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Title: Food shortages are associated with droughts, floods, frosts and ENSO in Papua New Guinea

Article Type: Research Paper

Keywords: El Nino Southern Oscillation; drought; water logging; sweet potato; coffee; rainfall data

Abstract: In Papua New Guinea extreme climate events have occasionally led to the collapse of normal subsistence food production systems causing large scale food shortages that threaten human health and survival (e.g. during the 1997 El Niño drought). Production of staple foods (e.g. sweet potato) and cash crops (e.g. coffee) are adversely affected by drought, water logging and frost. We investigated the association between El Nino Southern Oscillation (ENSO), extreme climate events and reported food shortages. Over the 120 year period between 1890 and 2009, there have been 15 widespread droughts and 13 of these were associated with El Niño events, and eight of the 12 widespread floods were associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. Since the early 1900s eleven major and widespread food shortages have been reported in the highlands but they have not been associated with drought alone but also with water surplus and frost. Eight of the eleven widespread food shortages were associated with El Niño years (1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these were preceded by La Niña events (1996, 1971, 1964, 1910). There was evidence of anomalous frosts at lower altitudes (1450 m) and more frequent frosts at higher altitudes (>2200 m) during clear skies in El Niño droughts that also contributed to food shortages. It is a combination of climatic extremes that causes the damage to crops that leads to a shortage of subsistence food in the highlands. The Standardised Precipitation Index provided a useful warning of success of more than 60% for El Niño droughts in 10 of the 18 locations, however the success rates of La Niña flood warnings at these locations was lower (<60%). Using seasonal climate forecasts based on ENSO and climate integrated crop models may provide early warning for farmers, industry agencies and government to help prepare for food shortages. Strategies that can help subsistence farmers cope with extreme climate events and the use, and value of seasonal climate forecast information are discussed.

AGSY 5158

Revision Notes

FOOD SHORTAGES AND EXTREME CLIMATE EVENTS IN PAPUA NEW GUINEA (title changed as per reviewer 2 comments – for new title see below)

Reviewer#1 – changes highlighted in yellow in ms

1. Page 5 the authors mention that "These ENSO events commonly commence each year in March-June and…" This is generally not the case and ENSO variability is far from periodic.

We agree that individual ENSO events are never exactly the same and vary in magnitude, spatial extent, onset, duration and cessation etc, however, because seasonal persistence is weakest in the austral autumn and the predictability barrier exists at this time, this is when ENSO events 'on-average' are likely to develop and existing conditions collapse (see Torrence and Compo 1998; Torrence and Webster 1998, 1999; Allan 2000). In addition to highlight the impact of ENSO on rainfall to practitioners, the ENSO year is often used as being April-March in annual descriptions of rainfall (see https://www.longpaddock.qld.gov.au/products/australiasvariableclimate/index.html).

As such, we have included references in the existing manuscript to support the text.

2. Page 5 what does "develop historical surface" imply? I am guessing it refers to maps of constant rainfall (or as generally referred in meteorological literature as the contour maps).

Have revised as reviewer suggested.

3. Page 7 It is mentioned that "...continuous good quality data with more than 30 years of record…" Subsequently, and on the same page it is mentioned that the rainfall data from 1890-2010, and which is lot more than 30-years. Please clarify.

The stations varied in length of record (LOR) and percentage missing data. For example, Port Moresby has a LOR of 135 year with 8.2% missing right down to Henganofi with 31 year LOR and 15.6% missing data (see Appendix 1 for other locations).

We have altered the text to avoid confusion as the reviewer has suggested.

4. Page 7 Couple of times there is a mention of some "poster." Not sure what is being referred to? Is this something that came out from the present analysis or is something produced by someone else?

The poster referred to is shown in Appendix 2 (rightly noted by Reviewer 2 –point 6 - as incorrectly labelled as Appendix 3). This poster was produced as part of this study.

We have amended the text to reflect this.

5. Page 8 How are the cutoff values for SPI for establishing drought and flood categories determined? Do these correspond to some percentile values for the distribution of corresponding SPI? Are these values a community standard and can be cited or determined arbitrarily in this analysis.

We used the cut-off values described by the developers of the SPI (McKee et al. 1993). We used the same classification system to define drought (and flood) intensities resulting from the SPI as McKee et al. 1993. They also defined the criteria for a drought event for any of the timescales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less (or more than 1.0). The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month that the event continues.

We have amended the text to include the McKee et al.1993 reference that describes the values and boundaries used in the SPI standard.

6. Page 9 Re some discussion on practical utility of seasonal forecasts

We have read the Kumar 2010 reference as the reviewer suggested and included the following discussion:

The use and value of seasonal forecasts

The extent to which seasonal climate forecast information is used in decision making in PNG is not known. Using a climate forecast is different to changing a decision during, or because of, drought (or flood) and more akin to changing a decision because of a forecast of impending or worsening drought (or flood) in future. Subsistence farmers plant different crops or different varieties of crop during drought compared to what they would in normal seasonal conditions (Bourke 1988), but this is not using seasonal forecast information. However it's likely that there is some use of seasonal climate forecast information in PNG because, for the most part, implementing drought coping strategies requires only a macro view of the differences in mean annual or seasonal rainfall between climatology, and El Nino and La Nina conditions (Kumar 2009). For almost all of PNG the annual median rainfall in El Nino conditions is only 20-40% of that in all years (see Figure 2b), so users of forecasts of El Nino could either implement some of the strategies referred to above that help cope with dry conditions, or they can switch management to actions that they have found successful in the past. On the other hand, the annual median rainfall in La Nina conditions is 60-70% of that in all years, however this shift in median values is only apparent in some provinces (coastal Sandaun and East Sepik, Western, Southern Highlands, western Gulf, eastern Central and Oro, Milne Bay) (see Figure 2c). Therefore a forecast of El Nino may be more valuable to PNG as a whole than a forecast of La Nina, because the former is associated with a much wider geographical area with a strong predictable signal. The impact and coping strategies used during previous droughts is well known by farmers, traders, industry organisations, but it is the responsibility of government, government agencies, support, welfare and research organisations to use this predictable signal in the climate to warn the community about forthcoming climatic events that have caused catastrophic economic, social and environmental hardship in the past (e.g. 1997, see Bourke et al. 2001).

A micro view of seasonal climate information requires detailed information about the climate history and the use of comprehensive application models (e.g. SCOPIC) (Kumar 2009). This paradigm can provide site-specific information for any season about the climate means, probability distributions, strength and predictability of the ENSO signal and forecast reliability, and when climate data is integrated with agricultural models (e.g. APSIM), similar information can be provided about the predicted production of that commodity (Hammer et al. 1996, Potgieter et al. 2003). Using these climate integrated agricultural production models to change decisions based on a climate driven *prediction of modelled production has significantly increased profitability (Hammer 2000, McKeon et al. 2000, Cobon and McKeon 2002) and resource sustainability (McKeon et al. 2004) at the farm, local and regional scales in Australia, another country that has regions with a strong predictable ENSO signal (McBride and Nicholls 1983). An integrated climate and coffee production model for Arabica species has been developed (Roger Stone, personal communication) but we are not aware of such a model for sweet potato. The limitation for the application of these models in developing countries is that long-term (>30 years) daily records of rainfall, temperature (max and min), radiation, evaporation and humidity are often needed to run the models and these records are either not always available or they have not been transferred from paper to digital format.*

As is the case with the use of seasonal climate forecast information, neither do we know the extent to which agricultural decision makers in PNG change decisions based on this information. Nor do we know the economic, social or environmental implications of any changed decisions. These metrics are difficult to obtain, even in developed agricultural economies (Kumar 2009), and are part of assessing the value of seasonal climate information. A seasonal forecast system has value if it is responsible for a change in management practice which is different to the status quo practice that was once based on the use of climatological data (Hammer 2000, Kumar, 2009).

7. Page 10 Re Warning success of 57% being associated with an assessment of skill

The success of a drought warnings were calculated as a simple percentage of the number of times the warning SPI threshold (-0.2) was reached that subsequently reach the drought SPI threshold (-2.0) (negative values for flood). It was used to help farmers understand how useful the warnings have been in the past, in laymen's terms. That is, based on history, this tool would be correct in predicting a drought about 1 month in advance 6 times in 10 (for some locations) – it was not meant to represent forecast quality but provide a simple tool (Figure 6) that farmers could understand. A full assessment of the skill of various forecast systems is described in another paper (Cobon et al. 2009a).

This reference has been included in the manuscript for those that would like an assessment of forecast skill for each of the 18 locations. Further explanation of the warning success has been given in the manuscript.

8. Re Provide some brief discussion on DPSIR model

We have provided a clearer and expanded explanation of the process that involves using DPSIR in the M&M.

Reviewer #2 - changes highlighted in green in ms

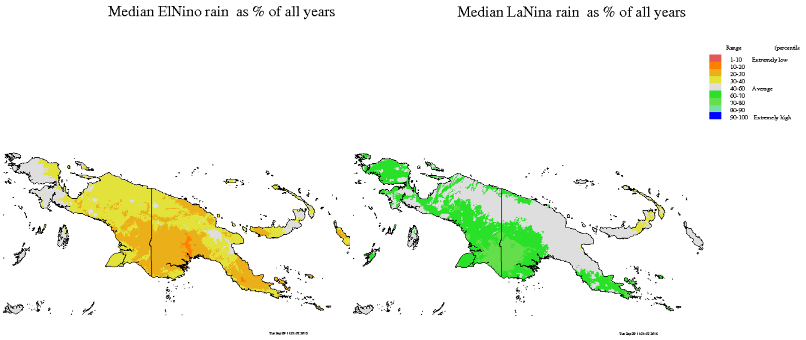
1. More concise presentation of Fig1 and Appendix 1 and 3

Fig 1 represents a three part summary of the key issues and responses required to reduce the impacts of climate extremes on a) food shortage for the rural population b) sweet potato production and c) coffee production in PNG. These 3 figures condense the knowledge of many experts that have worked in these areas for many years as well as reports and findings in the 'grey' literature. In addition these figures have been used in many presentations to explain the systems and are an effective learning and teaching tool in their current format. Condensing these figures into a table will save space but will remove the education, capacity building and learning advantages that the current figures provide. In this case, and for these reasons we have not altered Figure 1a-c.

Appendices 1 and 3 have been altered to reduce space.

2. Show rainfall composites for El Nino and La Nina years

We have rerun the analysis and compiled composite maps of El Nino and La Nina median rainfall as a percentage of all years. These (see below) have been included in the manuscript as Figure 2 b, c with some reference and relevant discussion in the Discussion section.



3. Show a relationship between ENSO induced droughts and food shortages.

In another study we have used price of sweet potato as a proxy for production of sweet potato as production data are not available, however this data and analysis and association with ENSO is the subject of another paper.

4. Why are the SPI thresholds selected?

See Reviewer #1 point 5 above for the response and changes to manuscript.

Reviewer #2 Minor points

1. The manuscript has no page numbers nor line numbers, which is not convenient for a reviewer to make comments on specific part of the manuscript.

Point noted

2. Title: "Extreme climate events" is vague. I would suggest replacing with "droughts/floods associated with ENSO".

Current title: Food shortages and extreme climate events in Papua New Guinea

New title: Food shortages are associated with droughts, floods, frosts and ENSO in Papua New Guinea.

Abbreviated ENSO in title. Acronym explained on line 5 and line 6 in abstract and introduction respectively.

Other possibilities for title but not favoured:

Food shortages and droughts, floods and frost associated with El Nino Southern Oscillation in Papua New Guinea.

Droughts, floods and frost cause food shortages that are associated with ENSO in PNG

Food shortages are associated with extreme events and ENSO in PNG

Food shortages and droughts, floods and frosts associated with ENSO in Papua New Guinea.

3. Replace ‘central Pacific Ocean’ with ‘central and eastern Pacific Ocean’

Done

4. Replace "develop mean and historical rainfall surfaces" with "assess mean and historical rainfall variations".

Done as part of Reviewer #1 point 2

5. Figure 6 caption not well explained.

More explanation provided as shown below:

Figure 6. A successful drought warning for Tari (November 1963) indicated by SPI 3 (y axis) and showing SPI 3 reaching the drought warning threshold of -0.2, subsequently reaching drought threshold -1.0 and afterwards going out of drought. Drought warning failures are also shown. Red circles indicate El Nino and blue circles represent La Nina events.

6. Appendix 2 is labelled as Appendix 3

Fixed

Additional references included in new draft

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AGSY 5158 Abstract

Title: Food shortages are associated with droughts, floods, frosts and ENSO in Papua New Guinea

In Papua New Guinea extreme climate events have occasionally led to the collapse of normal subsistence food production systems causing large scale food shortages that threaten human health and survival (e.g. during the 1997 El Niño drought). Production of staple foods (e.g. sweet potato) and cash crops (e.g. coffee) are adversely affected by drought, water logging and frost. We investigated the association between El Nino Southern Oscillation (ENSO), extreme climate events and reported food shortages. Over the 120 year period between 1890 and 2009, there have been 15 widespread droughts and 13 of these were associated with El Niño events, and eight of the 12 widespread floods were associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. Since the early 1900s eleven major and widespread food shortages have been reported in the highlands but they have not been associated with drought alone but also with water surplus and frost. Eight of the eleven widespread food shortages were associated with El Niño years (1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these were preceded by La Niña events (1996, 1971, 1964, 1910). There was evidence of anomalous frosts at lower altitudes (1450 m) and more frequent frosts at higher altitudes (>2200 m) during clear skies in El Niño droughts that also contributed to food shortages. It is a combination of climatic extremes that causes the damage to crops that leads to a shortage of subsistence food in the highlands. The Standardised Precipitation Index provided a useful warning of success of more than 60% for El Niño droughts in 10 of the 18 locations, however the success rates of La Niña flood warnings at these locations was lower (<60%). Using seasonal climate forecasts based on ENSO and climate integrated crop models may provide early warning for farmers, industry agencies and government to help prepare for food shortages. Strategies that can help subsistence farmers cope with extreme climate events and the use, and value of seasonal climate forecast information are discussed.

AGSY 5158 Highlights

Title: Food shortages are associated with droughts, floods, frosts and ENSO in Papua New Guinea

ENSO is associated with large scale food shortages that threaten human health

Sweet potato and coffee are adversely affected by drought, water logging and frost

Since the 1900s there have been 11 major and widespread food shortages

Food shortages are associated with droughts, water logging and frost

Seasonal climate forecasts based on ENSO may provide early warning for farmers.

Food shortages are associated with droughts, floods, frosts and ENSO in Papua New Guinea

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Key words: El Nino Southern Oscillation, drought, water logging, frost, sweet potato, coffee, rainfall data, use and value of seasonal climate forecasts

Abstract

In Papua New Guinea extreme climate events have occasionally led to the collapse of normal subsistence food production systems causing large scale food shortages that threaten human health and survival (e.g. during the 1997 El Niño drought). Production of staple foods (e.g. sweet potato) and cash crops (e.g. coffee) are adversely affected by drought, water logging and frost. We investigated the association between El Nino Southern Oscillation (ENSO), extreme climate events and reported food shortages. Over the 120 year period between 1890 and 2009, there have been 15 widespread droughts and 13 of these were associated with El Niño events, and eight of the 12 widespread floods were associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. Since the early 1900s eleven major and widespread food shortages have been reported in the highlands but they have not been associated with drought alone but also with water surplus and frost. Eight of the eleven widespread food shortages were associated with El Niño years (1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these were preceded by La Niña events (1996, 1971, 1964, 1910). There was evidence of anomalous frosts at lower altitudes (1450 m) and more frequent frosts at higher altitudes (>2200 m) during clear skies in El Niño droughts that also contributed to food shortages. It is a combination of climatic extremes that causes the damage to crops that leads to a shortage of subsistence food in the highlands. The Standardised Precipitation Index provided a useful warning of success of more than 60% for El Niño droughts in 10 of the 18 locations, however the success rates of La Niña flood warnings at these locations was lower (<60%). Using seasonal climate forecasts based on ENSO and climate integrated crop models may provide early warning for farmers, industry agencies and government to help prepare for food shortages. Strategies that can help subsistence farmers cope with extreme climate events and the use, and value of seasonal climate forecast information are discussed.

Introduction

The predominance of subsistence agriculture in Papua New Guinea (PNG) highlights the importance of food security (Bourke 2001, Manning 2001). Smallholder farmers have generally learnt to manage the localised shortages of food that occur regularly through the use of extended family and purchasing food from the sale of cash crops such as coffee and potatoes. It is the large scale shortages of food that occur irregularly that threaten human health and survival such as during the El Nino Southern Oscillation (ENSO) driven El Niño drought in 1997 (Allen and Bourke 2001).

During these extreme events (droughts, very high soil moisture levels and frosts) that cause widespread food shortages, the PNG government has relied upon food aid (national and international) and on villagers' self-reliance to purchase imported food. It is the more remote and isolated communities that are most vulnerable because of their poor access to food distribution points and markets to sell produce from cash crops.

Sweet potato is the dominant staple food. It is therefore the most important crop in PNG and over 60% of the rural population depend on it as their main food source (Bourke et al., 2009). However banana, taro, yams, cassava, corn and other traditional vegetables as well as pigs are important dietary components. About 75% of annual sweet potato production is grown in the highlands. Climatic extremes, particularly high soil moisture, droughts and frosts are among the main constraints to production. Sweet potato is relatively drought tolerant. However, excessively wet soil conditions soon after planting of vines followed by drought as the tubers increase in size causes a marked depression in tuber yield and this is commonly attributed to the drought. However it is the combination of climatic extremes that causes the damage which can lead to a shortage of subsistence food in the highlands (Bourke, 1988). Repeated frost events also significantly reduces yield of sweet potatoes. Successfully forecasting these events some months in advance could initiate alternative management and avoid significant reductions in yield.

Extreme events (droughts and excessively wet periods) have significant impacts on agricultural production and natural resource management. In the Pacific Rim, including PNG and eastern Australia, the tele-connections (relationship over a long distance) of climate-related anomalies with El Niño and La Niña events are strong and are reliable enough for use in decision making.

Smallholders produce over 90% of the coffee grown in PNG making it a valuable cash crop for many villages. It is grown mainly for export and represents ~40% of all agricultural exports. Although coffee is grown in over 70 countries, the conditions for growing quality beans exist in a relatively narrow climatic range. The optimal climatic regions for growing Arabica coffee are relatively cool climates in the sub-tropical (16-24°N and S latitude) and equatorial (<10° latitude) zones with the optimum temperature between 15-24°C year round. Photosynthesis is slowed above these temperatures and frost damage can occur when temperatures persist around 0°C. A large diurnal temperature range is beneficial to coffee quality.

The optimum rainfall for coffee is 1500-2500 mm of rain falling over an eight month growing period with a three month dry season coinciding with the harvest. Where rainfall is less, irrigation can be applied to compensate, although this is not relevant in the PNG context. A period of water deficiency in the soil followed by good rainfall will favour the onset of flowering and produce a homogenous flowering and defined harvesting season. These clearly defined dry and wet events are not common in many areas of the PNG highlands, where a non-seasonal rainfall pattern persists. This can lengthen the flowering and harvesting periods in these areas.

The El Niño Southern Oscillation (ENSO) is associated with warmer than normal water in the central and eastern Pacific Ocean (called El Niño), or cooler than normal water (called La Niña). El Niño is often associated with lower than normal rainfall and because of the dry atmosphere and clear skies during these periods lower minimum temperatures are experienced. La Niña is often associated with higher than normal rainfall and minimum temperatures. These ENSO events commonly commence and cease each year between March and June (Torrence and Compo 1998, Torrence and Webster

1998, 1999, Allan 2000) and persist for 9-12 months. In nearby Australia, the association between the Southern Oscillation Index (SOI) and 3 month Australian rainfall follows a ‘predictability barrier’ in autumn, builds in winter, reaches a peak in spring and dissipates in summer (McBride et al. 1983; Stone et al. 1996; Chiew et al. 1998, Cobon and Toombs 2013). Because of the oscillation between El Niño and La Niña, droughts can commonly be followed by floods (and vice versa) (McPhaden 2003).

Lessons learned from the 1997 drought in PNG demonstrated the vulnerability of agricultural production to climate impacts both in terms of food security and farm income. A review of the current hazard monitoring capabilities and procedures after the 1997 drought recommended development of improved systems that provide early warning of developing threats and regularly updated information on their characteristics and progress. It is therefore a priority in PNG to develop an effective climate forecasting and warning system focussing on drought response strategies, information on quantitative measures of drought and improved crop management practices. Here we report on a project which retrieved long-term rainfall data for PNG, examined its relationship with El Niño Southern Oscillation (ENSO) and investigated the utility of drought warning tools to help maintain food security (sweet potato) and farm income (coffee).

