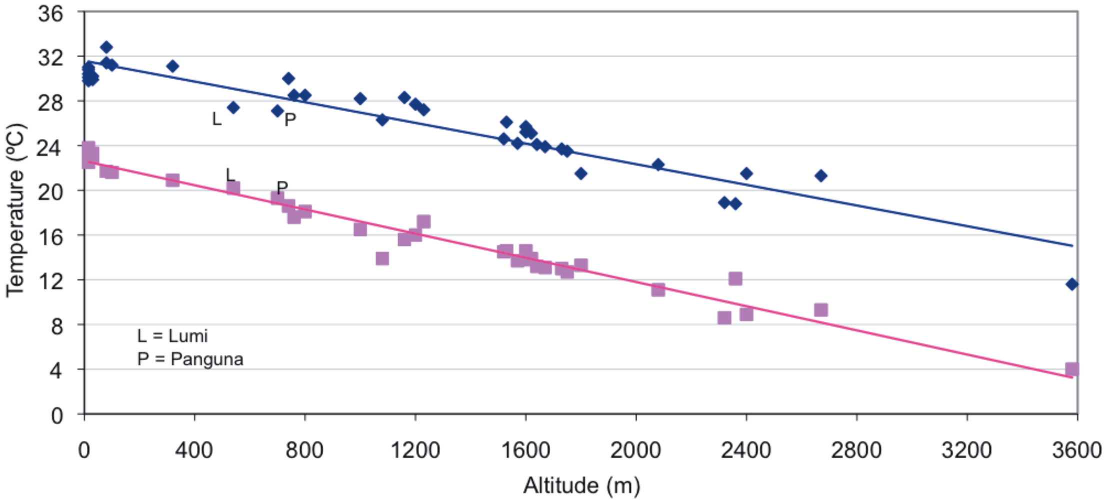

Figure A1. Mean maximum and minimum temperatures for seven coastal and 31 non-coastal locations in PNG, by altitude

Appendix 2. The influence of altitude on crop development and yield in Papua New Guinea

As well as setting limits to crop growth, altitude (that is, temperature) influences the rate of crop development and yield. There is very little information from PNG about the relationship between altitude and crop development or yield. Detailed studies, such as that done by Cooper (1979) which examined the influence of altitude on maize growth in Kenya, and that done by Laing et al. (1983) on the effect of altitude on *Phaseolus* beans in Colombia, have yet to be done in PNG.

It is widely recognised within PNG that crops require more time to attain maturity in the cooler highlands than in lowland locations. It is not generally recognised that the final crop yield per unit area is commonly higher in the highlands than in the lowlands. For example, an experimental yield for sweet potato of 20 tonnes per hectare (t/ha) would be considered high in the lowlands. In contrast, experimental yields at highland locations of 20-30 t/ha are not uncommon. This occurs because there is a longer period available for the plant to accumulate carbohydrate during its growth cycle in the highlands.

In this appendix, the available information on the influence of altitude on crop development and yield is brought together and summarised. Information is provided for the following crop species:

Arabica coffee	*Coffea arabica*
Marita pandanus	*Pandanus conoideus*
Potato	*Solanum tuberosum*
Pyrethrum	*Chrysanthemum cinerariaefolium*
Sweet potato	*Ipomoea batatas*

Arabica coffee

Despite the importance of Arabica coffee to the PNG economy and the wide altitudinal range over which it is grown (700-2050 m), very little is known about the influence of altitude on its growth. It has been observed by some that the harvesting season starts later at higher altitudes. For example, Joughin and Thistleton (1987:23), following a rapid rural appraisal, state that this is the case in the Jimi Valley over an altitudinal range of about 1400-2000 m. In that location, coffee harvesting is reported to start in April-May in the lower part of the valley, in May-June in the middle valley, and in July-August at higher locations. Similarly, in the Asaro Valley west of Goroka, the main coffee flush is reported as July-August at 1600 m, but in August-September at 1800-2000 m (B. Carrad, pers comm. 1990).

Marita pandanus

Marita pandanus is grown from just above sea level to a mean upper limit of 1700 m in PNG (although it is generally not grown adjacent to the ocean) (Table 4). Information on fruiting seasons of *marita* pandanus at 25 different locations in PNG was assembled by Bourke et al. (2004:155, 198). These data are qualitative not quantitative, except for those from the four highest locations. As well, the timing and duration of the fruiting season varies somewhat between years. Despite these limitations, the available information indicates a strong negative linear relationship between the length of the fruiting season and altitude. Near sea level, the fruit are available year round. The cropping season starts later in the year and is shorter at higher altitudes. Towards the top of the crop altitudinal range, the fruiting season is limited to four months.

The relationship between the length of the fruiting season and altitude can be expressed as follows:

$$Y = 10.01 - 0.004x \qquad r = 0.6542^{**}$$

where: Y is the fruiting season in months
x is the altitude in metres
r is the regression coefficient.

The relationship is highly significant and explains 43 per cent of the variation. When two outlying data points are excluded, the relationship becomes much stronger and explains 89 per cent of the variation. See Figure 92 in Bourke et al. (2004) and its reproduction in a modified form in Figure 1.13.4 by Allen and Bourke (2009).

Potato

In Simbu Province, Goodbody (1982) compared the performance of six cultivars of *Solanum* potato at two altitudes. At 1500 m, the crops needed 81-93 days to mature, whereas at a higher-altitude location (2400 m), they required a longer period (101 days). For all six cultivars, mean tuber weight was greater at 1500 m than at 2400 m. However, for five of the six cultivars, more tubers developed per plant at the higher-altitude location. This resulted in a higher yield per hectare at the higher location.

Pyrethrum

By 1980, pyrethrum cultivation was restricted to locations above 2400 m, but when the crop was first introduced to PNG villagers in the late 1960s, it was grown as low as 1800 m. Data on yields from village plantings in the 1960s from five locations in Enga were presented by Quinlan (1968). The mean yield of flowers harvested per eight months has been plotted against corrected altitudes (Figure A2). This shows a striking positive relationship between flower yield and altitude. These data show that mean yields at 2700 m are about three times greater than those at 1900 m. This suggests that the contraction of pyrethrum plantings by villagers from the 1970s onwards to locations above 2400 m occurred because yields are unacceptably low below this altitude.

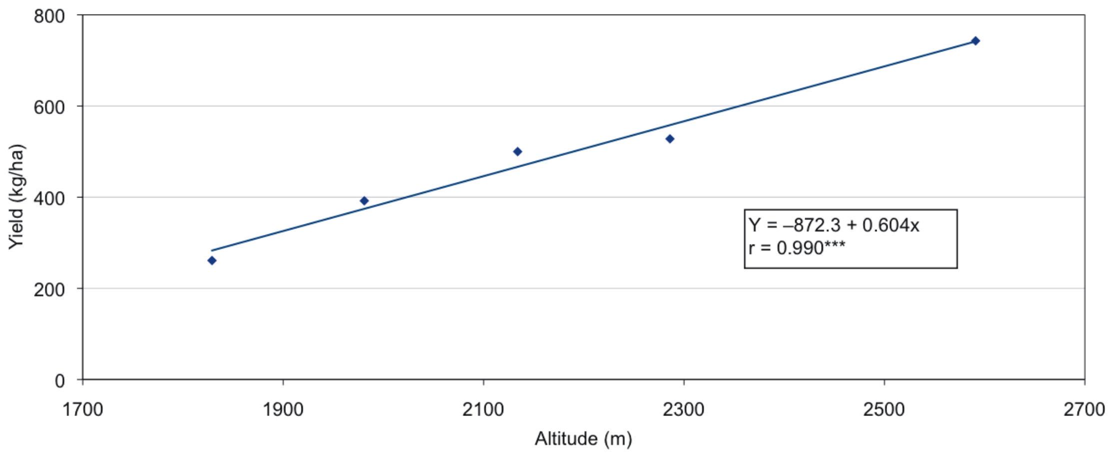

Figure A2. Yield of pyrethrum flowers over eight months in village plantings, Enga Province vs altitude (after Quinlan 1968)

The linear regression between pyrethrum flower yield and altitude is:

$$Y = -872.3 + 0.604x \qquad r = 0.990^{***}$$

where: Y is the yield of dried flowers in kg/ha
x is the altitude in metres
r is the regression coefficient.

The statistical relationship is very highly significant ($P < 0.001$) and explains 98 per cent of the variation.

Sweet potato

In Simbu Province, Goodbody (1984) recorded the time to first harvest and tuber yield from 72 village plantings of sweet potato over an altitudinal range of 1400 m to 2600 m. He found that the tuber yield was not related to altitude. However, the period to first harvest increased with increasing altitude. The relationship was as follows:

$$Y = -149 + 0.19x \qquad r = 0.86^{**}$$

where: Y is the number of days to first harvest
x is the altitude in metres
r is the regression coefficient.