With some reference to sweet potato as a staple food and coffee as a valuable cash crop, the aim of this study in PNG was to:

1. Provide an overview of the influence of climate on the food security of the rural population using the Driver Pressure State Impact Response (DPSIR) model;

2. Source data, develop maps of mean rainfall, percentile maps of annual rainfall, and show the association with ENSO;

3. Examine the number and extent of droughts, floods and food shortages;

4. Use the Standardised Precipitation Index (SPI) to examine success rate and warning length for ENSO triggered droughts and floods;

5. Examine the association between droughts, floods, frosts, food shortage; and

6. Investigate current practices to maximise production and minimise risk through drought management.

MATERIALS AND METHODS

The definition of drought in this study is a lack of available water relative to demand resulting from a period of below-average precipitation that may be harmful to crop production at a critical stage of development. Floods are generally described as the overflowing of water onto land that is normally dry and this can cause physical damage to landscapes. However, for the purposes of this study we are more interested in excess water and its impacts in an agricultural context that may occur in the absence of physical damage to the landscape, in particular, the effect that water in excess of soil water capacity and water logging of soil profiles may have on crop production.

The Driver Pressure State Impact Response (DPSIR) (OECD 1997) provided a framework or process to summarise how the rural population could respond to some of the key drivers threatening food security, including climatic extremes. Using the opinion of experts (extension officers, researchers, industry representatives) and published information we used the DPSIR process to assess the pressures that are most evident, what changes occur in the resources as a consequence, the impacts of those changes and how governments, research funders, extension officers and small holders should respond. In a similar way we investigated climate as one key driver of sweet potato and coffee production and identified the likely pressures, state (resource conditions of importance to production), impacts and responses required by different stakeholders in order to maximise production. The DPSIR model provided a framework to identify key

The long term monthly rainfall data were sourced from the PNG National Weather Service (NWS), the PNG colonial data archive (CDA - Bureau of Meteorology Australia), the Coffee Industry Corporation (CIC) at Aiyura and the National Agricultural Research Institute (NARI) at Tambul. The location, elevation and availability of monthly rainfall data for 18 meteorological stations across PNG are shown in Appendix 1ab. Because some stations were moved (e.g. Lae to Nadzab, Rabaul to Tokua) and others had short lengths of records, some data records were combined. Ten composite stations were prepared using analytical methods to combine and convert data and some missing data were patched. The methods used are described in Cobon et al. 2009b and have provided continuous good quality data for 2 stations in the high altitude zone (Tambul, Wabag), 7 stations in the highlands (Aiyura, Goroka, Mt Hagen, Kundiawa, Tari, Mendi, Henganofi) and 9 stations in the lowlands (Daru, Kavieng, Madang, Misima, Momote, Port Moresby, Wewak, Rabaul, Nadzab). The length of the data record, missing values and percentage of missing data for these stations are shown in Appendix 1a.

A poster showing PNG's variable rainfall was produced as part of this study showing 120 percentile maps of PNG rainfall from 1890 to 2009 (see Appendix 2). Rainfall data were sourced from the PNG NWS and the PNG CDA (see McAlpine et al. 1975 for stations, record length and years of record from 1890 to 1970). The maps were produced using interpolated (Jeffery et al. 2001) April to March rainfall data each year from 1890 to 2010 (Appendix 2). The number of rainfall stations used for the interpolation was less than 20 before 1913, between 1942 and 1945 (World War II) and after 1974. This spatial dataset was used to calculate the 1) mean April-March rainfall (1890-2009) (Figure 2a) 2) maps showing composites of median rainfall in El Nino and La Nina years as a percentage of all years (Figure 2 b, c) and 3) the area of PNG where annual rainfall (April-March) fell into drought (≤10 percentile) or flood (≥90 percentile) categories (Table 1).

The statistical model SCOPIC (Seasonal Climate Outlook for Pacific Island Countries) was used to assess the frequency (and severity) of droughts and floods using different indices of the Standardised Precipitation Index (SPI) (e.g. 1, 3 and 6 month time scales) (Edwards and McKee, 1997). SCOPIC is a decision support system for generating probabilistic predictions, seasonal climate forecasts or drought/flood analysis for rainfall or other parameters where climate plays an important role (e.g. production of crops) http://cosppac.bom.gov.au/products-and-services/seasonal-climate-outlooks-in-pacific-island-countries/.

The drought and flood analyses in this study were based on the growth period of the crops investigated and the time scale on which a water shortage or excess may have on crop production. For example, depending on location, the growth period of sweet potato is 4 to 9 months and it is about 8 months for coffee. In some locations (e.g. high altitudes) a 1 month period with little or no rainfall or a 1-3 month period of water excess may have a significant negative impact on crop production. For these reasons we have completed the drought and flood analyses using 1, 3 and 6 month periods of monthly moving average rainfall using SPI, to trigger warnings (drought SPI -0.2; flood, SPI 0.2) and identify periods (drought SPI -1; flood, SPI 1) (McKee et al. 1993).

Warnings that later resulted in either droughts or floods were classified as warning successes, calculated as a percentage of the number of event thresholds (drought or flood) to the number of warnings (drought or flood). The length of the warning (for successes only) was calculated from the time the warning was first issued to the time the drought or flood threshold was reached and the frequency of drought/flood was calculated per decade as an indicator of vulnerability to these extreme events.

The droughts and floods were classified into ENSO phases (after Allan et al. 1996, McKeon et al. 2004) at the time the warning was first issued using the Australian Bureau of Meteorology Southern Oscillation Index (SOI) for June to November. The classification of historical warnings into ENSO phases (El Niño, La Niña, Other) allows an assessment of the warning success associated with each ENSO phase. High historical warning success rates (>60%) associated with a particular ENSO phase provides some confidence that this association may continue into the future and therefore provides the basis for use as an early warning tool for droughts and floods.

RESULTS

A summary of how some of the drivers of food security in the rural population (climatic extremes, planting rates, village income and village isolation) and the pressures that are most evident, the changes that can occur in the resources as a consequence, the impacts of those changes and how governments, research funders, extension officers and small holders should respond is shown in Figure 1a. The following responses are likely to be effective: Providing access to technologies and information that increase farmers income from cash crops (e.g. coffee), providing early warning of extreme climatic and market driven events (e.g. seasonal climate forecasts using ENSO, trends in food prices such as rice), monitoring planting rates and yields of staple foods to pre-empt shortages in supply, provide technologies and information that improve food yields (protection from pests and disease, copping strategies for soil nutrient run-down, drought, floods and frost) and lastly provide food aid by importing and effective distribution of food.

A similar assessment for sweet potato production highlighted climate as a key driver (ENSO, Coral Sea and Indian Ocean temperatures) responsible for low soil moisture, water logging and frosts that can reduce production (Figure 1b). Sequences of climate together with changes in planting rates produce cycles of sweet potato production. Waterlogging or extreme rain over short periods (170-200mm/day) or high monthly rainfall for 2-3 months during tuber initiation (6-10 weeks post-planting), low soil moisture (<20% soil capacity) during tuber bulking (3-6 months post-planting), the association between altitude, drought and frost (frosts occur as low as 1450 m during drought, repeated frosts at altitudes over 2200 m) and changes in planting rates associated with availability all combine to produce shortages of sweet potato. Climate forecasts effectively relayed to villages with coping responses, drought tolerant and early maturing cultivars, crop diversification, monitoring and modelling of soil moisture status and extension officers trained in early warning detection and implementation of coping strategies are some responses that are likely to be effective.

In a similar fashion drought, floods and repeated frosts can reduce production of coffee (Figure 1c). Low soil moisture (<50% soil capacity) during the rapid expansion phase (10-18 weeks post-flowering; November-January) and extreme rainfall during this same period can reduce the size of the coffee bean. Repeated frosts that occur during droughts at over 2200 m altitude, temperatures outside the 15-24^{o}C range and rainfall less than 150-200 mm per month can reduce production of coffee, although most coffee is grown below 2000 m altitude. Similar responses to those used for sweet potato are likely to be most effective.

The mean annual (April-March) rainfall ranged from 1500-2000mm in the Eastern Highlands Province to 2500-3500 mm in Western and Southern Highlands Provinces (Figure 2).

There have been 12 major and widespread droughts in PNG in 1896, 1902, 1905, 1914, 1931, 1941, 1942, 1965, 1972, 1982, 1987 and 1997 (Allen 1989, Allen and Bourke 1997, Allen and Bourke 2000) as well as minor and less widespread droughts in 1992, 1993 and 2004 (SCOPIC analysis – current study) (Figure 3). These findings were largely supported by independent analysis completed for the PNG Rainfall poster (Appendix 2) where percentile 10 or less rainfall was received across large parts of PNG during these years. These widespread droughts were mostly associated with El Niño events (Figure 3) although localised or regional droughts did not always match this pattern.

The five most widespread droughts occurred in 1997, 1941, 1982, 1914 and 1902 (Table 1). In 1997 and 1941 over 80% of PNG received ≤10 percentile rainfall and therefore represent the worst droughts PNG has experienced since 1890 in terms of area affected. The five most widespread floods between 1890 and 2009 occurred in 1943, 1907, 1894, 1921 and 1998.

There have been 11 major and widespread food shortages reported in the PNG highlands in 1911-14, early 1930s, early 1940s, 1962, 1965-66, 1972-73, 1980-81, 1982-83, 1984-85, 1987-88 and 1997-98 (Appendix 3). These food shortages have not been associated with drought alone but also with water surplus and frost.

The SPI method provided an overall warning of success of 57% for El Niño droughts and 43% for La Niña floods. The success rate of El Niño drought warnings was useful (>60%) at Daru, Madang, Misima, Wewak, Aiyura, Mendi, Mt Hagen, Tari, Tambul and Kundiawa (Figure 4). The corresponding success rates of La Niña flood warnings at these locations was lower (<60%) and suggests that predicting floods using this method may not be useful in decision making.

The length of the warning was associated with the period of rainfall averaging. The average length of warning for El Niño droughts was 0.4, 1.2 and 1.7 months for SPI1, SPI3 and SPI6 respectively (Figure 5). The average length of warning for La Niña floods was 0.5, 1.4 and 1.9 months for SPI1, SPI3 and SPI6 respectively. An example from SCOPIC of the 3 month SPI time series at Tari from 1962-1964 showing a successful El Nino drought warning is shown in Figure 6.

The length of warnings for droughts and floods were analysed in conjunction with the success rates, and they appear to provide sufficient warning to be useful in smallholder systems where changes to management can be implemented relatively quickly provided the warnings are communicated quickly and effectively.

DISCUSSION

Climate and food shortage – sweet potato

Since the 1890s there have been 15 widespread droughts and 13 of these have been associated with El Niño events. In support of this ENSO signal, 8 of the 12 widespread floods have been associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. However, there are local and regional differences that are important to understand.

Of the 15 widespread droughts, 12 have been major and widespread droughts and three were minor and less widespread. There have been 11 major and widespread food shortages reported in the PNG highlands but they have not been associated with drought alone but also with water surplus and frost. Sweet potato is the dominant staple food in rural PNG. Excessively wet soil conditions soon after planting of sweet potato followed by drought as the tubers increase in size causes a marked depression in tuber yield. This is commonly attributed to the drought. It is the combined climate sequence of water surplus followed by drought that produces the most damaging food shortages (Bourke 1988). A climate sequence of water surplus followed by drought some 6-10 months later produces the most damaging food shortages. The timing of the water surplus during the sweet potato tuber initiation phase (6-10 weeks post-planting) and drought toward the end of the crop growth cycle during the rapid tuber bulking phase (3-6 months post-planting) most severely impacts on sweet potato production. The water surplus early in the growth cycle limits the depth of rooting so the plants are especially vulnerable to even mild droughts because their root systems are shallow.

Eight of the eleven widespread food shortages have been associated with El Niño years (e.g. 1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these have been preceded by La Niña events (1996, 1971, 1964, 1910) (Figure 3). Three of the most severe food shortages in PNG over the past 120 years are those in 1997, 1911-14 and 1972. Each of these was associated with drought, but was preceded by a La Niña events (very wet period) the previous year. Climatic extremes partly contribute to food shortages in PNG.

It is a combination of crop yield in response to certain climatic extremes and people's decisions about how much to plant that provides the best explanation for variation in food supply (Bourke 1988). Variation in the supply of sweet potato is an outcome of variation in yield and variation in the area planted over time. The effect of climatic variation on plant growth, in particular changes in soil moisture, solar radiation, daylength and temperature, has the major impact on crop yields in the highlands, however the major climatic influences on sweet potato yield variation are extremes of soil moisture, particularly water logging and frosts (see Box 1)

Climate and cash flow - coffee

The equatorial coffee growing regions are at altitudes between 1000-2000 m with high humidity produced by the abundant rainfall. Deep, porous, well-drained soils of volcanic origin that are rich in nutrients are best for growing coffee. Extreme wet periods in poorly drained soils have a large negative impact on production as does drought, particularly during cherry ripening and development when large quantities of nutrients and water are required for high yields. The best coffee production in PNG is likely to come from good rainfall from August to April, a 2-3 month dry period from May-July with no frosts and plenty of sunshine. The bulk of Arabica coffee in PNG is grown over an altitude range of 1500 to 2000 m, although some is grown over a wider range of 700-2050 m (Bourke 2010).

The coffee growing period of about eight months in the highlands starts with flowering from July-November, the pinhead stage of cell division (weeks 0-8; September-October), the rapid expansion phase (weeks 8-18; November-January), endosperm growth and cherry ripening phase (weeks 18-32; February-May). The main harvesting time is from May-September. The amount of soil moisture available during the rapid expansion phase determines the eventual size of the coffee bean so a drought at this stage will limit coffee production. However following the severe soil moisture stress during the 1997 El Nino drought, PNG produced near record Arabica coffee exports in 1998 (Hombunaka and von Enden (2000). The extreme dry period before rainfall in October/November 1997 provided a strong flowering stimulus that led to the near record coffee yields in June and July 1998.

Early warning – success rate and warning length

The success rate of El Niño drought warnings was >60% at Daru, Madang, Misima, Wewak, Aiyura, Mendi, Mt Hagen, Tari, Tambul and Kundiawa and at these levels could be considered useful. The corresponding success rates of La Niña flood warnings at these locations was <60% and suggests that predicting floods using this method may not be useful in decision making.

The length of successful warnings for droughts and floods were analysed in conjunction with the success rates, and they appear to provide sufficient warning to be useful in smallholder systems where changes to management can be implemented relatively quickly provided the warnings are communicated quickly and effectively.

Coping strategies for food shortage

Many highlanders have access to a range of soils with different drainage characteristics. For these people, any effects of drought can be greatly reduced by planting crops during a drought into soils that are considered too poorly drained for sweet potato under normal conditions (Bourke 1988). Excessive soil moisture is likely to be most detrimental when tubers are being initiated in the period immediately after field planting. Highlands's villagers using poorly drained soils are particularly vulnerable to prolonged periods of high rainfall, particularly in those parts of the region, such as in the Porgera area of Enga, where most soils are poorly drained. Conversely, plantings made into these soils are likely to give above average yields during very dry periods.

A review of drought coping strategies has been completed for PNG by Kapal et al. (2003) and a summary of the relevant responses to reduce the impacts on sweet potato is given here.

Pre-drought. There are four main strategies which can be adopted pre-drought in order to mitigate the effects:

1. Maintain reserve cash and food reserves, the latter by maintaining excess root crops stored underground on the plant

2. Monitoring - by monitoring a number of factors the impacts of drought can be reduced. These include: rainfall prospects, seasonal conditions in surrounding areas, water supply, market

prices, in-ground food supply and alternative food supplies. It is also important to monitor grass and forest dry matter and assess risk of wildfire.

3. Maintenance of planting materials - this enables rapid planting and food resupply post-drought. Traditional storage methods for sweet potato include leaving tubers in the ground or storing tubers on a platform in the sun. Above ground storage of tubers is usually only for 2-3 weeks prior to consumption. Plants which are grown from cuttings or other vegetative material can be grown in swamp areas or on river flats. This allows the material to grow and reproduce, alleviating both short and medium term food shortages, as well as generating material for planting post-drought.

In-drought. There are three main strategies which can be used during drought in order to reduce its impacts:

1. Maintenance and storage of planting materials - the usual production of sweet potato in PNG involves continuous planting and sequential harvesting. However, it is vulnerable to attack by sweet potato weevil during drought, as the cracks in the ground allow the weevil access to the tubers. Traditional storage of tubers on platforms in the sun can extend the length of storage time for up to a month.

2. Planting and harvesting strategies - these include minimising the disturbance to the plant leaves (which increases evaporation) and to the roots (which damages its ability to extract water from the soil). Evapotranspiration can be reduced by planting under tree canopies and in wind breaks. It is also important to fill any holes created in the soil in order to help protect roots and tubers. The use of smaller pieces of tuber in planting also helps to preserve planting materials. Leaving old vegetation on fields and leaving the ground in a cloddy and uneven state assists in maintaining groundcover and soil health whilst assisting in decreasing the risk of erosion when rain events occur.

3. Using deep-rooted early maturing varieties of sweet potato - these varieties are able to access deeper soil water, are less susceptible to weevil and are able to provide some food (and planting supplies) in a relatively short time frame.

Post-drought. Whilst it is essential to plant quickly maturing plants as soon as possible, it is also important to plant a mixture of crops, not just sweet potato. After a drought there are relatively high levels of nitrogen in the soil. These high nitrogen levels are not beneficial to sweet potato and can contribute to low yields (Kanua and Bang 2001). In these cases it is advantageous to plant a quick growing crop such as maize, followed by an early maturing sweet potato crop.

Long-term. Increasing the diversity of crops planted by the rural population in terms of both varieties within staple crops (e.g. sweet potato) and also across the species of crop grown will reduce the risk of crop failure.

In order to increase the reliability of sweet potato supply through droughts, NARI has developed and trialled a number of drought tolerant and/or early maturing varieties in different areas. This has enabled the development of recommended varieties for the Lowlands, Highlands and High Altitude zones.

It is also important to reduce reliance on a single staple crop. It has been recommended that other drought tolerant crops be planted in addition to sweet potato. These include cassava and drought tolerant cooking banana. This reduces the effects of a potential crop failure.

Crops such as maize and beans also grow well in a variety of climates and locations, making them ideal crops to be used for diversification. Whilst these crops are currently acknowledged as food sources, some degree of education is needed in processing, storage and preparation of these as dried food sources.

It is also possible for more reliable agricultural products to be produced with the introduction of simple irrigation techniques in appropriate areas. This would allow access to surface and shallow groundwater supplies in order to mitigate drought. There are a number of simple systems being trialled including gravity flow systems, rope and washer pumps, treadle (pressure) pumps and hydraulic ram pumps.

Climate forecasts effectively relayed to villages with coping responses, drought tolerant and early maturing cultivars, crop diversification, monitoring and modelling of soil moisture status and extension officers trained in early warning detection and implementation of coping strategies are some responses that are likely to be effective.

The use and value of seasonal forecasts

The extent to which seasonal climate forecast information is used in decision making in PNG is not known. Using a climate forecast is different to changing a decision during, or because of, drought (or flood) and more akin to changing a decision because of a forecast of impending or worsening drought (or flood) in future. Subsistence farmers plant different crops or different varieties of crop during drought compared to what they would in normal seasonal conditions (Bourke 1988), but this is not using seasonal forecast information. However it’s likely that there is some use of seasonal climate forecast information in PNG because, for the most part, implementing drought coping strategies requires only a macro view of the differences in mean annual or seasonal rainfall between climatology, and El Nino and La Nina conditions (Kumar 2009). For almost all of PNG the annual median rainfall in El Nino conditions is only 20-40% of that in all years (see Figure 2b), so users of forecasts of El Nino could either implement some of the strategies referred to above that help cope with dry conditions, or they can switch management to actions that they have found successful in the past. On the other hand, the annual median rainfall in La Nina conditions is 60-70% of that in all years, however this shift in median values is only apparent in some provinces (coastal Sandaun and East Sepik, Western, Southern Highlands, western Gulf, eastern Central and Oro, Milne Bay) (see Figure 2c). Therefore a forecast of El Nino may be more valuable to PNG as a whole than a forecast of La Nina, because the former is associated with a much wider geographical area with a strong predictable signal. The impact and coping strategies used during previous droughts is well known by farmers, traders, industry organisations, but it is the responsibility of government, government agencies, support, welfare and research organisations to use this predictable signal in the climate to warn the community about forthcoming climatic events that have caused catastrophic economic, social and environmental hardship in the past (e.g. 1997, see Bourke et al. 2001).