The relationship suggests that sweet potato would mature at sea level (x = 0) at 149 days before it was planted. Clearly this is not true and the linear regression found by Goodbody does not hold over the entire altitudinal range of sweet potato in PNG (sea level to 2850 m).

Appendix 3. Recording the altitude of locations in Papua New Guinea

The purpose of this note is to explain how to record the altitude of locations within PNG with reasonable accuracy. The most convenient method for recording altitude is to use an altimeter. However, altimeters measure air pressure, not altitude. Hence, it is necessary to adjust the instrument before it is used. It is also helpful to make certain corrections to ensure that the reading taken from the instrument is as accurate as possible.

The altitudes given on older maps and on signposts for many locations in PNG are frequently incorrect. This is because the readings are based on uncorrected readings taken from aircraft altimeters.

Adjusting the instrument

Altimeters can be adjusted so that the instrument reading is the same as the altitude of a known point. This is known as 'zeroing'. The altitudes of locations in PNG can be obtained from trigometric points or spot heights marked on the 1:100 000 topographic maps. For example, the trigometric point at Kundiawa airstrip is at exactly 1525 m above sea level. So persons working out of Kundiawa should adjust their altimeters to 1525 m at the airstrip or the government offices in Kundiawa before leaving town. The altitudes of some urban areas in the highlands are given in Table A2.

Correcting the reading

A good quality altimeter gives a reasonably accurate measure of the altitude of a location, provided that it has been correctly adjusted at a point of known altitude. However, there are still other sources of error that may influence the reading. It is possible to make corrections for these so that the reading is accurate to within plus or minus 20 m of the actual altitude of a location.

There are three sources of error in altimeter readings:

- Pressure surface flows into mountains;
- The effect of daily variation in air temperature on air pressure;
- Rapid changes in air pressure, often associated with storms.

Pressure surface flows

Air is constantly being forced into the highlands. The effect of this is to increase air pressure slightly. Hence, altimeter recordings are somewhat lower than they would be if this was not occurring. So even if an altimeter is adjusted accurately at sea level, the instrument will give a slightly low reading when it is taken into the highlands. This is the reason that many altitudes quoted for highland locations are too low.

I have found that it is possible to correct for pressure surface flows using a simple formula. The formula is accurate at least between sea level and 3000 m. The correction factor follows.

For locations higher than where an instrument was adjusted, add 10 m to the reading for every 200 m you have risen above where the instrument was zeroed. For example, on a flight between Lae and Goroka, an altimeter is adjusted to zero at Lae airstrip. When the aircraft reaches the hangar in Goroka, the altimeter is reading 1520 m. The correction factor is:

$$\frac{(1520 - 0) \times 10}{200} = 80 \text{ m}$$

So add 80 m to the reading of 1520 m to obtain the corrected reading of 1600 m. (The correction factor is rounded to the nearest 10 m.)

For places lower than where the instrument was adjusted, subtract 10 m from the reading for every 200 m you have descended since the instrument was zeroed. For example, if you zero your instrument at 1740 m on Mendi airstrip and then fly by helicopter into a village where the instrument reads 1320 m, the correction factor is:

$$\frac{(1740 - 1320) \times 10}{200} = 20 \text{ m}$$

So the corrected reading is 1320 – 20 = 1300 m.

When travelling between locations of known altitude over short periods, I have found that use of this correction factor gives a corrected altimeter reading that is generally accurate to within plus or minus 10 m of the true altitude.

Daily variation in air temperature

Changes in air temperature also influence air pressure and hence altimeter readings. Because temperature varies during the day, there is generally a daily cycle in instrument recordings. If an altimeter is kept in one location and read at hourly intervals, the pattern will be similar to that shown in Figure A3. (These recordings were made in Kundiawa at 1550 m. The instrument was not moved during the day.) During the early morning, there is little change in the instrument readings. Between late morning and early afternoon the reading rises fairly rapidly. Typically, the greatest change occurs between about 11 am and 2 pm. The reading is fairly steady between mid and late afternoon. It then declines steadily until late at night. The instrument reading increases and decreases by 20 m to 30 m during a typical day in the highlands.

It is possible to adjust for this source of error by adjusting the instrument at a location of known altitude. This is best done in the early afternoon when the effects of changes in air temperature have stabilised. In practice, it is often not possible to adjust the instrument during field work because the exact altitude of locations will not be known. However, it is still possible to make a crude adjustment.

To do this, record the time of day that any altitude recordings are made. Also record the instrument reading when you return to your base at the end of the day. The reading will typically be 20-30 m greater than when you adjusted the instrument at the base in the morning. Assume that this increase occurred evenly between 11 am and 1-2 pm and adjust the field recordings accordingly. For example, you set your instrument to 2080 m at Wabag at 8 am. When you return to Wabag at 4 pm it is reading 2110 m; that is, the reading is 30 m higher. So deduct

10 m from any recordings made between 11 am and noon, deduct 20 m from any recordings made between noon and 1 pm and deduct 30 m from any recordings made after 1 pm.

Rapid changes in air pressure

In general, air pressure is quite stable in PNG. However, large changes in air pressure sometimes occur, often associated with low-pressure fronts and storms. These rapid changes in air pressure will markedly affect an altimeter reading. Just before a storm there is sometimes a rapid drop in air pressure and this results in an increase in the instrument reading. There is no simple correction for this unless one maintains a base recording station. In practice, however, sudden changes in air pressure and hence in altimeter readings are not common in PNG. But these changes in air pressure highlight the need for instruments to be adjusted correctly at a point where the altitude is known before they can be used to record the altitude of other places.

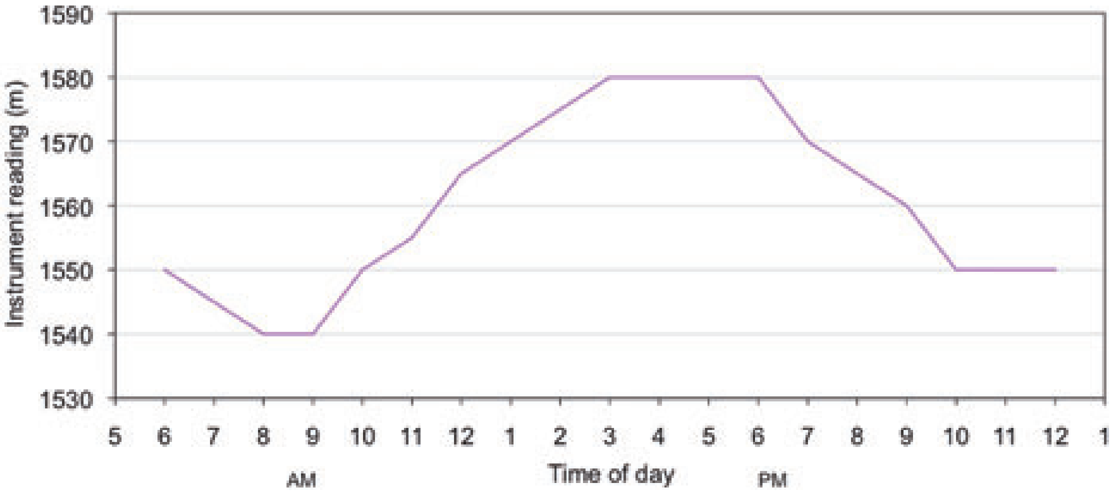

Figure A3. A typical pattern for hourly altimeter readings for a highland location during the course of the day (where the instrument is not moved)

Conclusion

An altimeter can be used in PNG to record the altitude of locations usually within an accuracy of plus or minus 20 m of the actual altitude. It is necessary for the instrument to be adjusted before use at a location where the altitude is known accurately.

The recordings obtained are highly accurate only when taken soon after adjusting and only at similar altitudes to the point where the instrument was adjusted. When the instrument is used several hours after adjustment and more than 200 m higher or lower than the point of adjustment, it is necessary to make certain corrections to allow for this. When these corrections have been made, recordings are generally within plus or minus 20 m of a location's actual altitude.