A micro view of seasonal climate information requires detailed information about the climate history and the use of comprehensive application models (e.g. SCOPIC) (Kumar 2009). This paradigm can provide site-specific information for any season about the climate means, probability distributions, strength and predictability of the ENSO signal and forecast reliability, and when climate data is integrated with agricultural models (e.g. APSIM), similar information can be provided about the predicted production of that commodity (Hammer et al. 1996, Potgieter et al. 2003). Using these climate integrated agricultural production models to change decisions based on a climate driven prediction of modelled production has significantly increased profitability (Hammer 2000, McKeon et al. 2000, Cobon and McKeon 2002) and resource sustainability (McKeon et al. 2004) at the farm, local and regional scales in Australia, another country that has regions with a strong predictable ENSO signal (McBride and Nicholls 1983). An integrated climate and coffee production model for Arabica species has been developed (Roger Stone, personal communication) but we are not aware of such a model for sweet potato. The limitation for the application of these models in developing countries is that long-term (>30 years) daily records of rainfall, temperature (max and min), radiation, evaporation and humidity are often needed to run the models and these records are either not always available or they have not been transferred from paper to digital format.

As is the case with the use of seasonal climate forecast information, neither do we know the extent to which agricultural decision makers in PNG change decisions based on this information. Nor do we know the economic, social or environmental implications of any changed decisions. These metrics are difficult to obtain, even in developed agricultural economies (Kumar 2009), and are part of assessing the value of seasonal climate information. A seasonal forecast system has value if it is responsible for a change in management practice which is different to the status quo practice that was once based on the use of climatological data (Hammer 2000, Kumar, 2009).

CONCLUSION

The timing of extreme climate events has a major and sometimes devastating impact on staple food (e.g. sweet potato) and cash crop (e.g. coffee) production in Papua New Guinea. The growth and production of sweet potato in Papua New Guinea is non-seasonal however waterlogging in the early stages of growth, low soil moisture in the later growth stages and repeated frost reduce production. Sweet potato is relatively tolerant of drought but it is the sequence of water logging, frost then drought that leads to food shortages The growth cycle of coffee begins with flowering in July-November and ends with harvesting in May-September. Low soil moisture from September-May reduces production that restricts farmers income from the sale of coffee beans, limits the purchase of staple foods and decreases their capacity to be self-reliant. Coping strategies are available but often poor yields of sweet potato are not realised until harvest so early warning of extreme climate events and potential low production of crops could initiate early action and reduce the impacts. Effective dissemination to small holder farmers of seasonal climate forecasts and the outcomes of integrated climate and crop modelling are valuable means of managing climate variability in agricultural systems in other countries that have a weaker ENSO signal than Papua New Guinea.

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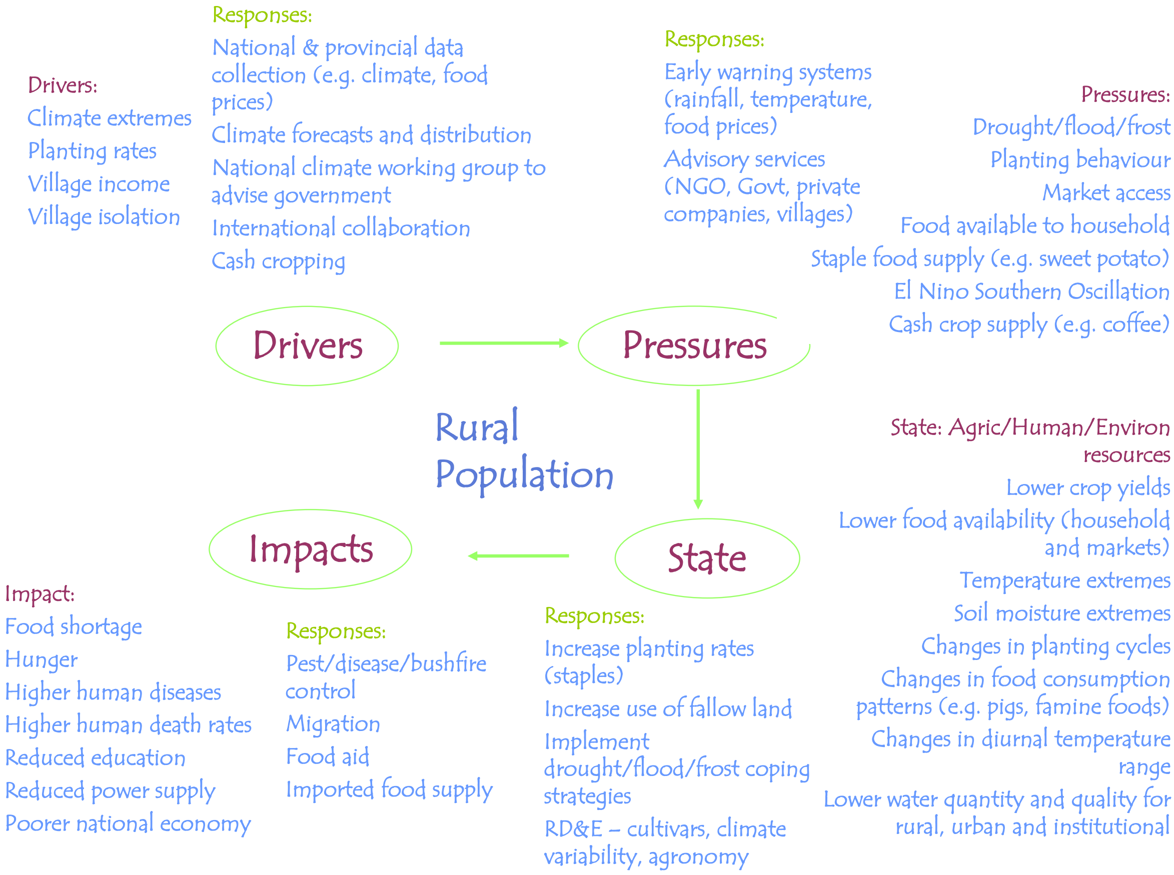

Drivers:
Climate extremes
Planting rates
Village income
Village isolation
Responses:
National & provincial data collection (e.g. climate, food prices)
Climate forecasts and distribution
National climate working group to advise government
International collaboration
Cash cropping
Responses:
Early warning systems (rainfall, temperature, food prices)
Advisory services (NGO, Govt, private companies, villages)
Pressures:
Drought/flood/frost
Planting behaviour
Market access
Food available to household
Staple food supply (e.g. sweet potato)
El Nino Southern Oscillation
Cash crop supply (e.g. coffee)
Drivers
Pressures
Rural Population
Impacts
State
State: Agric/Human/Environ resources
Lower crop yields
Lower food availability (household and markets)
Temperature extremes
Soil moisture extremes
Changes in planting cycles
Changes in food consumption patterns (e.g. pigs, famine foods)
Changes in diurnal temperature range
Lower water quantity and quality for rural, urban and institutional
Impact:
Food shortage
Hunger
Higher human diseases
Higher human death rates
Reduced education
Reduced power supply
Poorer national economy
Responses:
Pest/disease/bushfire control
Migration
Food aid
Imported food supply
Responses:
Increase planting rates (staples)
Increase use of fallow land
Implement drought/flood/frost coping strategies
RD&E – cultivars, climate variability, agronomy

b)

Drivers:
- Climate
- Altitude and topography
- Soil fertility
- Pest and disease
- Food available to household
- Cash supplies

Responses:
- Climate forecasts and distribution
- International collaboration
- Extension services and communication
- Cash cropping

Responses:
- Early warning systems – Climate predictors for rainfall, temperature, and food prices identified and tested for different locations
- RD&E – cultivars, climate variability, agronomy
- Crop diversification (e.g. banana, cassava)

Pressures:
- Climate drivers (El Nino Southern Oscillation, Coral sea and Indian Ocean temperatures)
- Drought, floods, frost - low soil moisture, water logging and repeated frosts reduce production
- Planting behaviour
- Fallow land available
- Staple food supply (e.g. sweet potato)
- Cash crop supply (e.g. coffee)

State: Agric/Human/Environ resources
- Water logging – extreme rain over short period (170-200mm /day) or high monthly rainfall for 2-3 months during tuber initiation (6-10 weeks post-planting)
- Low soil moisture (<20% soil capacity) during tuber bulking (3-6months post-planting)
- Association between altitude, drought and frost – during drought frosts occur as low as 1450m – repeated frosts occur >2200m
- Climatic sequences – e.g. wet conditions cause shallow rooting which increases vulnerability of plants to future drought
- Changes in planting rates – during food shortages planting rates can increase from 30 to 180m2/week

Responses:
- Official collection of rainfall and temperature (incl. min temp) data in the highlands
- Vulnerable regions identified
- Model soil moisture status
- Prompt and organised analysis of data, forecast issued and communicated
- Extension Offices trained in early warning detection
- Forecasts relayed to villages with adaptation responses

Impact:
- Lower yields
- Food shortage

Responses:
- Increase use of fallow land
- Implement drought/flood/frost coping strategies eg mulching,
- Increase planting rates (staples)
- Pest/disease/bushfire control
- Use of wantoks
- Migration
- Food aid
- Imported food supply

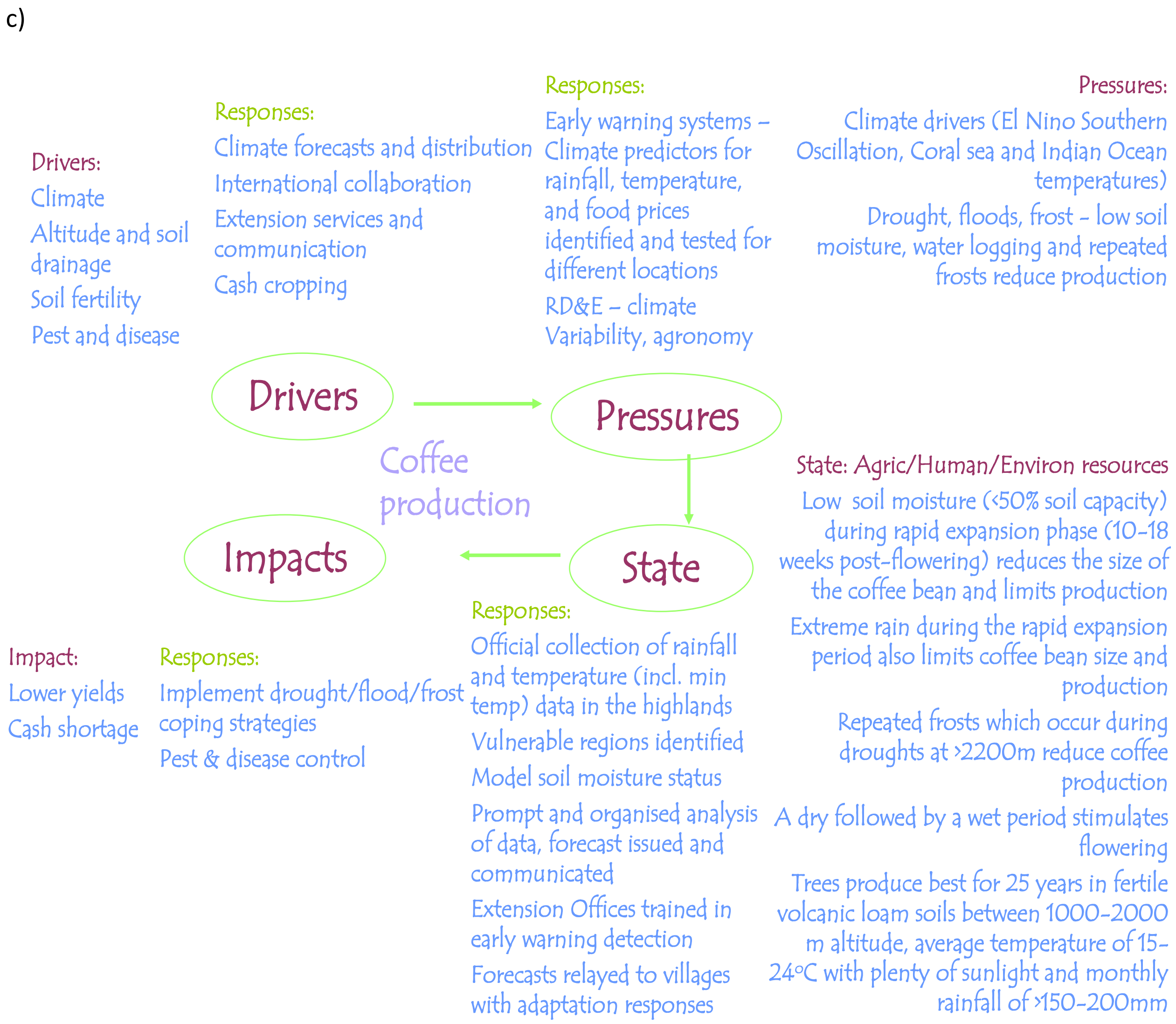
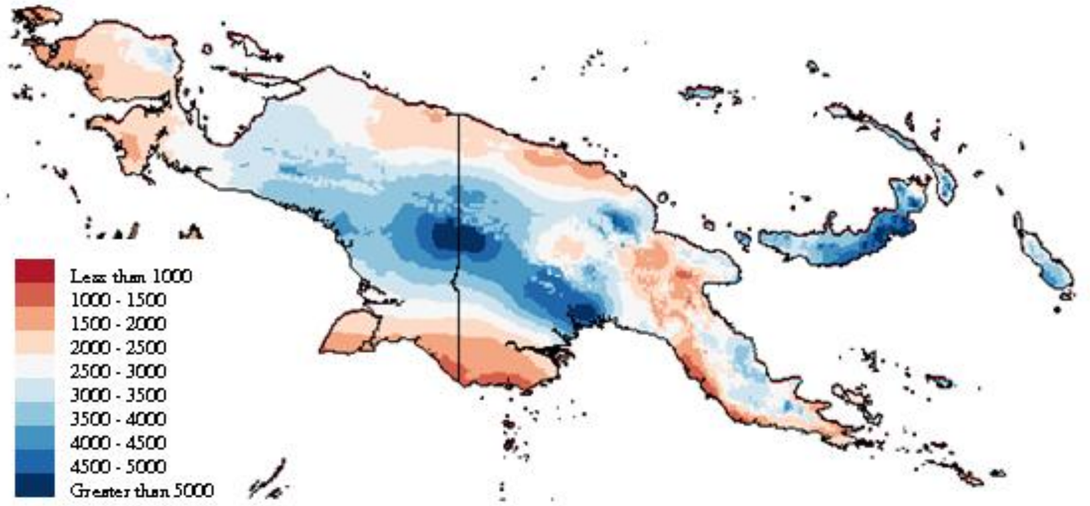
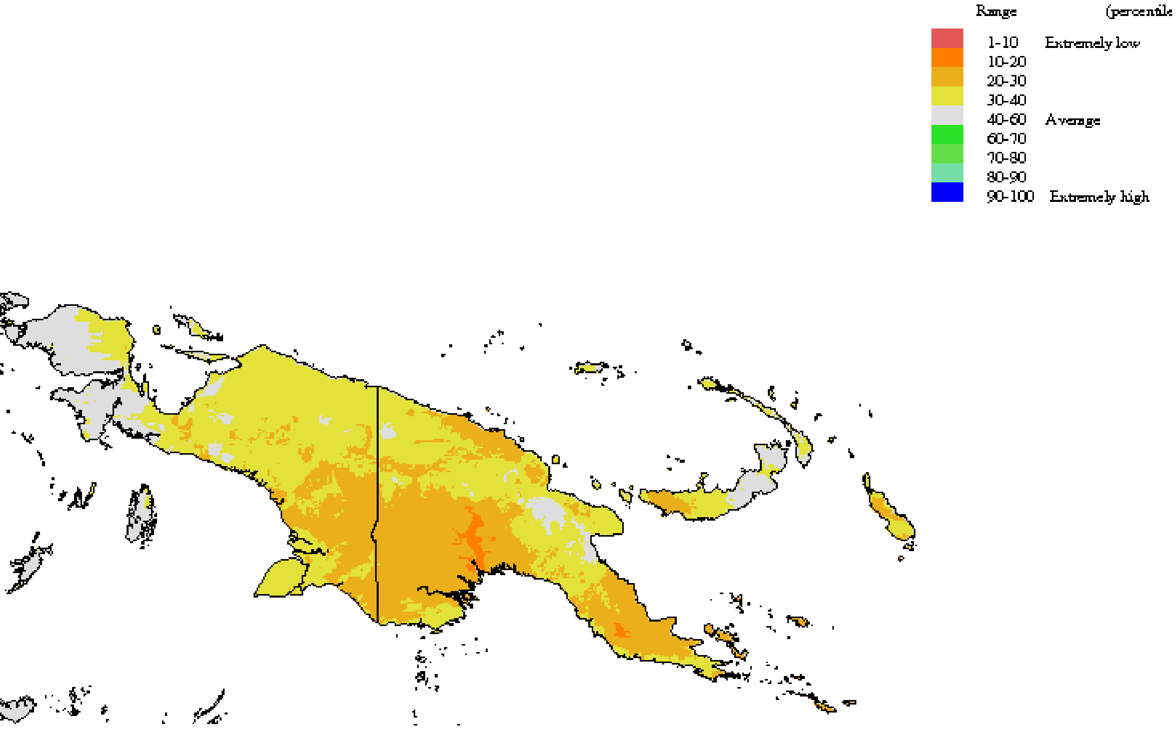


FIGURE 1. Driver Pressure State Impact Response model showing some likely responses to reduce the impacts of climate extremes on a) food shortage for the rural population b) sweet potato production and c) coffee production in PNG.

a)


Less than 1000
1000 - 1500
1500 - 2000
2000 - 2500
2500 - 3000
3000 - 3500
3500 - 4000
4000 - 4500
4500 - 5000
Greater than 5000

b)


Range
(percentile
🟥 1-10 Extremely low
10-20
20-30
30-40
40-60 Average
🟩 60-70
70-80
80-90
🟦 90-100 Extremely high

c)

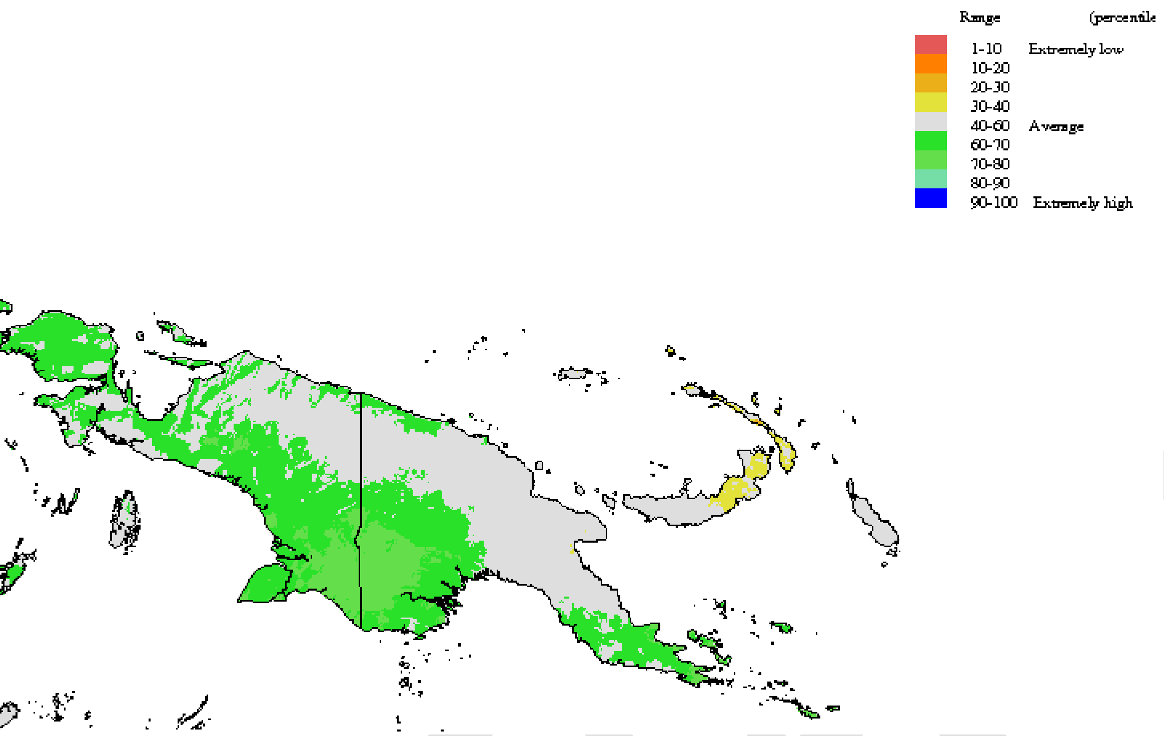


FIGURE 2. The island of New Guinea and nearby islands in Indonesian Papua and Papua New Guinea showing a) Mean April-March rainfall (mm) (1890-2009 and the median annual April-March rainfall in b) El Nino and c) La Nina years as a percentage of all years.