Table A1. Mean annual temperatures for non-coastal stations in PNG

Station[1]	Altitude (m asl)	Annual temperature (°C)			Source[2]
		Mean max.	Mean annual	Mean min.	
Aiome	80	31.4	26.5	21.7	1
Erap	80	32.8	27.2	21.7	1
Popondetta	100	31.2	26.4	21.6	1
Kaiapit	320	31.1	26.0	20.9	1
Lumi	540	27.4	23.8	20.2	1
Panguna	700	27.1	23.2	19.3	2
Bulolo Forestry College	740	30.0	24.3	18.6	1
Garaina	760	28.5	23.0	17.6	1
Lake Kutubu	800	28.5	23.3	18.1	1
Wau Forestry	1000	28.2	22.3	16.5	1
Erave	1080	26.3	20.1	13.9	1
Baiyer River	1160	28.3	21.9	15.6	1
Menyamya	1200	27.7	21.8	16.0	1
Wau Ecology Institute	1230	27.2	21.1	17.2	3
Telefomin	1520	24.6	19.6	14.5	1
Kundiawa	1530	26.1	20.4	14.6	1
Kainantu	1570	24.2	19.0	13.7	1
Goroka	1600	25.7	20.1	14.6	1
Minj	1600	25.2	19.5	13.8	1
Kagamuga	1620	25.1	19.5	13.9	1
Aiyura	1640	24.1	18.6	13.2	1
Tari	1670	23.9	18.5	13.1	1
Mount Hagen	1730	23.7	18.3	13.0	1
Mendi	1750	23.5	18.1	12.7	1
Mount Kaindi	1800	21.5	16.4	13.3	3
Wabag	2080	22.3	16.7	11.1	1
Tambul	2320	18.9	13.8	8.6	4
Mount Kaindi	2360	18.8	14.7	12.1	3
Toromambuno	2400	21.5	15.2	8.9	5
Yumbisa (Wage V, Enga)	2670	21.3	15.4	9.3	6
Mount Wilhelm	3580	11.6	7.8	4.0	7

1 The altitudes of stations were obtained from the 1:100 000 map sheets or adjusted altimeter recordings made by the author.

2 Sources used for temperature data are as follows:

1. McAlpine, Keig and Short (1975)
2. N.A. Marshman, Bougainville Copper Ltd (pers comm. 1982)
3. Gressitt and Nadkarni (1978:8)
4. A. Menge-Nang (pers comm. 1982)
5. Humphreys (1984:104)
6. Wohlt and Humphreys (1981)
7. Hnatiuk, Smith and McVean (1976)

Table A2. Altitudes of some urban areas and airstrips in the PNG highlands

Location[1]	Altitude (m)
Aiyura airstrip	1640
Goroka airstrip	1600
Kagamuga airstrip (Mount Hagen)	1620
Kainantu airstrip	1570
Kandep airstrip	2360
Kundiawa airstrip	1525
Mendi airstrip	1740
Tambul (DPI station)	2320
Tari airstrip	1670
Wabag airstrip	2080
Wau (Katherine Lehman School)	1000

1. The altitudes given for airstrips are for the higher end for all locations. Some of these airstrips are no longer in use.

References

Alkämper, J. 1973. *Die Getreideproduktion Athiopiens: Stand, Leistung und Möglichkeiten für eine bessere Versorgung der Bevölkerung*. Abteilung Pflanzenbau und Pflanzenzüchtung in den Tropen und Subtropen. Gieβen: Tropeninstitut der Justus Liebig-Universität.

Allen, B.J. 1982. Subsistence agriculture: three case studies. In B. Carrad, D.A.M. Lea and K.K. Talyaga (eds) *Enga: Foundations for Development: Volume 3,* pp93-127. Armidale: University of New England.

Allen, B.J. and R.M. Bourke 2009. Part 1. People, Land and Environment. In R.M. Bourke and T. Harwood (eds) *Food and Agriculture in Papua New Guinea*, pp27-127. Canberra: The Australian National University.

Bayliss-Smith, T. 1985. Pre-Ipomoean agriculture in the New Guinea highlands above 2000 metres: some experimental data on taro cultivation. In I.S. Farrington (ed.) *Prehistoric Intensive Agriculture in the Tropics*, pp285-320. Oxford: British Archaeological Reports International Series 232.

Bayliss-Smith, T. 1988. Prehistoric agriculture in the New Guinea highlands: problems in defining the altitudinal limits to growth. In J.L. Bintliff, D.A. Davidson and E.G. Grant (eds) *Conceptual Issues in Environmental Archaeology*, pp153-160. Edinburgh: Edinburgh University Press.

Bourke, R.M. 1984. The altitudinal range of coffee and some associated shade crops in Papua New Guinea. *Coffee Industry Board Research Newsletter* 3(1):7-12. Goroka: Coffee Industry Board.

Bourke, R.M. 1988. Gumine Land Use Workshop: Consultant's Report. Kundiawa. South Simbu Rural Development Project.

Bourke, R.M. 2009a. An overview of edible fruit and nuts in Papua New Guinea. *Proceedings of Papua New Guinea Fruit and Nut Workshop*. NARI Conference Proceedings No 9. Lae: National Agricultural Research Institute.