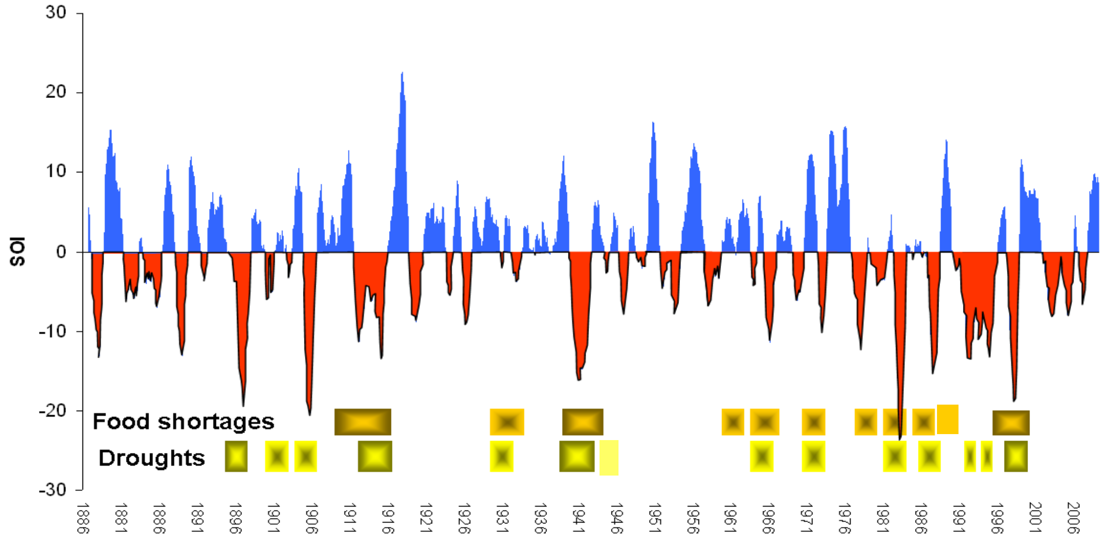
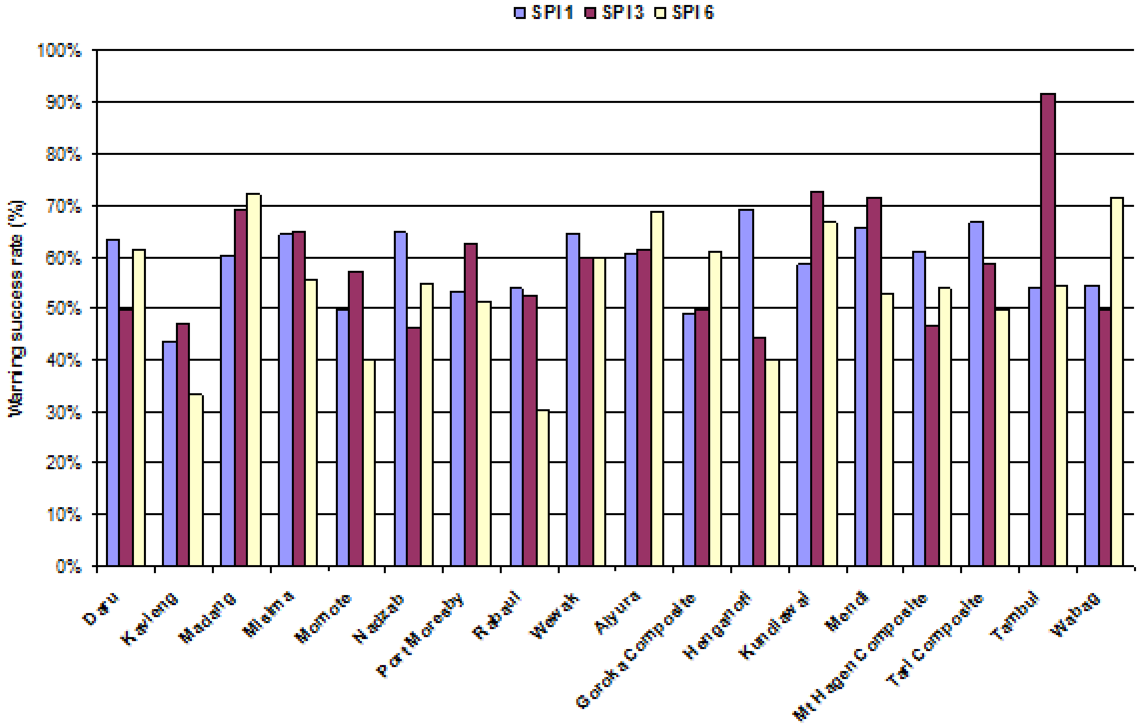


FIGURE 3. Southern Oscillation Index (11 year moving average) and corresponding droughts and food shortages in Papua New Guinea.



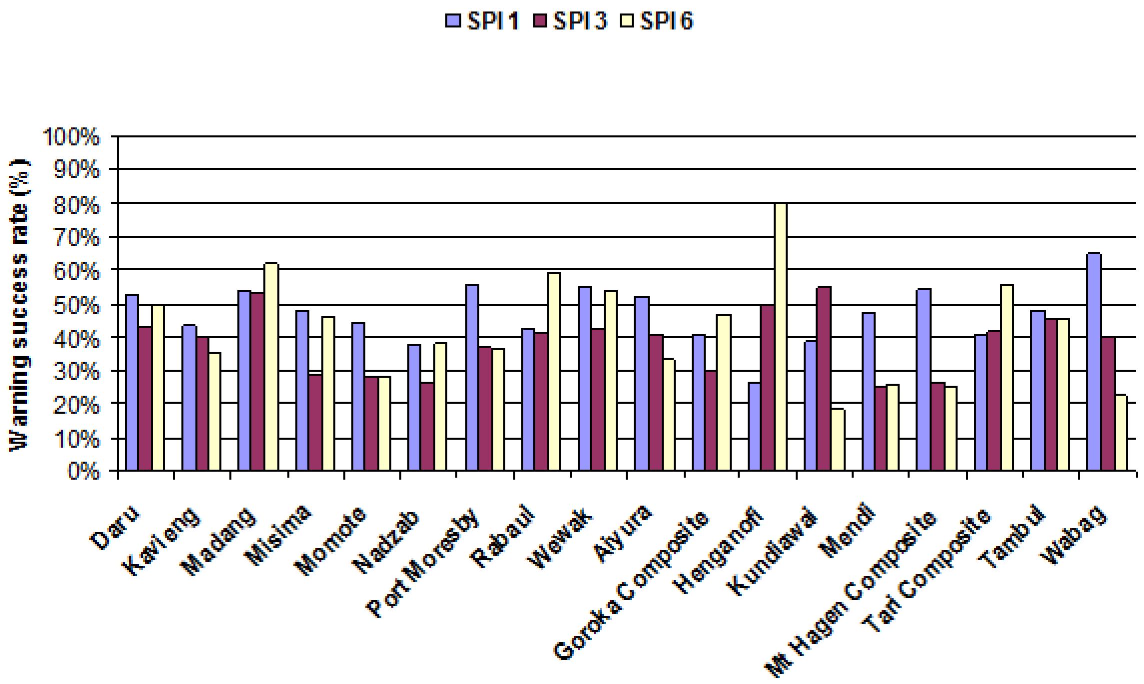
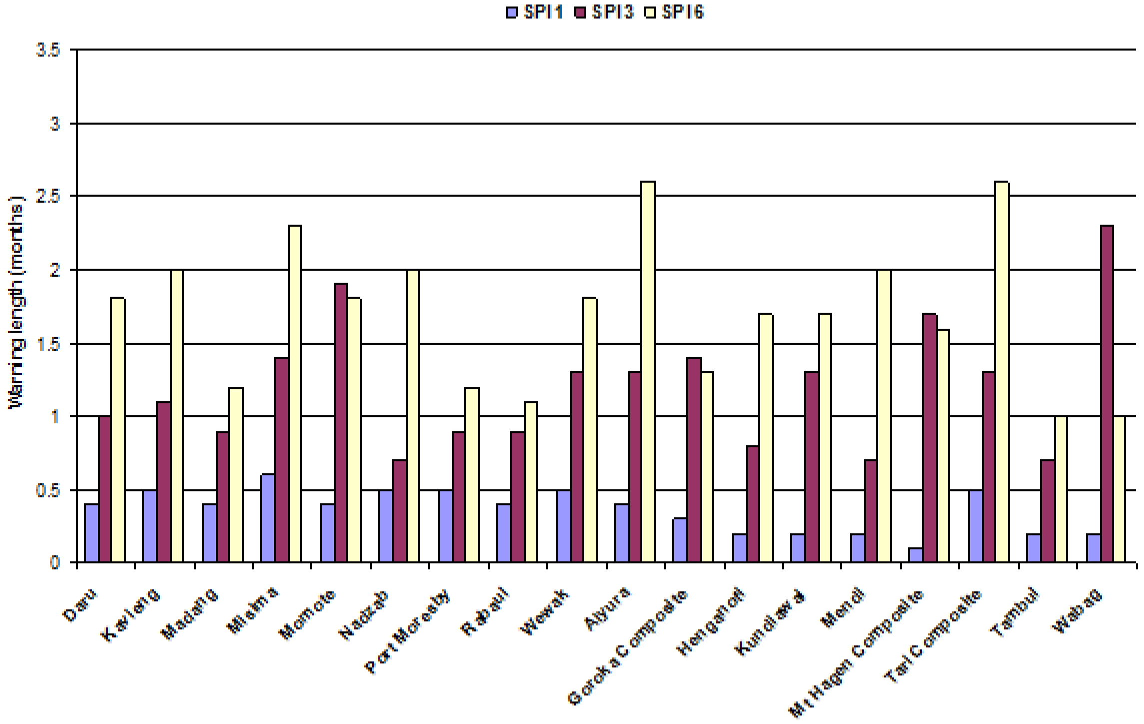


Figure 4. Warning success rates of El Niño droughts (top panel) and La Niña floods (bottom panel) for 18 locations in PNG.



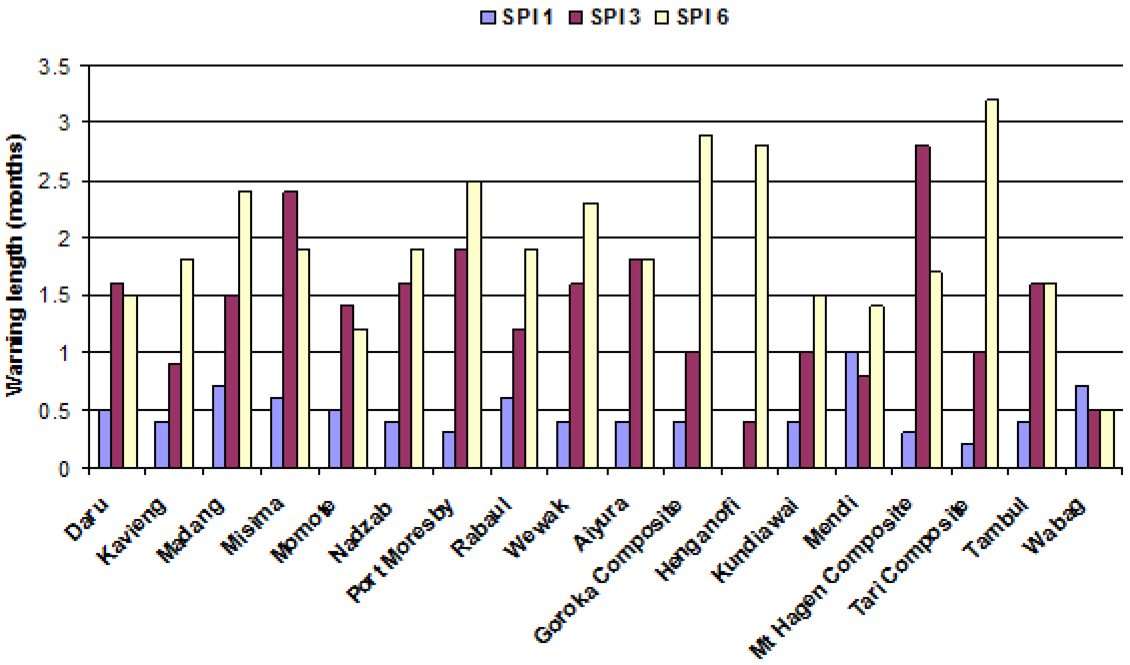
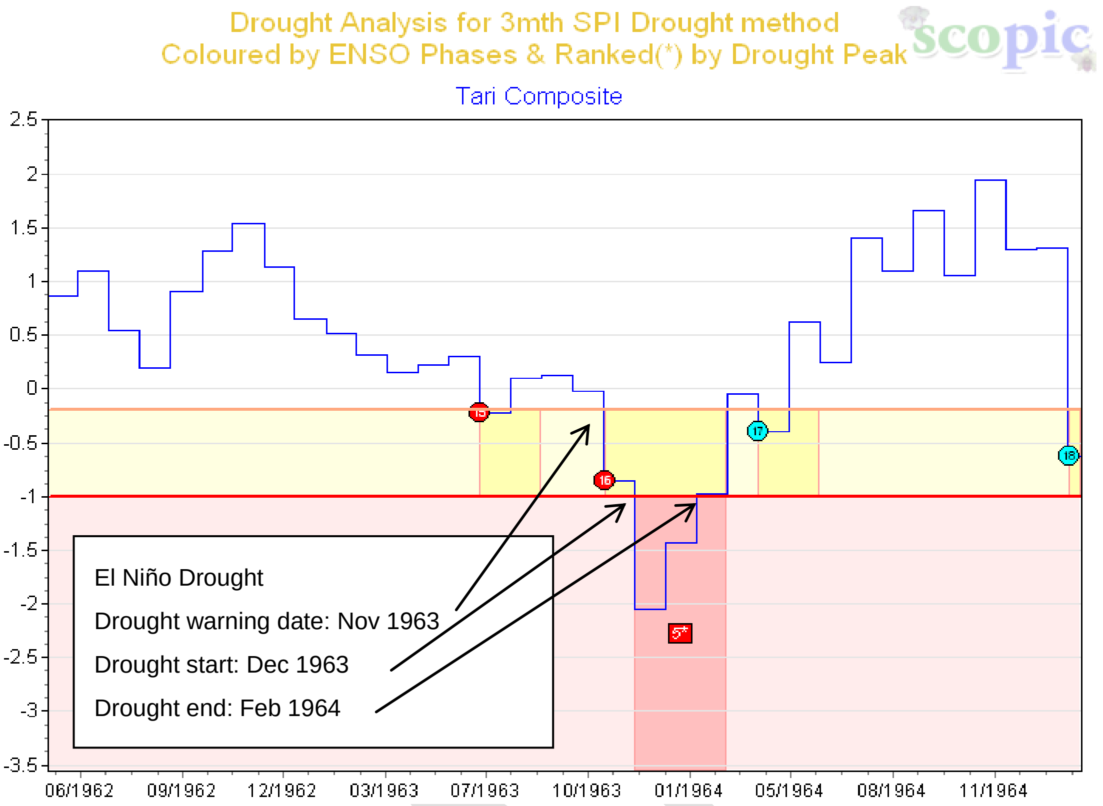


Figure 5. Warning lengths of El Niño droughts (top panel) and La Niña floods (bottom panel) for 18 locations in PNG.



Drought Analysis for 3mth SPI Drought method
Coloured by ENSO Phases & Ranked(*) by Drought Peak

Tari Composite

El Niño Drought
Drought warning date: Nov 1963
Drought start: Dec 1963
Drought end: Feb 1964

Figure 6. A successful drought warning for Tari (November 1963) indicated by SPI 3 (y axis) and showing SPI 3 reaching the drought warning threshold of -0.2, subsequently reaching drought threshold -1.0 and afterwards going out of drought. Drought warning failures are also shown. Red circles indicate El Nino and blue circles represent La Nina events.

TABLE 1. Percentage area of Papua New Guinea in drought (≤ percentile 10 April-March rainfall) or flood (≥ percentile 90 April-March rainfall) calculated by the proportion of pixels in the interpolated rainfall surface showing these values

Year	**Area in drought (%)**	**Year**	**Area in drought (%)**	**Year**	**Area in flood (%)**	**Year**	**Area in flood (%)**
1997	83.18	1972	41.0	1943	86.7	1985	28.1
1941	83.0	1980	39.0	1907	70.5	1970	24.1
1982	72.9	1931	37.7	1894	47.5	1939	23.9
1914	66.9	1905	32.1	1921	42.8	1925	23.8
1902	61.0	1924	31.7	1998	41.2	1949	23.4
1911	50.3	1965	27.0	1900	39.4	1891	22.6
1987	48.6	1976	27.0	1908	39.0	1964	22.4

1899	43.6	1923	24.7	2000	31.8	1906	22.0
1979	41.1	1993	24.3	1942	31.4	1999	20.3

Box 1. The effect of climatic variation on growth of sweet potato in the PNG highlands, in particular changes in daylength, solar radiation, temperature, frost and soil moisture (after Bourke 1988)

Daylength and Solar Radiation

Short days with low light intensity promote tuber formation while long days tend to favour vine growth at the expense of tubers, however, the annual variation in daylength in the PNG highlands (45 minutes) is small and is unlikely to influence yield.

Temperature

Contrasting day and night temperatures (29/20oC) give greater tuber yields than a constant temperature regime (29oC) suggesting that the moderately large diurnal temperature variation that occurs in the highlands would favour higher yields.

Temperature influences the rate of crop development and the period from planting to harvesting in PNG. Crop development is delayed by lower temperatures in PNG but crop yields are not affected because of a longer period to maturity. For example, average experimental yields of 15 to 30 t/ha occur at Aiyura (1620 m) for 7 to 9 month crops. Experimental yields in the PNG lowlands are 15-20 t/ha for 5 or 6 month crops.

Sweet potato plants are subject to chilling injury when exposed to temperatures in the range of 0 to 10-12oC. If exposure to the chilling temperatures is brief, the changes in plant tissue are reversible, but they become irreversible after prolonged exposure. Prolonged exposure to these temperatures may reduce sweet potato yields in the highlands.

The intolerance of sweet potato to frost is widely acknowledged and at times frost is an important constraint on sweet potato production in high altitude locations in the PNG highlands. The effect of frost on yield appears to vary with the developmental stage of a crop. If a crop is frosted before tuber bulking occurs, crop maturity is delayed but the same tuber yield is still achieved. The time of harvesting, which is normally between 9 and 12 months after planting at these altitudes, is extended up to 15 months. In contrast, crops frosted during tuber bulking (about 6 to 9 months) yield watery, inedible tubers. For crops frosted after nine months, tubers cease to grow but remain edible for up to four months after the frost.

Frost severity and frequency and any subsequent damage vary considerably between locations and over time. In the Eastern Highlands, only a few minor frosts have been recorded since the early 1930s, but they occur more frequently in the Southern Highlands. In the Southern Highlands, Enga and the Western Highlands, frost damage has occurred in most months of the year, but it is more common between July and November. Frosts are sometimes associated with drought. Three droughts that occurred in the Southern Highlands between 1952 and 1984 (1965, 1972, 1982) coincided with frosts, but other frosts in 1953, 1958, 1960, 1961, 1974 and 1980 did not coincide with droughts.

The most severe frosts undoubtedly result in major shortfalls in food supply. This is particularly so at very high altitude locations (above 2200 m). Crop vulnerability to frost damage is very vulnerable in regions in Enga, Southern Highlands Province, and Western Highlands Province and least vulnerable in all Eastern Highlands Province above 1600m.

Soil Moisture

Extremes of soil moisture have the main climatic influence on variability in sweet potato yield. Sweet potato is generally tolerant of drought and there is little evidence from PNG to show that low soil moisture levels affect yield, except in the most severe drought. The international literature indicates that soil moisture levels of less than 20 per cent of field capacity depress yield. As such, very low levels of soil moisture may be detrimental early in crop life when tubers are being initiated but low soil moisture levels are most critical toward the end of the growing period when rapid tuber bulking is occurring.

Waterlogging or very high soil moisture levels are most detrimental to high tuber yields, particularly when either occurs during the tuber initiation phase.