Bourke, R.M. 2009b. History of agriculture in Papua New Guinea. In R.M. Bourke and T. Harwood (eds) *Food and Agriculture in Papua New Guinea*, pp10-26. Canberra: ANU E Press, The Australian National University. http://epress.anu.edu.au/food_agriculture_citation.html

Bourke, R.M. In press. Environmental influences on food crop distribution and production in Papua New Guinea. In J. Golson, T. Denham, P. Swadling and J. Muke (eds) *Ten Thousand Years of Gardening in the New Guinea Highlands*.

Bourke, R.M. and D.A.M. Lea 1982. Subsistence horticulture. In B. Carrad, D.A.M. Lea and K.K. Talyaga (eds) *Enga: Foundations for Development: Volume 3*, pp76-92. Armidale: University of New England.

Bourke, R.M. and T.N. Tarepe 1982. Locations for commercial citrus production in Papua New Guinea. *Harvest* 8(4):147-155. Port Moresby: Department of Primary Industry.

Bourke, R.M., G.S. Humphreys and M. Hart 2002. Warming in Papua New Guinea: some implications for food productivity. Unpublished paper. Canberra: Department of Human Geography, Research School of Pacific and Asian Studies, The Australian National University.

Bourke, R.M., C. Camarotto, E.J. D'Souza, K. Nema, T.N. Tarepe and S. Woodhouse 2004. *Production Patterns of 180 Economic Crops in Papua New Guinea*. Canberra: Coombs Academic Publishing, The Australian National University, 213pp.

Bowers, N. 1968. The ascending grasslands: an anthropological study of ecological succession in a high mountain valley of New Guinea. Unpublished PhD thesis. New York: Columbia University.

Brookfield, H.C. 1964. The ecology of Highland settlement: some suggestions. *American Anthropologist* 66(4):20-38.

Brookfield, H. 1991. Research in the mountains of the island of New Guinea. *Mountain Research and Development* 11(3):203-211.

Brookfield, H.C. with D. Hart 1971. *Melanesia: A Geographical Interpretation of an Island World*. London: Methuen.

Brush, S.B. 1976. Man's use of an Andean ecosystem. *Human Ecology* 4(2):147-166.

Bull, P.B. and R.M. Bourke 1983. Growing introduced vegetables in the lowlands. [Articles 2 and 3]. *Harvest* 9(2):68-79. Port Moresby: Department of Primary Industry.

Bulmer, R.N.H. 1960. Leadership and social structure among the Kyaka people of the Western Highlands District of New Guinea. Unpublished PhD thesis. Canberra: Australian National University.

Cooper, P.J.M. 1979. The association between altitude, environmental variables, maize growth and yields in Kenya. *Journal of Agricultural Science* 93:635–649.

Cull, B.W. and T. Trochoulias 1982. Macadamias – environmental range for commercial production. In D. Noel (ed.) *Tree Crops: The Third Component. Proceedings of the First Australasian Conference on Tree and Nut Crops, Perth, Western Australia, 1982*, pp54-61. Perth: Cornucopia Press.

Dronia, H. 1983. Bodentemperaturmessungen in tropischen gebirgen: Virunga-Vulkane (Ruanda), Sierra Nevada (Kolumbien), Papua-Neuguinea. [Ground (soil) temperature measurements in tropical mountains]. *Erdkunde* 37:292-295.

Fitzpatrick, E.A. 1965. Climate of the Wabag-Tari area. In *General Report on Lands of the Wabag-Tari area, Territory of Papua and New Guinea, 1960-61*, pp56-69. Melbourne: Land Research Series No. 15. CSIRO.

Ford, R.E. 1990. The dynamics of human-environment interactions in the tropical montane agrosystems of Rwanda: implications for economic development and environmental stability. *Mountain Research and Development* 10(1):43–63.

French, B.R. 1986. *Food Plants of Papua New Guinea. A Compendium*. Tasmania: Published privately, Sheffield.

Gardner, R.O. 2003. Piper (Piperaceae) in New Guinea: the non-climbing species. *Blumea* 48(1):47-68.

Giddings, L.E. 1980. The physical environment of the highlands. In M. S. Mani and L. E. Giddings (eds) *Ecology of Highlands*. Monographicae Biologicae 40, pp11-34. The Hague, Boston and London: Dr W Junk.

Goodbody, S. 1982. The performance of Irish potato in the highlands. *Harvest* 8(3):123-125. Port Moresby: Department of Primary Industry.

Goodbody, S. 1984. Research Report of the Simbu Land Use Project Volume 3. Agronomy. Unpublished report. Kundiawa: Simbu Land Use Project.

Gressitt, J.L. and N. Nadkarni 1978. *Guide to Mt Kaindi: Background to Montane New Guinea Ecology*. Handbook No. 5. Wau: Wau Ecology Institute.

Haberle, S.G. 1993. Late Quaternary environmental history of the Tari Basin, Papua New Guinea. Unpublished PhD thesis. Canberra: The Australian National University.

Henty, E.E. 1969. *A Manual of the Grasses of New Guinea*. Botany Bulletin No. 1. Lae: Division of Botany, Department of Forests.

Henty, E.E. 1982. Some nut-bearing plants in Papua New Guinea. In R.M. Bourke and V. Kesavan (eds) *Proceedings of the Second Papua New Guinea Food Crops Conference. Part 3,* pp78-85. Port Moresby: Department of Primary Industry.

Henty, E.E. and G.H. Pritchard 1975. *Weeds of New Guinea and their Control*. Botany Bulletin No. 7. Lae: Division of Botany, Department of Forests.

Hide, R.L. with S. Goodbody and G. Gertru 1984. Agriculture. In R.L. Hide (ed.) *Research Report of the Simbu Land Use Project Volume 6. South Simbu: Studies in Demography, Nutrition, and Subsistence*, pp207-289. Port Moresby: Institute of Applied Social and Economic Research.

Hide, R., M. Kimin, A. Kora, G. Kua and K. Kua 1979. A Checklist of Some Plants in the Territory of the Sinasina Nimai (Simbu Province, Papua New Guinea), with Notes on their Uses. Working Paper No. 54. Auckland: Department of Anthropology, University of Auckland.

Hnatiuk, R.J., J.M.B. Smith and D.N. McVean 1976. *The Climate of Mt Wilhelm.* Mt Wilhelm Studies 2. Canberra: Department of Biogeography and Geomorphology Publication BG/4. Australian National University.

Howlett, D.R. 1962. A decade of change in the Goroka Valley, New Guinea: land use and development in the 1950s. Unpublished PhD thesis. Canberra: Australian National University.

Humphreys, G.S. 1981a. Lapse rates for Papua New Guinea. Unpublished paper. Kundiawa: Simbu Land Use Project.

Humphreys, G.S. 1981b. Soil temperature data for Papua New Guinea. Unpublished paper. Kundiawa: Simbu Land Use Project.

Humphreys, G.S. 1984. *The Environment and Soils of Chimbu Province, Papua New Guinea with particular reference to soil erosion.* Research Bulletin No. 35. Port Moresby: Department of Primary Industry.

Hynes, R.A. 1974. Altitudinal zonation in New Guinea Nothofagus forests. In J.R. Flenley (ed.). *Altitudinal Zonation in Malesia*, pp75-120. Department of Geography Miscellaneous Series No. 16. Hull: University of Hull.

IBPGR 1980. Fruits [in Indonesia]. Rome: International Board for Plant Genetic Resources.

IBPGR 1981a. Roots and Tuber Crops [in Indonesia]. Rome: International Board for Plant Genetic Resources.

IBPGR 1981b. Vegetables [in Indonesia]. Rome: International Board for Plant Genetic Resources.

Jana, R.K. 1982. Status of sweet potato cultivation in East Africa. In R.L. Villareal and T.D. Griggs (eds). *Sweet Potato. Proceedings of the First International Symposium*, pp63-72. Tainan: Asian Vegetable Research and Development Centre.

Joughin, J. and B. Thistleton 1987. *A Rapid RuralAappraisal in the Jimi Valley, Western Highlands Province, Papua New Guinea.* DAL Discussion Paper 87/3. Port Moresby: Department of Agriculture and Livestock.

Kocher Schmid, C. 1991. *Of People and Plants: A Botanical Ethnography of Nokopo Village, Madang and Morobe Provinces, Papua New Guinea*. Basler Beiträge zur Ethnologie, Band 33. Basel: Ethnologisches Seminar der Universität und Museum für Völkerkunde.

Laing, D.R., P.J. Kretchmer, S. Zuluaga and P.G. Jones 1983. Field beans. In *Potential Productivity of Field Crops Under Different Environments*, pp227-248. Los Baños: International Rice Research Institute.

McAlpine, J.R. 1970. Climate of the Goroka-Mount Hagen area. In *Lands of the Goroka-Mount Hagen Area, Territory of Papua and New Guinea*, pp66-79. Land Research Series No. 27. Australia: CSIRO.

McAlpine, J.R. and G. Keig with R. Falls 1983. *Climate of Papua New Guinea*. Canberra: Australian National University Press.