Appendix 1a. Monthly rainfall data retrieved and compiled for Papua New Guinea

The long term monthly rainfall data were sourced from the PNG National Weather Service (NWS), the PNG colonial data archive (CDA - Bureau of Meteorology, Australia), the Coffee Industry Corporation (CIC) at Aiyura and the National Agricultural Research Institute (NARI) at Tambul. The location, elevation and availability of monthly rainfall data for 18 meteorological stations across PNG are shown. Because some stations were moved (e.g. Lae to Nadzab, Rabaul to Tokua) and others had short lengths of records, some data records were combined. Ten composite stations were prepared using analytical methods to combine and convert data and some missing data were patched. The methods used are described in Cobon et al. 2009b and have provided continuous good quality data with more than 30 years of records for 2 stations in the high altitude zone, 7 stations in the highlands and 9 stations in the lowlands.

Station	Latitude, Longitude	Elevation (m), Length of record (years), Missing data (%)	Data period	Source
Aiyura (25001)	-6.19, 145.55	1640, 73, 6	June 1937-June 1941, Jan 1945-Mar 2010. Missing values for (Jan –May 1937; July 1941-Dec 1944; Dec 1972; Sep-Dec 1975; July 1988).	CDA, NWS, CIC
Daru (65029)	-9.08, 143.20	6, 116, 7.7	July 1894-Jun 1899, Jul 1900-May 1902, Jul 1903-Dec 2007, Jan 2009-Feb 2010. Missing values (Jan-June 1894; Nov 1898; Jul 1899-June 1900; July- Oct 1901; June 1902-June 1903; Nov 1905; Mar-May 1906; Jan 1907; Dec 1912; Jan 1913; Dec 1913-Mar 1914; Nov 1914; Jan 1918; June 1922; Aug-Oct 1922; Apr- July 1923; Dec 1923; Aug-Sept 1925; July-Sept 1926; Sept- Dec 1927; June 1929; Apr –Jun 1931; Aug-Sep 1931; Mar-July 1932; Jan 1933; Apr – May 1933; Feb 1934; Apr 1934; Aug 1934; Apr 1935; Dec 1936; May	CDA, NWS

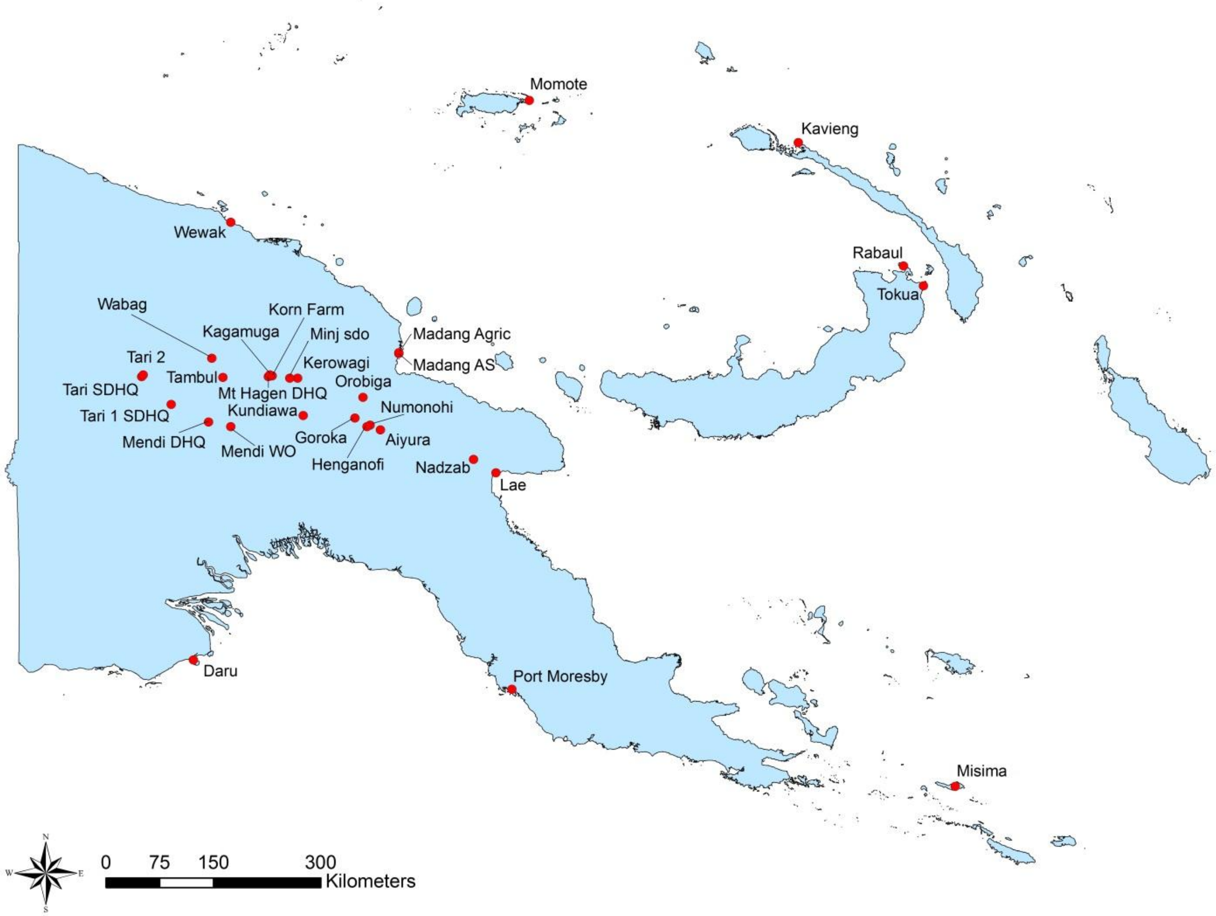
			1938; Aug 1938; July-Nov 1942; Nov 1994; Jan-Dec 2008; May 2009.	
Kavieng (20001)	-2.58, 150.8	7, 94,14.5	Feb 1916-Oct 1941, Sept 1949-Jul 1952, Sept 1953-April 1954, Jun 1955-Dec 1955, Dec 1956-Apr 2010. Missing values (Jan, Oct 1916; Jan-Mar 1925; July-Sept 1925; Feb-Mar 1928; Jan 1933; Jan, Aug 1941; Nov 1941-Aug 1949; Feb –Aug 1950; Jan-Aug 1951; Feb-June 1952; Aug 1952-Aug 1953; May 1954-Jun 1955, Jan 1956-Nov 1956).	CDA, NWS
Madang Composite		8, 94, 6.2	Feb 1916-Aug 1941, Nov 1944-Mar 1947, Jan 1948-Apr 2010	
- Madang Agric ((200070)	-5.23, 145.78	8, na, na	Missing values (Jan 1916; Dec 1916; Aug-Oct 1924; Dec 1924; Sept 1941-Oct 1944, April 1946-Dec 1947).	CDA
- Madang AS (10003)	-5.22, 145.78	4, na, na		CDA, NWS
Misima (50033)	-10.67, 152.77	20, 93, 9.5	Feb 1917-Dec 1941, Jan 1946-Feb 1948, Aug 1949-Dec 1951, Nov 1953-Apr 2010. Missing values (Jan 1917; Jan 1925; Jan 1939; June-July 1939; Sept-Nov 1939); June 1941; Jan 1942-Dec 1945, Aug-Dec 1946; Dec 1947; Jan 1948; Mar 1948-Jul 1949, Dec 1949- Feb 1950; Jan 1952-Oct 1953).	CDA, NWS
Momote (15003)	-2.05, 147.42	4, 61, 1.9	May 1949-Apr 2010 Missing Values: (Jan –April 1949; Aug 1949; Jan-Mar 1950; Jan-June 1951)	CDA, NWS
Port Moresby (55006)	-9.45, 147.20	42, 135, 8.2	Jan 1875-Sept 1876, Oct 1881-May 1883, Jan 1891-May 1901,	CDA, NWS

			Jul 1902-Apr 2010 Missing values (June-July 1876; Oct 1876-Sept 1881; Apr-Dec 1882; Apr 1883; Jun 1883-Dec 1890; May 1891; Sept 1893; July 1894; July 1897; June 1898; July 1900; Jun 1901-Jun 1902).	
Wewak (80002)	-3.58, 143.67	5, 54, 0.5	Jan 1956-Apr 2010 Missing Values: (Feb-Mar 2009; May 2009)	CDA, NWS
Rabaul Composite		4, 119, 10.6	Jan 1891-Dec 1897, Jan 1899-Dec 1908, Jan 1910-Dec 1910, Jan 1912-Dec 1912, Sept 1913-Dec 1937, April 1946-Apr 2010. Missing values (Feb-Mar 1893; July-Aug 1897; Jan 1898-Dec 1898; July 1899; June 1906 Jan-Dec 1909; Jan -Dec 1911; Jan 1913-Aug-1913; Mar 1915; Jan 1938-Mar 1946; July-Aug 1946).	
-Rabaul (40005, 200340)	-4.13, 152.12	4, na, na		CDA, NWS
-Tokua (40056)	-4.38, 152.37	10, na, na		NWS
Nadzab Composite		70, 85, 13.4	May 1925-May 1930, Mar 1937-Nov 1941, Jul 1945-Apr 2010. Missing values (Jan- Apr 1925; Nov-Dec 1925; Feb-June 1928; June 1930-Feb 1937; Jan-Feb 1941; Dec 1941-Jun 1945). About 10 years of missing data	
-Lae (30002)	-6.73, 147.00	8, na, na		CDA, NWS
-Nadzab (30045)	-6.56, 146.72	70, na, na		NWS
Goroka Composite		1600, 61, 6.2	Mar 1948-Dec 1969, Dec 1970-Oct 1980, Feb 1982-Mar 2009 Missing values (Jan-Feb 1948; Jul 1949; Dec 1949; Oct-Dec 1950; Feb-Apr 1951; Jan-Nov 1970, Nov 1980-Jan 1982; Dec 2008; Apr-Dec 2009).	
- Goroka (25002)	-6.04, 145.23	1600, na, na		CDA, NWS
- Numonohi (25062)	-6.13, 145.42	1530, na, na		NWS
- Orobiga (25064)	-5.78, 145.33	1500, na, na		NWS
Mt Hagen Composite		1730, 39, 4.6	Jan 1951-Aug 1990	

- Mt Hagen DHQ (75023, 200243)	-5.52, 144.14	1730, na, na	Missing Values: (May-Dec 1975; Jul-Aug 1984; Dec 1984; Oct-Dec 1986; Feb 1988; Jan 1990; May 1990; July 1990; Sept – Dec 1990)	CDA,
- Kuk (75044)	na	1600, na, na		ARS
- Korn Farm (75011, 200398)	-5.51, 144.19	1600, na, na		Highlands Agric College
- Kagamuga (75015, 200468)	-5.50, 144.16	1620, na, na		
				NWS
Kundiawa Composite		1550, 48, 21	May 1950-Nov 1950, April 1952-Dec 1952, Dec 1953-Dec 1985, April 1990-Jun 1993, Jan 1995-Feb 1998	
- Kerowagi (90001, 200052)	-5.54, 144.51	1550, na, na		CDA, NWS
- Kundiawa (90002, 200182)	-6.01, 144.58	1530, na, na	Missing values (Jan-Apr 1950; Dec 1950-Mar 1952, Jan 1953-Nov 1953, Aug-Sept 1984; Dec 1984; Aug-Dec 1985; Jan 1986-Mar 1990, Jul 1993-Dec 1994; Mar-Dec 1998).	CDA, NWS
- Minj sdo (75004, 200240)	-5.54, 144.41	1600, na, na		CDA, NWS
Tambul Composite		2320, 52, 35	Feb 1957-Jan 1973, Oct 1974-Dec 1991; Jul 2004-Jan 2009	
- Tambul pp (75010, 200348)	-5.53, 143.57	2320, na, na	Missing values (Jan 1957; Dec 1966; Oct-Nov 1972; Feb 1973-Sep 1974; Jan 1978; Aug-Dec 1978; May-Sept 1979;Nov 1980; Dec 1981; Apr 1983; June-Dec 1984; Jan-Apr 1989;Jan-June 1991;Jan 1992-June 2004; Feb-Dec 2009).	CDA, NWS
- Tambul haes (75022)	na	na		NARI HAES
Tari Composite		1670, 48, 13.8	June 1952-Nov 1982, Jan 1988-Dec 2000	
- Kugu (4km E of Tari), SHP)	na	na	Missing values (Jan-May 1952; Aug 1953; Mar 19568; May-Dec 1970; Dec 1972; Apr-June 1981; Dec 1982-Dec 1987).	AWS
- Tari SDHQ (70002, 200256)	-5.52, 142.55	1670		CDA, NWS
- Tari 1 SDHQ	-5.87, 142.92	1670		GHCN

- Tari 2 (70024)	-5.50, 142.57	1670		NWS
Mendi Composite - Mendi WO (70038) - Mendi DHQ (70005, 200339)	 -6.15, 143.67 -6.09, 143.39	1750, 55, 5.5 1750 1750	May 1951-Jun 2006 Missing values: (Jan-Apr 1951; Dec 1953; Jan 1954; Feb 1968; May 1968; Apr-Aug 1969; Oct – Dec 1969; Jan-Feb 1970; Apr 1970; May-July 1971; July 1992; Dec 1992; Oct-Dec 1997; Dec 1998; Dec 2000; July-Dec 2006.)	 CDA, NWS CDA, NWS
Wabag Composite with Amapyaka (05012, 200265)	-5.29, 143.43	2080, 55, 39.7	April 1950-Dec 1969, March 1987-Dec 1997, Jun 2000-Mar 2002, Jan-Sep 2003; Jan 2005; Jul-Aug 2005 Missing values (Jan-Mar 1950; Jan-Feb 1970; Apr-Aug 1970; Aug 1970-Nov 1971; Mar-Apr 1972; June 1972-Dec 1981; Aug 1982-Apr 1984; July 1984-Feb 1987; Dec 1987-Jan 1988; Dec 1988-Jan 1989; Dec 1989-Jan 1990; Sept-Oct 1994; Dec 1994; Jan 1998-May 2000; Apr-Dec 2002; Oct 2003-Dec 2004; Feb-June 2005; Sept-Dec 2005)	
Henganofi (25006, 200312)	-6.15, 145.38	1570, 31, 15.6	Oct 1955-Feb 1982; April 1984-June 1986 Missing values: Jan-Sept 1955; Mar 1970; Nov 1970; Mar-Apr 1971; Oct 1972; Mar-Dec 1973; July 1975; June 1978; May- June 1970; Mar 1982-Mar 1984; June 1985; July – Dec 1986.	

Appendix 1b. Location of stations in Appendix 1a where rainfall data was retrieved and compiled for Papua New Guinea



Appendix 3. The timing, location and cause of reported food shortages in the Papua New Guinea highlands, 1910 to 2009

Year	Time of year	Province /District	Cause	Notes	Source
1911-1914		# Aiyura area, EHP			Bourke 1988
1930s and 1940s	early	#	Frost and drought	An informant born about 1923 recalled two major shortages; Oral accounts report numerous deaths as a direct result of food shortages in 1941 in Enga Province	Bourke 1988
1937		Kainantu			Bourke 1988
1938-39		Kainantu	Drought		Bourke 1988
1940		Kainantu			Bourke 1988
1955	JASOND	SHP			Bourke 1988
1962	JASOND	# EHP Kainantu, SHP	Waterlogging in SHP	This food shortage may be due to excess rainfall during tuber initiation phase. Tambul Feb 62 - 425mm. Mendi Aug 62 - 410mm, Sept 62 - 386mm and Oct - 428 mm	Bourke 1988 Bourke 1988 p 174-80
1964-65		Kainantu, Henganofi	Water surplus then drought		Bourke 1988 (p 184)
1965-66	JASONDJFM	# SHP	Water surplus then drought 1965 JJASON Frost	Tari Nov 64 – 679 mm, Mendi Mar 65 – 405 mm, Aug-Nov 64 - above average rainfall Mendi and Tari	Bourke 1988 (p 196)
1967-68	JASONDJFM	SHP	Water surplus Jul-Aug 67; Planting rate cycles	Mendi Jul 67 - 370mm, Aug 67 - 351mm	Bourke 1988 (p 224)
1970-71	JASONDJFM	SHP	Water surplus MJJASON 1970	Mendi May 70 - 384, Jun 70 - 218, Jul 70 - 342, Aug 70 - 280, Sept 70 - 345, Oct 70 - 435mm, Nov 70 - 363mm	Bourke 1988
1972-73	JASONDJFM	# Enga, SHP, WHP	Water surplus, Frost - Severe at high alt; Drought; Climate extreme exacerbated by low in planting cycle in SHP,	Major food shortage; Large scale food relief operation till May 73; It is possible that this food aid averted increases in death rates. Mendi Feb 72 - 369, Mar 72 - 387mm; Tambul Mar 72 - 383mm, Apr 72 - 351; Tari Feb 72 - 407,	Bourke 1988 (p 224)

			which were in turn initiated by very wet periods in early 1970	Mar 72 - 362mm, Apr 72 - 246	
1978-79	JASONDJF	Upa SHP	Water surplus, Drought	Selling small tubers, Mendi May-Oct 77 water surplus, Aug 77 - 557mm	Bourke 1988
1980-81	SONDJFMA	# Upa SHP, WHP, Enga	Frost – high alt; Waterlogging SHP Water surplus EHP	Rise in price of SP at Upa Village; Extremely high water surplus at Mendi July-Aug 80; reports of hairy tubers in SHP support waterlogging;	Bourke 1988 (p 181-3,192
1982-83	ASONDJF	# EHP, SHP, Chimba, WHP, Enga	Drought/frost; High alt more severe; Late 1981-early 1982 was an extended period of water surplus Aiyura, Goroka, Mendi	Food inadequate in EHP till June 83; Rise in price of SP from 10 to 20 toea/kg compared to last year; claim of unsuccessful request for food aid at Upa; Climatic extreme does not usually affect planting rate of SP, but very wet period in early 1982 in EHP was an exception	Bourke 1988 (p 183, 186, 226
1984-85	JJASONDJFM	# EHP, Chimba, SHP	Water surplus; Severe; Exceptionally wet weather in late 1983 to mid 1984 in SHP provides partial explanation for food shortage in 1984; Planting rate cycles SHP, EHP and Chimbu); Low in planting cycle exacerbated by climate extreme in SHP. Water surplus for extended period May 83-Jul 84 at Mendi and Oct 83-Dec 83 at Goroka and Dec 83 at Kundiawa	Cash from sales of coffee muted impact; Food intake was limited but no indication that food intake was seriously reduced; intake of imported food rose; intake of pigs reduced. Mendi JFMAMJ 1984 - 327, 376, 308, 302, 311, 363 Minor drought in JFM 1984 where rainfall at Aiyura, Mt Hagen, Kundiawa, Goroka all below average.	Bourke 1988 (p 192, 224) SCOPIC
1987-88	AMJJASOND	# EHP, SHP,	Water surplus from Apr 87-	Aiyura SPI drought rank 4; Mendi SPI drought rank 8;	SCOPIC

		WHP	Jun 87 at Tambul; Drought	Aiyura Jan 87 374 mm; no prior water surplus evident at Mendi	
1990	FMAMJ	EHP, SHP		Mendi SPI drought rank 4	SCOPIC
1991-96		Islands and Coastal		Long period of drought; severe in places; Wewak, Madang and Misima either SPI drought rank 1 or 2	SCOPIC
1992	SOND	EHP, Chimba, Enga	Water surplus Oct 91-Jun 92 in EHP & Chimba and Apr 92-Jul 92 Enga		SCOPIC
1993	MJJASON	EHP, SHP, WHP, Chimba, Enga		Minor drought in highlands	SCOPIC
1997-98	AMJJASONDJ FMA	# EHP, WHP, Enga, SHP, Chimba	Water surplus July-Nov 1996; Drought/frost; Severe	Major international food aid effort; 1.2M people or 40% of rural population in PNG in a severe and life threatening food shortage – many others were affected less severely; Mendi Jan 97 302, Feb 97 305mm – v wet ASO 96; Tari Sept 96 345 mm Oct 350 mm; Misima Mar 97 756 mm – v wet SOND 96;	Allen and Bourke 1997ab SCOPIC
2001-02	SONDJF	EHP	Water surplus Apr-Jul 01; Drought	Goroka rainfall low, SPI drought rank 3	SCOPIC
2002-03	JASONDJFM	SHP	Water surplus Apr-Jun 02; Drought	Mendi low rainfall JASO, Mendi SPI drought rank 6; Mendi Sept 01 - 401mm, Oct 01 - 396mm	SCOPIC
2004-05	ASONDJFMA M	SHP	Water surplus Feb-Mar 04; Drought	Mendi SPI drought rank 10; Mendi Dec 03 - 256mm, Jan 04 - 281mm, Feb 2004 - 395mm	SCOPIC
2006-07	ONDJFMAMJ J	WHP	Water surplus Jan-Jun 06; Drought followed		SCOPIC

EHP – Eastern Highlands Province, SHP - Southern Highlands Province; WHP - Western Highlands Province; # – widespread drought; SPI – Standard Precipitation Index; SCOPIC indicates a drought but not necessarily a food shortage.