McAlpine, J.R., G. Keig and K. Short 1975. *Climatic Tables for Papua New Guinea*. Division of Land Use Research Technical Paper No. 37. Canberra: CSIRO.

Meggitt, M.J. 1958. The Enga of the New Guinea highlands: some preliminary observations. *Oceania* 28(4):253-330.

Morgan, W.T.W. 1968. The role of temperate crops in the Kenya highlands. *Acta Geographica* 20:273-278.

Ochse, J.J. and R.C. Bakhuizen van der Brink 1977. *Vegetables of the Dutch East Indies*. Canberra: Australian National University Press.

Peekel, P.G. 1984. *Flora of the Bismarck Archipelago for Naturalists*. E.E. Henty (translator). Lae: Office of Forests, Division of Botany.

Quinlan, T.J. 1968. Cultivation of pyrethrum in Papua and New Guinea. *Rural Digest* 9(5): 7-13. Port Moresby: Department of Agriculture, Stock and Fisheries.

Sillitoe, P. 1983. Natural resources exploited by the Wola in the manufacture of artifacts. *Science in New Guinea* 10(2):111-132.

Simpson, J.A. and F. Arentz 1982. Notes on tree fruits cultivated in the Bulolo and Wau Valleys with particular reference to diseases and pests. In R.M. Bourke and V. Kesavan (eds) *Proceedings of the Second Papua New Guinea Food Crops Conference. Part 3*, pp458-466. Port Moresby: Department of Primary Industry.

Smith, J.M.B. 1977a. Man's impact upon some New Guinea mountain ecosystems. In T.P. Bayliss-Smith and R.G. Feachem (eds) *Subsistence and Survival. Rural Ecology in the Pacific*, pp185-214. London: Academic Press.

Smith, J.M.B. 1977b. Vegetation and microclimate of east- and west-facing slopes in the grasslands of Mt. Wilhelm, Papua New Guinea. *Journal of Ecology* 65:39-53.

Smith, J.M.B. 1978. Relationship of slope aspect to deforestation in highland Papua New Guinea. *Queensland Geographical Journal* (3rd Series) 4:69-75.

Stadel, C. 1986. Del valle al monte: altitudinal patterns of agricultural activities in the Patate-Pelileo area of Ecuador. *Mountain Research and Development* 6(1):53-64.

Treide, B. 1967. Wildpflanzen in der Ernährung der Grundbevölkerung Melanesiens. Veröffentlichungen des Museums für Völkerkunde zu Leipzig Heft 16. Berlin: Akademie-Verlag.

Van Steenis, C.G.G.J. 1961. An attempt towards an explanation of the effect of mountain mass elevation. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschobben. Series C. *Biological and Medical Sciences* 64:435-442.

Verdcourt, B. 1979. *A Manual of New Guinea Legumes*. Botany Bulletin No. 11. Lae: Division of Botany, Department of Forests.

Whitmore, T.C. 1984. *Tropical Rain Forests of the Far East*. Second edition. Oxford: Oxford University Press.

Wohlt, P.B. 1978. Ecology, agriculture and social organization: the dynamics of group composition in the highlands of Papua New Guinea. Unpubished PhD thesis. Minneapolis: University of Minnesota.

Wohlt, P.B. and A. Goie 1986. *Research Report of the Simbu Land Use Project Volume 5. North Simbu Land Use*. Port Moresby: Institute of Applied Social and Economic Research.

Wohlt, P.B. and G.S. Humphreys 1981. A summary of some climate data for Yumbisa (2670 m a.s.l.), Enga Province. Unpublished paper. Kundiawa: Simbu Land Use Project.

Wu, H.B-F., T-T. Yu and T-D. Liou 1974. Physiological and biochemical comparisons of sweet potato varieties sensitive (Tai-long 57) and insensitive (Red-tuber-tail) to chilling temperature. In R.L. Bieleski, A.R. Ferguson and M.M. Creswell (eds) *Mechanisms of Regulation of Plant Growth*, pp483-486. New Zealand: Royal Society of New Zealand Bulletin 12.

Yen, D.E. 1974. *The Sweet Potato and Oceania. An Essay in Ethnobotany*. Bernice P. Bishop Museum Bulletin 236. Honolulu: Bishop Museum Press.

Yu Xiao-gan and Sun Shang-zhi 1981. The upper limit of agriculture in Xizang and its factor analysis. In *Geological and Ecological Studies of Qinghai-Xizang [Tibet] Plateau. Volume 2. Proceedings of the Symposium on Quinghai-Xizang [Tibet] Plateau*, pp2033-2044. Beijing: Science Press.