Footnote - The apparent increase in the frequency of food shortages closer to the present is most likely to reflect greater availability of data and better reporting rather than an increase in food shortages over time.

FOOD SHORTAGES AND EXTREME CLIMATE EVENTS IN PAPUA NEW GUINEA

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Abstract

In Papua New Guinea extreme climate events have occasionally led to the collapse of normal subsistence food production systems causing large scale food shortages that threaten human health and survival (e.g. during the 1997 El Niño drought). Production of staple foods (e.g. sweet potato) and cash crops (e.g. coffee) are adversely affected by drought, water logging and frost. We investigated the association between El Nino Southern Oscillation (ENSO), extreme climate events and reported food shortages. Over the 120 year period between 1890 and 2009, there have been 15 widespread droughts and 13 of these were associated with El Niño events, and eight of the 12 widespread floods were associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. Since the early 1900s eleven major and widespread food shortages have been reported in the highlands but they have not been associated with drought alone but also with water surplus and frost. Eight of the eleven widespread food shortages were associated with El Niño years (1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these were preceded by La Niña events (1996, 1971, 1964, 1910). There was evidence of anomalous frosts at lower altitudes (1450 m) and more frequent frosts at higher altitudes (>2200 m) during clear skies in El Niño droughts that also contributed to food

shortages. It is a combination of climatic extremes that causes the damage to crops that leads to a shortage of subsistence food in the highlands. The Standardised Precipitation Index provided a useful warning of success of more than 60% for El Niño droughts in 10 of the 18 locations, however the success rates of La Niña flood warnings at these locations was lower (<60%). Using seasonal climate forecasts based on ENSO and climate integrated crop models may provide early warning for farmers, industry agencies and government to help prepare for food shortages. Strategies that can help subsistence farmers cope with extreme climate events are discussed.

Introduction

The predominance of subsistence agriculture in Papua New Guinea (PNG) highlights the importance of food security (Bourke 2001, Manning 2001). Smallholder farmers have generally learnt to manage the localised shortages of food that occur regularly through the use of extended family and purchasing food from the sale of cash crops such as coffee and potatoes. It is the large scale shortages of food that occur irregularly that threaten human health and survival such as during the 1997 El Niño (Allen and Bourke 2001).

During these extreme events (droughts, very high soil moisture levels and frosts) that cause widespread food shortages, the PNG government has relied upon food aid (national and international) and on villagers' self-reliance to purchase imported food. It is the more remote and isolated communities that are most vulnerable because of their poor access to food distribution points and markets to sell produce from cash crops.

Sweet potato is the dominant staple food. It is therefore the most important crop in PNG and over 60% of the rural population depend on it as their main food source (Bourke et al., 2009). However banana, taro, yams, cassava, corn and other traditional vegetables as well as pigs are important dietary components. About 75% of annual sweet potato production is grown in the highlands. Climatic extremes, particularly high soil moisture, droughts and frosts are among the main constraints to production. Sweet potato is relatively drought tolerant. However, excessively wet soil conditions soon after planting of vines followed by drought as the tubers increase in size causes a marked depression in tuber yield and this is commonly attributed to the drought. However it is the combination of climatic extremes that causes the damage which can lead to a shortage of subsistence food in the highlands (Bourke, 1988). Repeated frost events also significantly reduces yield of sweet potatoes. Successfully forecasting these events some months in advance could initiate alternative management and avoid significant reductions in yield.

Extreme events (droughts and excessively wet periods) have significant impacts on agricultural production and natural resource management. In the Pacific Rim, including PNG and eastern Australia, the tele-connections (relationship over a long distance) of climate-related anomalies with El Niño and La Niña events are strong and are reliable enough for use in decision making.

Smallholders produce over 90% of the coffee grown in PNG making it a valuable cash crop for many villages. It is grown mainly for export and represents ~40% of all agricultural exports. Although coffee is grown in over 70 countries, the conditions for growing quality beans exist in a relatively narrow climatic range. The optimal climatic regions for growing Arabica coffee are relatively cool climates in the sub-tropical (16-24^{o}N and S latitude) and equatorial (<10^{o} latitude) zones with the optimum temperature between 15-24^{o}C year round. Photosynthesis is slowed above these temperatures and frost damage can occur when temperatures persist around 0^{o}C. A large diurnal temperature range is beneficial to coffee quality.

The optimum rainfall for coffee is 1500-2500 mm of rain falling over an eight month growing period with a three month dry season coinciding with the harvest. Where rainfall is less, irrigation can be applied to compensate, although this is not relevant in the PNG context. A period of water deficiency in the soil followed by good rainfall will favour the onset of flowering and produce a homogenous flowering and defined harvesting season. These clearly defined dry and wet events are not common in many areas of the PNG highlands, where a non-seasonal rainfall pattern persists. This can lengthen the flowering and harvesting periods in these areas.

The El Niño Southern Oscillation (ENSO) is associated with warmer than normal water in the central Pacific Ocean (called El Niño), or cooler than normal water (called La Niña). El Niño is often associated with lower than normal rainfall and because of the dry atmosphere and clear skies during these periods lower minimum temperatures are experienced. La Niña is often associated with higher than normal rainfall and minimum temperatures. These ENSO events commonly commence each year in March-June and persist for 9-12 months and because of the oscillation between El Niño and La Niña, droughts can commonly be followed by floods (and vice versa) from March to May.

Lessons learned from the 1997 drought in PNG demonstrated the vulnerability of agricultural production to climate impacts both in terms of food security and farm income. A review of the current hazard monitoring capabilities and procedures after the 1997 drought recommended development of improved systems that provide early warning of developing threats and regularly updated information on their characteristics and progress. It is therefore a priority in PNG to develop an effective climate forecasting and warning system focussing on drought response strategies, information on quantitative measures of drought and improved crop management practices. Here we report on a project which retrieved long-term rainfall data for PNG, examined its relationship with El Niño Southern Oscillation (ENSO) and investigated the utility of drought warning tools to help maintain food security (sweet potato) and farm income (coffee).

With some reference to sweet potato as a staple food and coffee as a valuable cash crop, the aim of this study in PNG was to:

1. Provide an overview of the influence of climate on the food security of the rural population using the Driver Pressure State Impact Response (DPSIR) model;

2. Source data, develop mean and historical rainfall surfaces and show the association with ENSO;

3. Examine the number and extent of droughts, floods and food shortages;

4. Use the Standardised Precipitation Index (SPI) to examine success rate and warning length for ENSO triggered droughts and floods;

5. Examine the association between droughts, floods, frosts, food shortage; and

6. Investigate current practices to maximise production and minimise risk through drought management.

MATERIALS AND METHODS

The definition of drought in this study is a lack of available water relative to demand resulting from a period of below-average precipitation that may be harmful to crop production at a critical stage of development. Floods are generally described as the overflowing of water onto land that is normally dry and this can cause physical damage to landscapes. However, for the purposes of this study we are more interested in excess water and its impacts in an agricultural context that may occur in the absence of physical damage to the landscape, in particular, the effect that water in excess of soil water capacity and water logging of soil profiles may have on crop production.

The Driver Pressure State Impact Response (DPSIR) model (OECD 1997) was used to provide a summary of how the rural population could respond to some of the key drivers threatening food security including climatic extremes. We assessed the pressures that are most evident, what changes occur in the resources as a consequence, the impacts of those changes and how governments, research funders, extension officers and small holders should respond. In a similar way we investigated climate as one key driver of sweet potato and coffee production and identified the likely pressures, state (resource conditions of importance to production), impacts and responses required by different stakeholders in order to maximise production.

The long term monthly rainfall data were sourced from the PNG National Weather Service (NWS), the PNG colonial data archive (CDA - Bureau of Meteorology Australia), the Coffee Industry Corporation (CIC) at Aiyura and the National Agricultural Research Institute (NARI) at Tambul. The location, elevation and availability of monthly rainfall data for 18 meteorological stations across PNG are shown in Appendix 1. Because some stations were moved (e.g. Lae to Nadzab, Rabaul to Tokua) and others had short lengths of records, some data records were combined. Ten composite stations were prepared using analytical methods to combine and convert data and some missing data were patched. The methods used are described in Cobon et al. 2009 and have provided continuous good quality data with more than 30 years of records for 2 stations in the high altitude zone (Tambul, Wabag), 7 stations in the highlands (Aiyura, Goroka, Mt Hagen, Kundiawa, Tari, Mendi, Henganofi) and 9 stations in the lowlands (Daru, Kavieng, Madang, Misima, Momote, Port Moresby, Wewak, Rabaul, Nadzab).

A poster showing PNG's variable rainfall was produced showing 120 percentile maps of PNG rainfall from 1890 to 2009. Rainfall data were sourced from the PNG NWS and the PNG CDA (see McAlpine et al. 1975 for stations, record length and years of record from 1890 to 1970). The maps were produced using interpolated (Jeffery et al. 2001) April to March rainfall data each year from 1890 to 2010 (Appendix 2). The number of rainfall stations used for the interpolation was less than 20 before 1913, between 1942 and 1945 (World War II) and after 1974. This spatial dataset was used to calculate the mean April-March rainfall (1890-2009) (Figure 2) and the area of PNG where annual rainfall (April-March) fell into drought (≤10 percentile) or flood (≥90 percentile) categories (Table 1).

The statistical model SCOPIC (Seasonal Climate Outlook for Pacific Island Countries) was used to assess the frequency (and severity) of droughts and floods using different indices of the Standardised Precipitation Index (SPI) (e.g. 1, 3 and 6 month time scales) (Edwards and McKee, 1997). SCOPIC is a decision support system for generating probabilistic predictions, seasonal climate forecasts or drought/flood analysis for rainfall or other parameters where climate plays an important role (e.g. production of crops) http://cosppac.bom.gov.au/products-and-services/seasonal-climate-outlooks-in-pacific-island-countries/.

The drought and flood analyses in this study were based on the growth period of the crops investigated and the time scale on which a water shortage or excess may have on crop production. For example, depending on location, the growth period of sweet potato is 4 to 9 months and it is about 8 months for coffee. In some locations (e.g. high altitudes) a 1 month period with little or no rainfall or a 1-3 month period of water excess may have a significant negative impact on crop production. For these reasons we have completed the drought and flood analyses using 1, 3 and 6 month periods of monthly moving average rainfall using SPI, to trigger warnings (drought SPI -0.2; flood, SPI 0.2) and identify periods (drought SPI -1; flood, SPI 1).

Warnings that later resulted in either droughts or floods were classified as warning successes, the length of the warning (for successes only) was calculated from the time the warning was first issued to the time the drought or flood threshold was reached and the frequency of drought/flood was calculated per decade as an indicator of vulnerability to these extreme events.

The droughts and floods were classified into ENSO phases (after Allan et al. 1996, McKeon et al. 2004) at the time the warning was first issued using the Australian Bureau of Meteorology Southern Oscillation Index (SOI) for June to November. The classification of historical warnings into ENSO phases (El Niño, La Niña, Other) allows an assessment of the warning success associated with each ENSO phase. High historical warning success rates (>60%) associated with a particular ENSO phase provides some confidence that this association may continue into the future and therefore provides the basis for use as an early warning tool for droughts and floods.

RESULTS

A summary of how some of the drivers of food security in the rural population (climatic extremes, planting rates, village income and village isolation) and the pressures that are most evident, the changes that can occur in the resources as a consequence, the impacts of those changes and how governments, research funders, extension officers and small holders should respond is shown in Figure 1a. The following responses are likely to be effective: Providing access to technologies and information that increase farmers income from cash crops (e.g. coffee), providing early warning of extreme climatic and market driven events (e.g. seasonal climate forecasts using ENSO, trends in food prices such as rice), monitoring planting rates and yields of staple foods to pre-empt shortages in supply, provide technologies and information that improve food yields (protection from pests and disease, copping strategies for soil nutrient run-down, drought, floods and frost) and lastly provide food aid by importing and effective distribution of food.

A similar assessment for sweet potato production highlighted climate as a key driver (ENSO, Coral Sea and Indian Ocean temperatures) responsible for low soil moisture, water logging and frosts that can reduce production (Figure 1b). Sequences of climate together with changes in planting rates produce cycles of sweet potato production. Waterlogging or extreme rain over short periods (170-200mm/day) or high monthly rainfall for 2-3 months during tuber initiation (6-10 weeks post-planting), low soil moisture (<20% soil capacity) during tuber bulking (3-6 months post-planting), the association between altitude, drought and frost (frosts occur as low as 1450 m during drought, repeated frosts at altitudes over 2200 m) and changes in planting rates associated with availability all combine to produce shortages of sweet potato. Climate forecasts effectively relayed to villages with coping responses, drought tolerant and early maturing cultivars, crop diversification, monitoring and modelling of soil moisture status and extension officers trained in early warning detection and implementation of coping strategies are some responses that are likely to be effective.

In a similar fashion drought, floods and repeated frosts can reduce production of coffee (Figure 1c). Low soil moisture (<50% soil capacity) during the rapid expansion phase (10-18 weeks post-flowering; November-January) and extreme rainfall during this same period can reduce the size of the coffee bean. Repeated frosts that occur during droughts at over 2200 m altitude, temperatures outside the 15-24°C range and rainfall less than 150-200 mm per month can reduce production of coffee, although most coffee is grown below 2000 m altitude. Similar responses to those used for sweet potato are likely to be most effective.

The mean annual (April-March) rainfall ranged from 1500-2000mm in the Eastern Highlands Province to 2500-3500 mm in Western and Southern Highlands Provinces (Figure 2).

There have been 12 major and widespread droughts in PNG in 1896, 1902, 1905, 1914, 1931, 1941, 1942, 1965, 1972, 1982, 1987 and 1997 (Allen 1989, Allen and Bourke 1997, Allen and Bourke 2000) as well as minor and less widespread droughts in 1992, 1993 and 2004 (SCOPIC analysis – current study) (Figure 3). These findings were largely supported by independent analysis completed for the PNG Rainfall poster (Appendix 2) where percentile 10 or less rainfall was received across large parts of PNG during these years. These widespread droughts were mostly associated with El Niño events (Figure 3) although localised or regional droughts did not always match this pattern.

The five most widespread droughts occurred in 1997, 1941, 1982, 1914 and 1902 (Table 1). In 1997 and 1941 over 80% of PNG received ≤10 percentile rainfall and therefore represent the worst droughts PNG has experienced since 1890 in terms of area affected. The five most widespread floods between 1890 and 2009 occurred in 1943, 1907, 1894, 1921 and 1998.

There have been 11 major and widespread food shortages reported in the PNG highlands in 1911-14, early 1930s, early 1940s, 1962, 1965-66, 1972-73, 1980-81, 1982-83, 1984-85, 1987-88 and 1997-98 (Appendix 3). These food shortages have not been associated with drought alone but also with water surplus and frost.

The SPI method provided an overall warning of success of 57% for El Niño droughts and 43% for La Niña floods. The success rate of El Niño drought warnings was useful (>60%) at Daru, Madang, Misima, Wewak, Aiyura, Mendi, Mt Hagen, Tari, Tambul and Kundiawa (Figure 4). The corresponding success rates of La Niña flood warnings at these locations was lower (<60%) and suggests that predicting floods using this method may not be useful in decision making.

The length of the warning was associated with the period of rainfall averaging. The average length of warning for El Niño droughts was 0.4, 1.2 and 1.7 months for SPI1, SPI3 and SPI6 respectively (Figure 5). The average length of warning for La Niña floods was 0.5, 1.4 and 1.9 months for SPI1, SPI3 and SPI6 respectively. An example from SCOPIC of the 3 month SPI time series at Tari from 1962-1964 showing a successful El Nino drought warning is shown in Figure 6.

The length of warnings for droughts and floods were analysed in conjunction with the success rates, and they appear to provide sufficient warning to be useful in smallholder systems where changes to management can be implemented relatively quickly provided the warnings are communicated quickly and effectively.

DISCUSSION

Climate and food shortage – sweet potato

Since the 1890s there have been 15 widespread droughts and 13 of these have been associated with El Niño events. In support of this ENSO signal, 8 of the 12 widespread floods have been associated with La Niña events. On a national scale droughts were associated with El Niño systems and wet events were associated with La Niña systems. However, there are local and regional differences that are important to understand.

Of the 15 widespread droughts, 12 have been major and widespread droughts and three were minor and less widespread. There have been 11 major and widespread food shortages reported in the PNG highlands but they have not been associated with drought alone but also with water surplus and frost. Sweet potato is the dominant staple food in rural PNG. Excessively wet soil conditions soon after planting of sweet potato followed by drought as the tubers increase in size causes a marked depression in tuber yield. This is commonly attributed to the drought. It is the combined climate sequence of water surplus followed by drought that produces the most damaging food shortages (Bourke 1988). A climate sequence of water surplus followed by drought some 6-10 months later produces the most damaging food shortages. The timing of the water surplus during the sweet potato tuber initiation phase (6-10 weeks post-planting) and drought toward the end of the crop growth cycle during the rapid tuber bulking phase (3-6 months post-planting) most severely impacts on sweet potato production. The water surplus early in the growth cycle limits the depth of rooting so the plants are especially vulnerable to even mild droughts because their root systems are shallow.

Eight of the eleven widespread food shortages have been associated with El Niño years (e.g. 1997, 1987, 1982, 1972, 1965, 1941, 1932, 1911-14) and four of these have been preceded by La Niña events (1996, 1971, 1964, 1910) (Figure 3). Three of the most severe food shortages in PNG over the past 120 years are those in 1997, 1911-14 and 1972. Each of these was associated with drought, but was preceded by a La Niña events (very wet period) the previous year. Climatic extremes partly contribute to food shortages in PNG.

It is a combination of crop yield in response to certain climatic extremes and people's decisions about how much to plant that provides the best explanation for variation in food supply (Bourke 1988). Variation in the supply of sweet potato is an outcome of variation in yield and variation in the area planted over time. The effect of climatic variation on plant growth, in particular changes in soil moisture, solar radiation, daylength and temperature, has the major impact on crop yields in the highlands, however the major climatic influences on sweet potato yield variation are extremes of soil moisture, particularly water logging and frosts (see Box 1)

Climate and cash flow - coffee

The equatorial coffee growing regions are at altitudes between 1000-2000 m with high humidity produced by the abundant rainfall. Deep, porous, well-drained soils of volcanic origin that are rich in nutrients are best for growing coffee. Extreme wet periods in poorly drained soils have a large negative impact on production as does drought, particularly during cherry ripening and development when large quantities of nutrients and water are required for high yields. The best coffee production in PNG is likely to come from good rainfall from August to April, a 2-3 month dry period from May-July with no frosts and plenty of sunshine. The bulk of Arabica coffee in PNG is grown over an altitude range of 1500 to 2000 m, although some is grown over a wider range of 700-2050 m (Bourke 2010).

The coffee growing period of about eight months in the highlands starts with flowering from July-November, the pinhead stage of cell division (weeks 0-8; September-October), the rapid expansion phase (weeks 8-18; November-January), endosperm growth and cherry ripening phase (weeks 18-32; February-May). The main harvesting time is from May-September. The amount of soil moisture available during the rapid expansion phase determines the eventual size of the coffee bean so a drought at this stage will limit coffee production. However following the severe soil moisture stress during the 1997 El Nino drought, PNG produced near record Arabica coffee exports in 1998 (Hombunaka and von Enden (2000). The extreme dry period before rainfall in October/November 1997 provided a strong flowering stimulus that led to the near record coffee yields in June and July 1998.

Early warning – success rate and warning length

The success rate of El Niño drought warnings was >60% at Daru, Madang, Misima, Wewak, Aiyura, Mendi, Mt Hagen, Tari, Tambul and Kundiawa and at these levels could be considered useful. The corresponding success rates of La Niña flood warnings at these locations was <60% and suggests that predicting floods using this method may not be useful in decision making.

The length of successful warnings for droughts and floods were analysed in conjunction with the success rates, and they appear to provide sufficient warning to be useful in smallholder systems where changes to management can be implemented relatively quickly provided the warnings are communicated quickly and effectively.

Coping strategies for food shortage

Many highlanders have access to a range of soils with different drainage characteristics. For these people, any effects of drought can be greatly reduced by planting crops during a drought into soils that are considered too poorly drained for sweet potato under normal conditions (Bourke 1988). Excessive soil moisture is likely to be most detrimental when tubers are being initiated in the period immediately after field planting. Highlands's villagers using poorly drained soils are particularly vulnerable to prolonged periods of high rainfall, particularly in those parts of the region, such as in the Porgera area of Enga, where most soils are poorly drained. Conversely, plantings made into these soils are likely to give above average yields during very dry periods.

A review of drought coping strategies has been completed for PNG by Kapal et al. (2003) and a summary of the relevant responses to reduce the impacts on sweet potato is given here.

Pre-drought. There are four main strategies which can be adopted pre-drought in order to mitigate the effects:

1. Maintain reserve cash and food reserves, the latter by maintaining excess root crops stored underground on the plant

2. Monitoring - by monitoring a number of factors the impacts of drought can be reduced. These include: rainfall prospects, seasonal conditions in surrounding areas, water supply, market prices, in-ground food supply and alternative food supplies. It is also important to monitor grass and forest dry matter and assess risk of wildfire.

3. Maintenance of planting materials - this enables rapid planting and food resupply post-drought. Traditional storage methods for sweet potato include leaving tubers in the ground or

storing tubers on a platform in the sun. Above ground storage of tubers is usually only for 2-3 weeks prior to consumption. Plants which are grown from cuttings or other vegetative material can be grown in swamp areas or on river flats. This allows the material to grow and reproduce, alleviating both short and medium term food shortages, as well as generating material for planting post-drought.

In-drought. There are three main strategies which can be used during drought in order to reduce its impacts:

1. Maintenance and storage of planting materials - the usual production of sweet potato in PNG involves continuous planting and sequential harvesting. However, it is vulnerable to attack by sweet potato weevil during drought, as the cracks in the ground allow the weevil access to the tubers. Traditional storage of tubers on platforms in the sun can extend the length of storage time for up to a month.

2. Planting and harvesting strategies - these include minimising the disturbance to the plant leaves (which increases evaporation) and to the roots (which damages its ability to extract water from the soil). Evapotranspiration can be reduced by planting under tree canopies and in wind breaks. It is also important to fill any holes created in the soil in order to help protect roots and tubers. The use of smaller pieces of tuber in planting also helps to preserve planting materials. Leaving old vegetation on fields and leaving the ground in a cloddy and uneven state assists in maintaining groundcover and soil health whilst assisting in decreasing the risk of erosion when rain events occur.

3. Using deep-rooted early maturing varieties of sweet potato - these varieties are able to access deeper soil water, are less susceptible to weevil and are able to provide some food (and planting supplies) in a relatively short time frame.

Post-drought. Whilst it is essential to plant quickly maturing plants as soon as possible, it is also important to plant a mixture of crops, not just sweet potato. After a drought there are relatively high levels of nitrogen in the soil. These high nitrogen levels are not beneficial to sweet potato and can contribute to low yields (Kanua and Bang 2001). In these cases it is advantageous to plant a quick growing crop such as maize, followed by an early maturing sweet potato crop.

Long-term. Increasing the diversity of crops planted by the rural population in terms of both varieties within staple crops (e.g. sweet potato) and also across the species of crop grown will reduce the risk of crop failure.

In order to increase the reliability of sweet potato supply through droughts, NARI has developed and trialled a number of drought tolerant and/or early maturing varieties in different areas. This has enabled the development of recommended varieties for the Lowlands, Highlands and High Altitude zones.

It is also important to reduce reliance on a single staple crop. It has been recommended that other drought tolerant crops be planted in addition to sweet potato. These include cassava and drought tolerant cooking banana. This reduces the effects of a potential crop failure.

Crops such as maize and beans also grow well in a variety of climates and locations, making them ideal crops to be used for diversification. Whilst these crops are currently acknowledged as food sources, some degree of education is needed in processing, storage and preparation of these as dried food sources.

It is also possible for more reliable agricultural products to be produced with the introduction of simple irrigation techniques in appropriate areas. This would allow access to surface and shallow groundwater supplies in order to mitigate drought. There are a number of simple systems being trialled including gravity flow systems, rope and washer pumps, treadle (pressure) pumps and hydraulic ram pumps.

CONCLUSION

The timing of extreme climate events has a major and sometimes devastating impact on staple food (e.g. sweet potato) and cash crop (e.g. coffee) production in Papua New Guinea. The growth and production of sweet potato in Papua New Guinea is non-seasonal however waterlogging in the early stages of growth, low soil moisture in the later growth stages and repeated frost reduce production. Sweet potato is relatively tolerant of drought but it is the sequence of water logging, frost then drought that leads to food shortages The growth cycle of coffee begins with flowering in July-November and ends with harvesting in May-September. Low soil moisture from September-May reduces production that restricts farmers income from the sale of coffee beans, limits the purchase of staple foods and decreases their capacity to be self-reliant. Coping strategies are available but often poor yields of sweet potato are not realised until harvest so early warning of extreme climate events and potential low production of crops could initiate early action and reduce the impacts. Effective dissemination to small holder farmers of seasonal climate forecasts and the outcomes of integrated climate and crop modelling are valuable means of managing climate variability in agricultural systems in other countries that have a weaker ENSO signal than Papua New Guinea.

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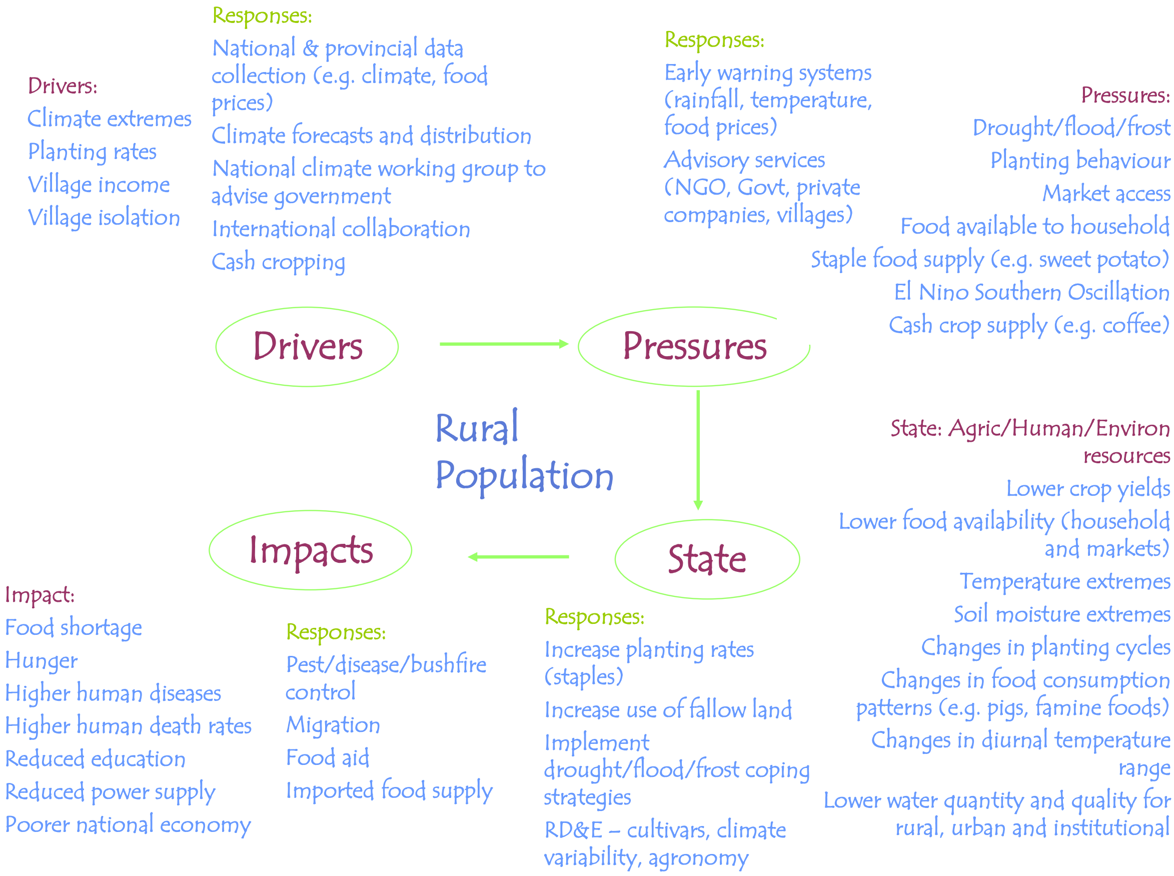
a)



Drivers:
Climate extremes
Planting rates
Village income
Village isolation

Responses:
National & provincial data collection (e.g. climate, food prices)
Climate forecasts and distribution
National climate working group to advise government
International collaboration
Cash cropping

Responses:
Early warning systems (rainfall, temperature, food prices)
Advisory services (NGO, Govt, private companies, villages)

Pressures:
Drought/flood/frost
Planting behaviour
Market access
Food available to household
Staple food supply (e.g. sweet potato)
El Nino Southern Oscillation
Cash crop supply (e.g. coffee)

State: Agric/Human/Environ resources
Lower crop yields
Lower food availability (household and markets)
Temperature extremes
Soil moisture extremes
Changes in planting cycles
Changes in food consumption patterns (e.g. pigs, famine foods)
Changes in diurnal temperature range
Lower water quantity and quality for rural, urban and institutional

Impact:
Food shortage
Hunger
Higher human diseases
Higher human death rates
Reduced education
Reduced power supply
Poorer national economy

Responses:
Pest/disease/bushfire control
Migration
Food aid
Imported food supply

Responses:
Increase planting rates (staples)
Increase use of fallow land
Implement drought/flood/frost coping strategies
RD&E – cultivars, climate variability, agronomy

b)

Drivers:
Climate
Altitude and topography
Soil fertility
Pest and disease
Food available to household
Cash supplies

Responses:
Climate forecasts and distribution
International collaboration
Extension services and communication
Cash cropping

Responses:
Early warning systems – Climate predictors for rainfall, temperature, and food prices identified and tested for different locations
RD&E – cultivars, climate variability, agronomy
Crop diversification (e.g. banana, cassava)

Pressures:
Climate drivers (El Nino Southern Oscillation, Coral sea and Indian Ocean temperatures)
Drought, floods, frost - low soil moisture, water logging and repeated frosts reduce production
Planting behaviour
Fallow land available
Staple food supply (e.g. sweet potato)
Cash crop supply (e.g. coffee)

State: Agric/Human/Environ resources
Water logging – extreme rain over short period (170-200mm /day) or high monthly rainfall for 2-3 months during tuber initiation (6-10 weeks post-planting)
Low soil moisture (<20% soil capacity) during tuber bulking (3-6months post-planting)
Association between altitude, drought and frost – during drought frosts occur as low as 1450m – repeated frosts occur >2200m
Climatic sequences – e.g. wet conditions cause shallow rooting which increases vulnerability of plants to future drought
Changes in planting rates – during food shortages planting rates can increase from 30 to 180m2/week

Responses:
Official collection of rainfall and temperature (incl. min temp) data in the highlands
Vulnerable regions identified
Model soil moisture status
Prompt and organised analysis of data, forecast issued and communicated
Extension Offices trained in early warning detection
Forecasts relayed to villages with adaptation responses

Impact:
Lower yields
Food shortage

Responses:
Increase use of fallow land
Implement drought/flood/frost coping strategies eg mulching,
Increase planting rates (staples)
Pest/disease/bushfire control
Use of wantoks
Migration
Food aid
Imported food supply

c)

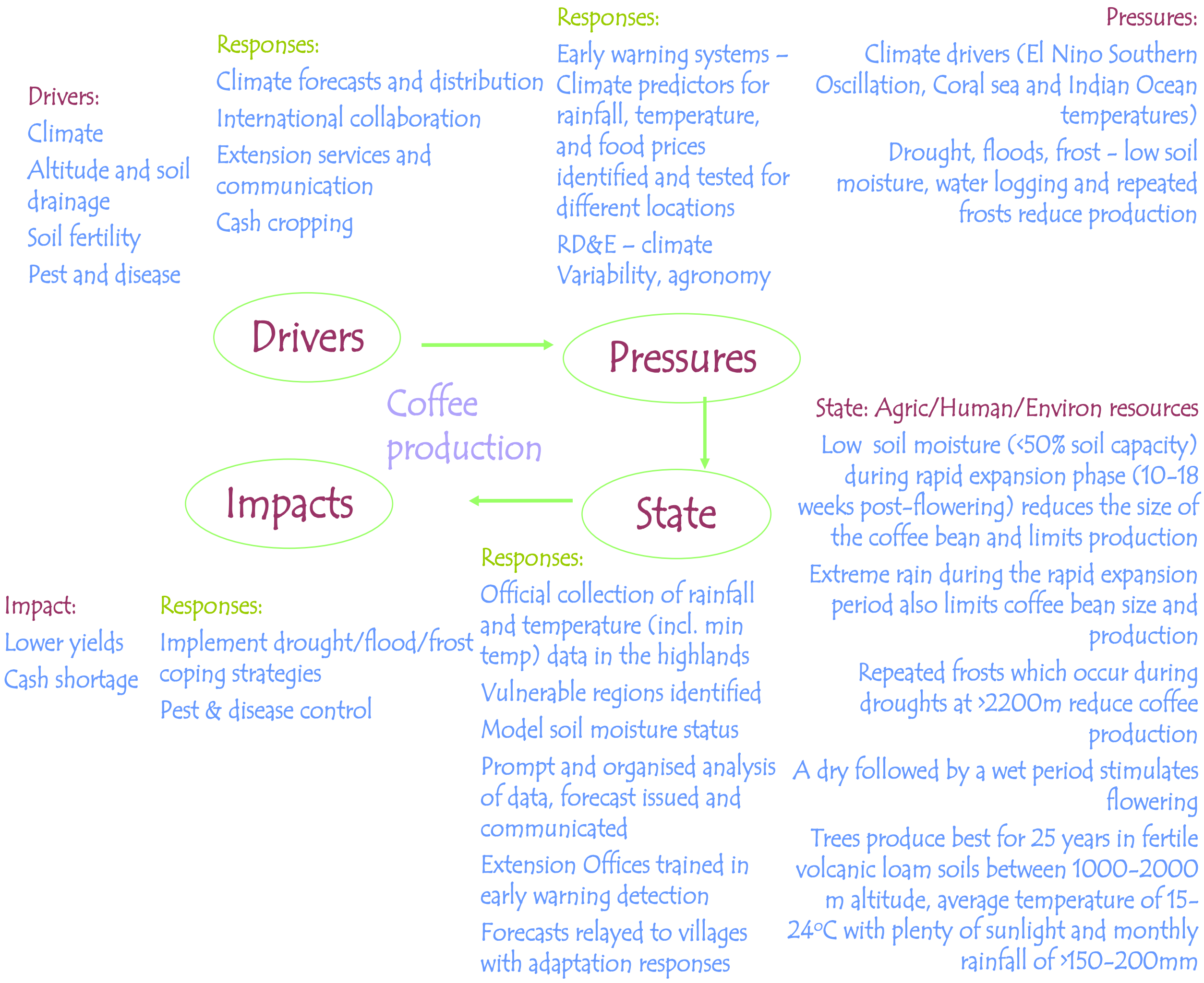


FIGURE 1. Driver Pressure State Impact Response model showing some likely responses to reduce the impacts of climate extremes on a) food shortage for the rural population b) sweet potato production and c) coffee production in PNG.

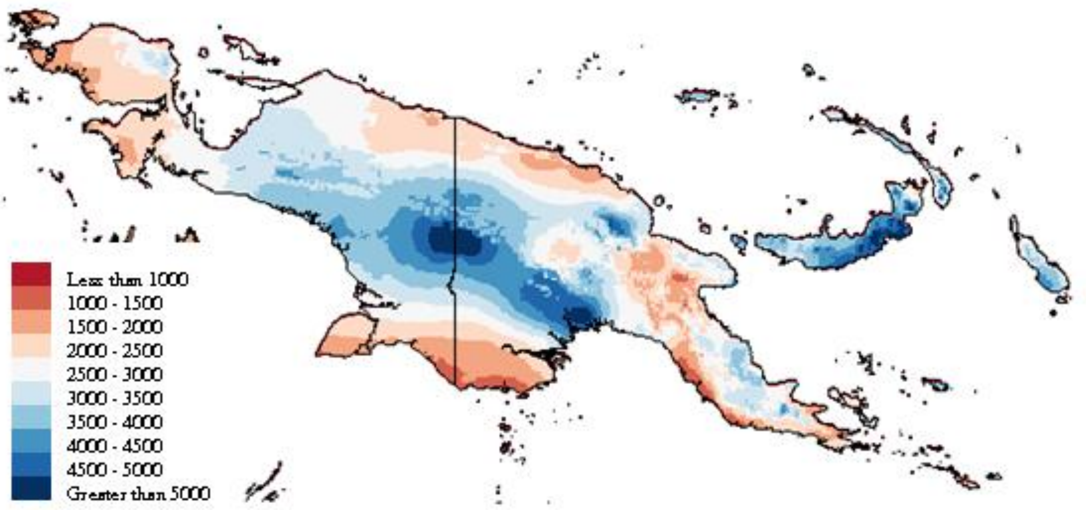


FIGURE 2. Mean April-March rainfall (mm) (1890-2009) in the island of New Guinea and nearby islands in Indonesian Papua and Papua New Guinea

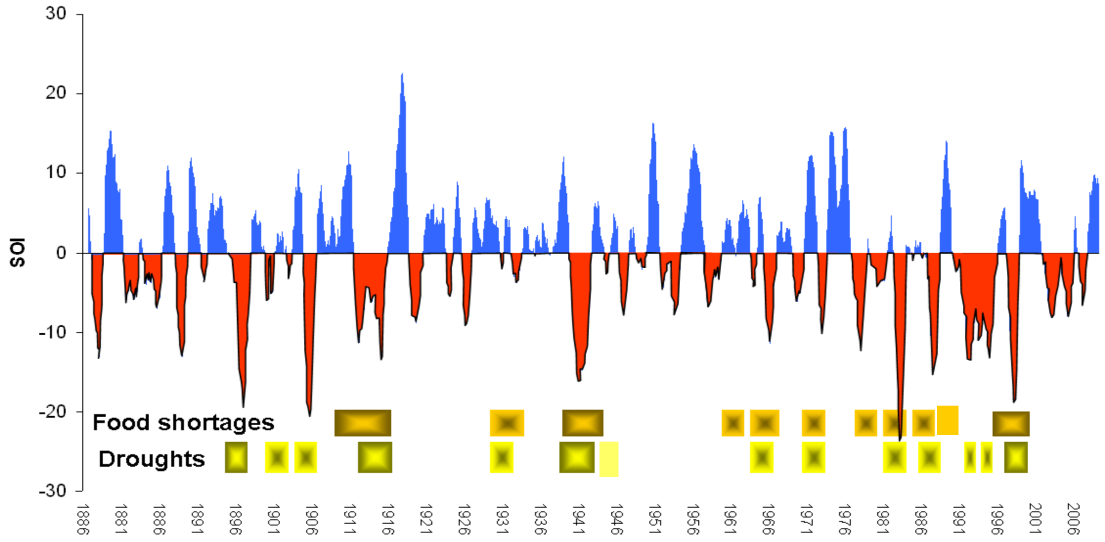


FIGURE 3. Southern Oscillation Index (11 year moving average) and corresponding droughts and food shortages in Papua New Guinea.

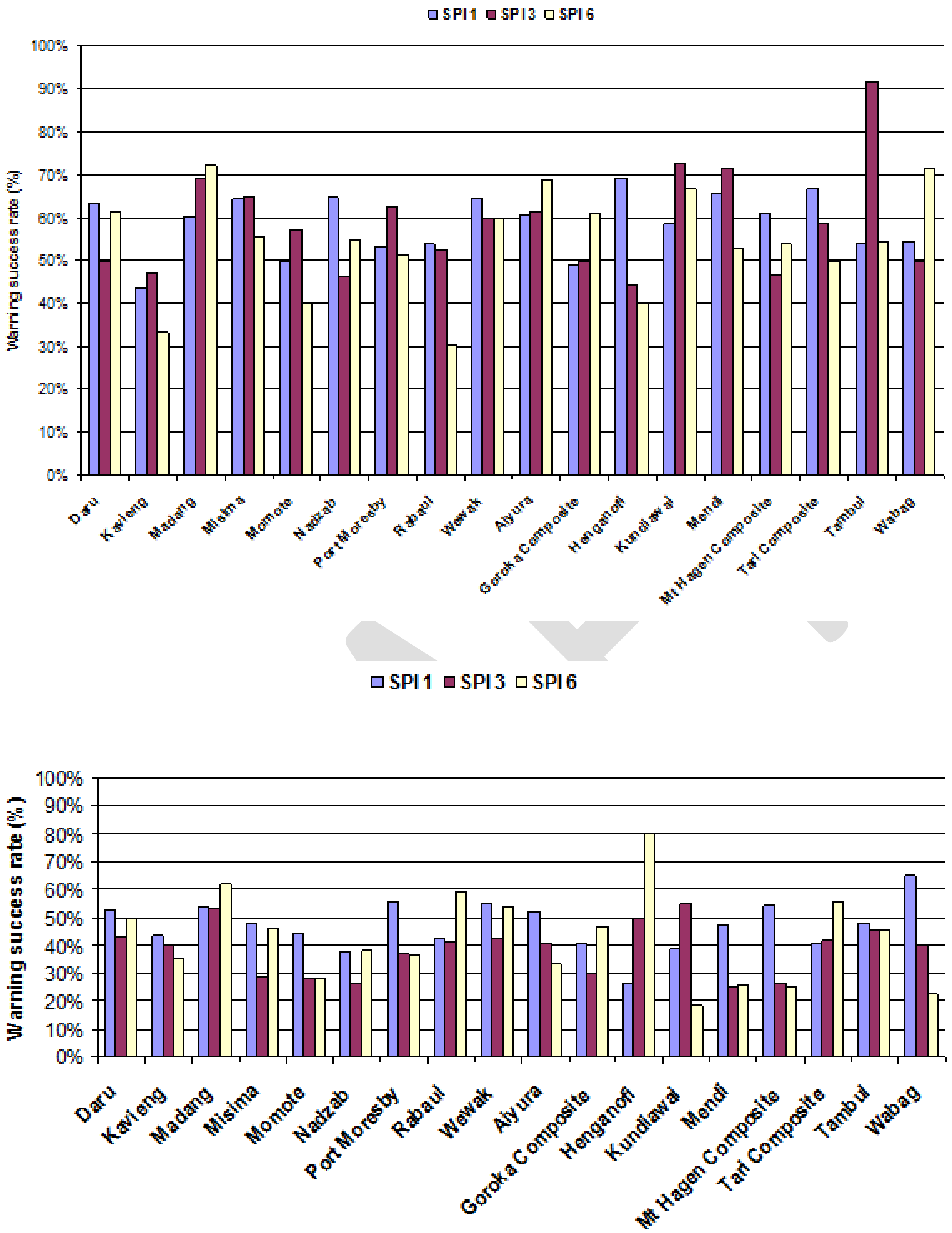


Figure 4. Warning success rates of El Niño droughts (top panel) and La Niña floods (bottom panel) for 18 locations in PNG.

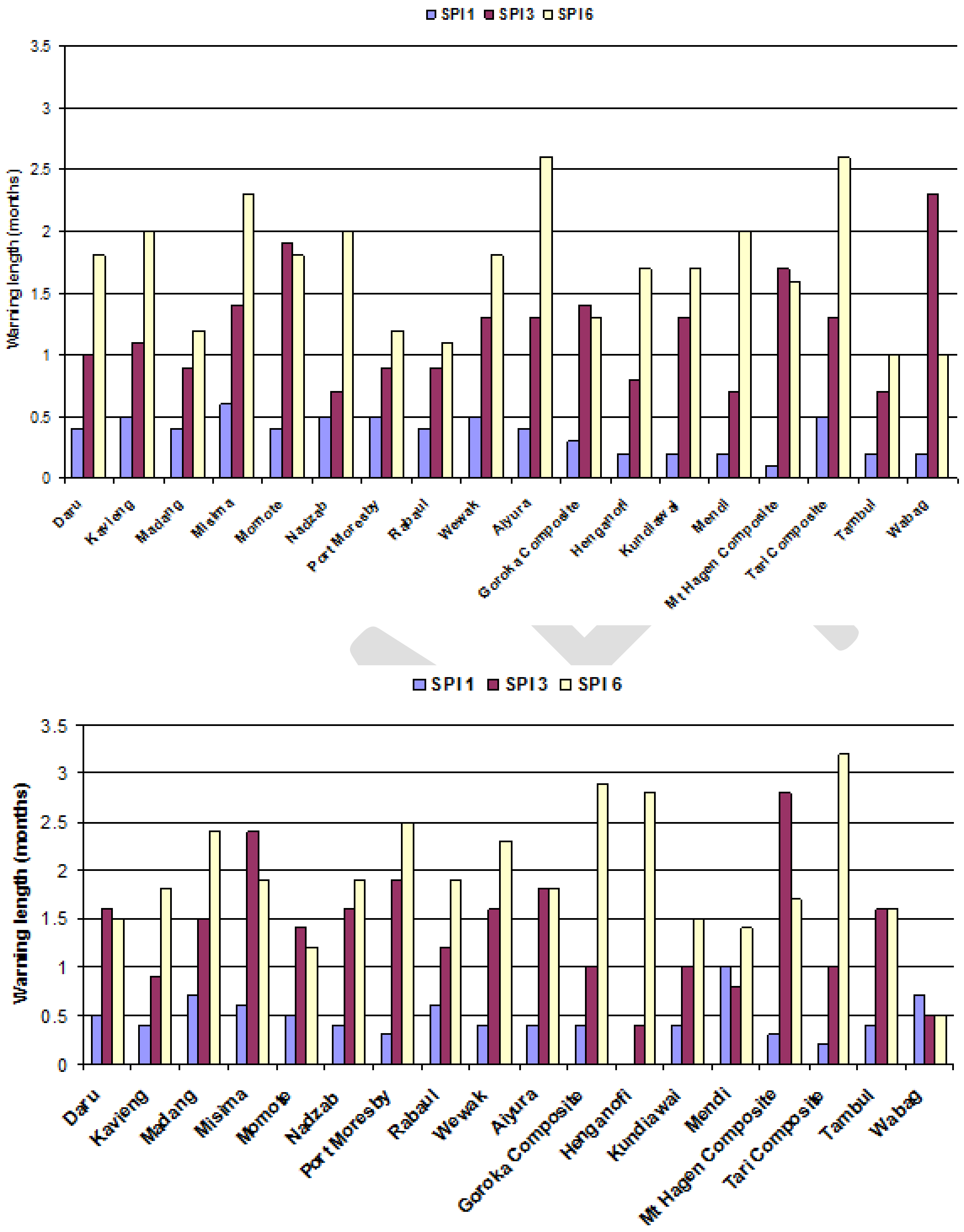
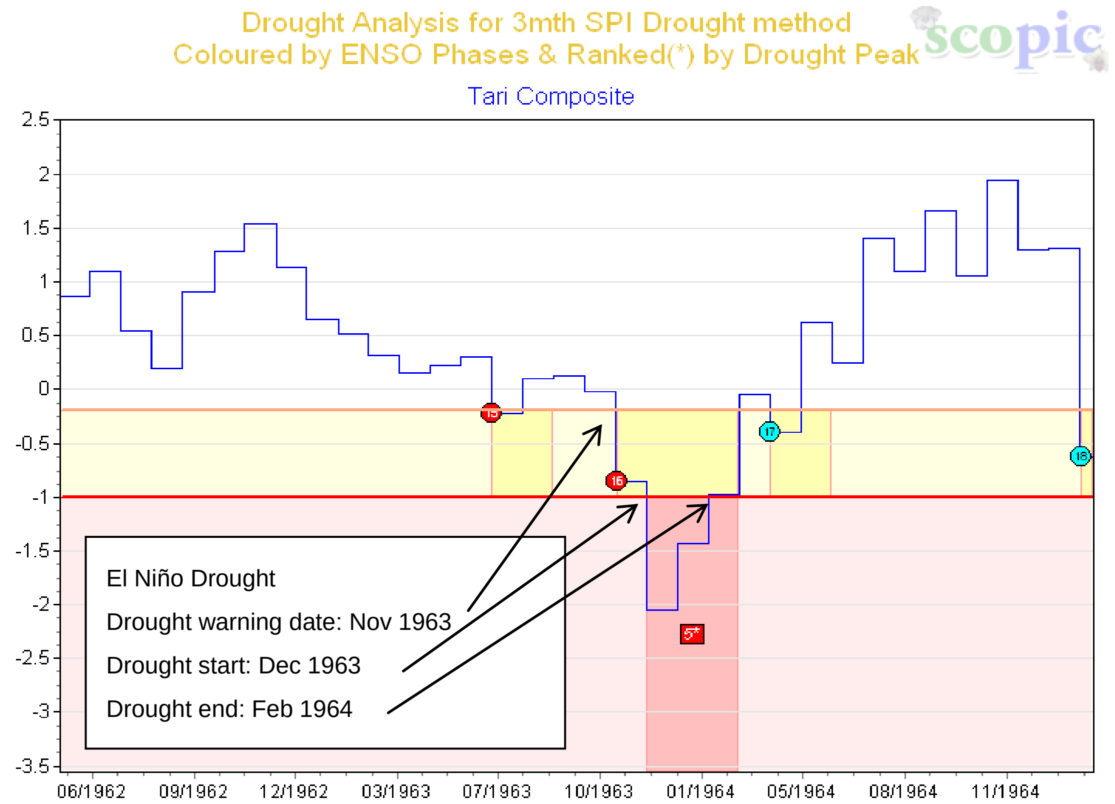


Figure 5. Warning lengths of El Niño droughts (top panel) and La Niña floods (bottom panel) for 18 locations in PNG.



El Niño Drought

Drought warning date: Nov 1963

Drought start: Dec 1963

Drought end: Feb 1964

Figure 6. A successful drought warning for Tari (November 1963) indicated by SPI 3 (y axis).

TABLE 1. Percentage area of Papua New Guinea in drought (≤ percentile 10 April-March rainfall) or flood (≥ percentile 90 April-March rainfall) calculated by the proportion of pixels in the interpolated rainfall surface showing these values

Year	**Area in drought (%)**	**Year**	**Area in drought (%)**	**Year**	**Area in flood (%)**	**Year**	**Area in flood (%)**
1997	83.18	1972	41.0	1943	86.7	1985	28.1
1941	83.0	1980	39.0	1907	70.5	1970	24.1
1982	72.9	1931	37.7	1894	47.5	1939	23.9
1914	66.9	1905	32.1	1921	42.8	1925	23.8
1902	61.0	1924	31.7	1998	41.2	1949	23.4
1911	50.3	1965	27.0	1900	39.4	1891	22.6
1987	48.6	1976	27.0	1908	39.0	1964	22.4
1899	43.6	1923	24.7	2000	31.8	1906	22.0
1979	41.1	1993	24.3	1942	31.4	1999	20.3

Box 1. The effect of climatic variation on growth of sweet potato in the PNG highlands, in particular changes in daylength, solar radiation, temperature, frost and soil moisture (after Bourke 1988)

Daylength and Solar Radiation

Short days with low light intensity promote tuber formation while long days tend to favour vine growth at the expense of tubers, however, the annual variation in daylength in the PNG highlands (45 minutes) is small and is unlikely to influence yield.

Temperature

Contrasting day and night temperatures (29/20oC) give greater tuber yields than a constant temperature regime (29oC) suggesting that the moderately large diurnal temperature variation that occurs in the highlands would favour higher yields.

Temperature influences the rate of crop development and the period from planting to harvesting in PNG. Crop development is delayed by lower temperatures in PNG but crop yields are not affected because of a longer period to maturity. For example, average experimental yields of 15 to 30 t/ha occur at Aiyura (1620 m) for 7 to 9 month crops. Experimental yields in the PNG lowlands are 15-20 t/ha for 5 or 6 month crops.

Sweet potato plants are subject to chilling injury when exposed to temperatures in the range of 0 to 10-12oC. If exposure to the chilling temperatures is brief, the changes in plant tissue are reversible, but they become irreversible after prolonged exposure. Prolonged exposure to these temperatures may reduce sweet potato yields in the highlands.

The intolerance of sweet potato to frost is widely acknowledged and at times frost is an important constraint on sweet potato production in high altitude locations in the PNG highlands. The effect of frost on yield appears to vary with the developmental stage of a crop. If a crop is frosted before tuber bulking occurs, crop maturity is delayed but the same tuber yield is still achieved. The time of harvesting, which is normally between 9 and 12 months after planting at these altitudes, is extended up to 15 months. In contrast, crops frosted during tuber bulking (about 6 to 9 months) yield watery, inedible tubers. For crops frosted after nine months, tubers cease to grow but remain edible for up to four months after the frost.

Frost severity and frequency and any subsequent damage vary considerably between locations and over time. In the Eastern Highlands, only a few minor frosts have been recorded since the early 1930s, but they occur more frequently in the Southern Highlands. In the Southern Highlands, Enga and the Western Highlands, frost damage has occurred in most months of the year, but it is more common between July and November. Frosts are sometimes associated with drought. Three droughts that occurred in the Southern Highlands between 1952 and 1984 (1965, 1972, 1982) coincided with frosts, but other frosts in 1953, 1958, 1960, 1961, 1974 and 1980 did not coincide with droughts.

The most severe frosts undoubtedly result in major shortfalls in food supply. This is particularly so at very high altitude locations (above 2200 m). Crop vulnerability to frost damage is very vulnerable in regions in Enga, Southern Highlands Province, and Western Highlands Province and least vulnerable in all Eastern Highlands Province above 1600m.

Soil Moisture

Extremes of soil moisture have the main climatic influence on variability in sweet potato yield. Sweet potato is generally tolerant of drought and there is little evidence from PNG to show that low soil moisture levels affect yield, except in the most severe drought. The international literature indicates that soil moisture levels of less than 20 per cent of field capacity depress yield. As such, very low levels of soil moisture may be detrimental early in crop life when tubers are being initiated but low soil moisture levels are most critical toward the end of the growing period when rapid tuber bulking is occurring.

Waterlogging or very high soil moisture levels are most detrimental to high tuber yields, particularly when either occurs during the tuber initiation phase.

Appendix 1. Monthly rainfall data retrieved and compiled for Papua New Guinea

The long term monthly rainfall data were sourced from the PNG National Weather Service (NWS), the PNG colonial data archive (CDA - Bureau of Meteorology, Australia), the Coffee Industry Corporation (CIC) at Aiyura and the National Agricultural Research Institute (NARI) at Tambul. The location, elevation and availability of monthly rainfall data for 18 meteorological stations across PNG are shown. Because some stations were moved (e.g. Lae to Nadzab, Rabaul to Tokua) and others had short lengths of records, some data records were combined. Ten composite stations were prepared using analytical methods to combine and convert data and some missing data were patched. The methods used are described in Cobon et al. 2009 and have provided continuous good quality data with more than 30 years of records for 2 stations in the high altitude zone, 7 stations in the highlands and 9 stations in the lowlands.

Station	Latitude, Longitude	Elevation (m)	Data period	Length Of Record (Years)	Missing data (%)	Source
Aiyura (25001)	-6.19, 145.55	1640	June 1937-June 1941, Jan 1945-Mar 2010. Missing values for (Jan – May 1937; July 1941-Dec 1944; Dec 1972; Sep-Dec 1975; July 1988).	73	6%	CDA, NWS, CIC
Daru (65029)	-9.08, 143.20	6	July 1894-Jun 1899, Jul 1900-May 1902, Jul 1903-Dec 2007, Jan 2009-Feb 2010.	116	7.7%	CDA, NWS

			Missing values (Jan-June 1894; Nov 1898; Jul 1899-June 1900; July- Oct 1901; June 1902-June 1903; Nov 1905; Mar-May 1906; Jan 1907; Dec 1912; Jan 1913; Dec 1913-Mar 1914; Nov 1914; Jan 1918; June 1922; Aug-Oct 1922; Apr- July 1923; Dec 1923; Aug-Sept 1925; July-Sept 1926; Sept-Dec 1927; June 1929; Apr – Jun 1931; Aug-Sep 1931; Mar-July 1932; Jan 1933; Apr – May 1933; Feb 1934; Apr 1934; Aug 1934; Apr 1935; Dec 1936; May 1938; Aug 1938; July-Nov 1942; Nov 1994; Jan-Dec 2008; May 2009.			
Kavieng (20001)	-2.58, 150.8	7	Feb 1916-Oct 1941,Sept 1949-Jul 1952, Sept 1953-April 1954, Jun 1955-Dec 1955, Dec 1956-Apr 2010. Missing values (Jan, Oct 1916; Jan-Mar 1925; July-	94	14.5%	CDA, NWS

			Sept 1925; Feb-Mar 1928; Jan 1933; Jan, Aug 1941; Nov 1941-Aug 1949; Feb – Aug 1950; Jan-Aug 1951; Feb-June 1952; Aug 1952-Aug 1953; May 1954-Jun 1955, Jan 1956-Nov 1956).			
Madang Composite - Madang Agric ((200070) - Madang AS (10003)	-5.23, 145.78 -5.22, 145.78	8 4	Feb 1916-Aug 1941, Nov 1944-Mar 1947, Jan 1948-Apr 2010 Missing values (Jan 1916; dec 1916; Aug-Oct 1924; Dec 1924; Sept 1941-Oct 1944, April 1946-Dec 1947).	94	6.2%	CDA CDA, NWS
Misima (50033)	-10.67, 152.77	20	Feb 1917-Dec 1941, Jan 1946-Feb 1948, Aug 1949-Dec 1951, Nov 1953-Apr 2010. Missing values (Jan 1917; Jan 1925; Jan 1939; June-July 1939; Sept-Nov 1939); June 1941; Jan 1942-Dec	93	9.5%	CDA, NWS

			1945, Aug-Dec 1946; Dec 1947; Jan 1948; Mar 1948-Jul 1949, Dec 1949- Feb 1950; Jan 1952-Oct 1953).			
Momote (15003)	-2.05, 147.42	4	May 1949-Apr 2010 Missing Values: (Jan –April 1949; Aug 1949; Jan-Mar 1950; Jan-June 1951)	61	1.9%	CDA, NWS
Port Moresby (55006)	-9.45, 14720	42	Jan 1875-Sept 1876, Oct 1881-May 1883, Jan 1891-May 1901, Jul 1902-Apr 2010 Missing values (June-July 1876; Oct 1876-Sept 1881; Apr-Dec 1882; Apr 1883; Jun 1883-Dec 1890; May 1891; Sept 1893; July 1894; July 1897; June 1898; July 1900; Jun 1901-Jun 1902).	135	8.2%	CDA, NWS
Wewak (80002)	-3.58, 143.67	5	Jan 1956-Apr 2010	54	0.5%	CDA, NWS

			Missing Values: (Feb-Mar 2009; May 2009)			
Rabaul Composite -Rabaul (40005, 200340) -Tokua (40056)	-4.13, 152.12 -4.38, 152.37	4 10	Jan 1891-Dec 1897, Jan 1899-Dec 1908, Jan 1910-Dec 1910, Jan 1912-Dec 1912, Sept 1913-Dec 1937, April 1946-Apr 2010. Missing values (Feb-Mar 1893; July-Aug 1897; Jan 1898-Dec 1898; July 1899; June 1906 Jan-Dec 1909; Jan -Dec 1911; Jan 1913-Aug-1913; Mar 1915; Jan 1938-Mar 1946; July-Aug 1946).	119	10.6%	CDA, NWS NWS
Nadzab Composite -Lae (30002) -Nadzab (30045)	-6.73, 147.00 -6.56, 146.72	8 70	May 1925-May 1930, Mar 1937-Nov 1941, Jul 1945-Apr 2010. Missing values (Jan- Apr 1925; Nov-Dec 1925; Feb-June 1928; June 1930-Feb 1937; Jan-Feb 1941; Dec 1941-Jun 1945). About 10	85	13.4%	CDA, NWS NWS

			years of missing data			
Goroka Composite - Goroka (25002) - Numonohi (25062) - Orobiga (25064)	 -6.04, 145.23 -6.13, 145.42 -5.78, 145.33	 1600 1530 1500	Mar 1948-Dec 1969, Dec 1970-Oct 1980, Feb 1982-Mar 2009 Missing values (Jan-Feb 1948; Jul 1949; Dec 1949; Oct-Dec 1950; Feb-Apr 1951; Jan-Nov 1970, Nov 1980-Jan 1982; Dec 2008; Apr-Dec 2009).	61	6.2%	 CDA, NWS NWS NWS
Mt Hagen Composite - Mt Hagen DHQ (75023, 200243) - Kuk (75044) - Korn Farm (75011, 200398) - Kagamuga (75015, 200468)	 -5.52, 144.14 na -5.51, 144.19 -5.50, 144.16	 1730 1600 1600 1620	Jan 1951-Aug 1990 Missing Values: (May-Dec 1975; Jul-Aug 1984; Dec 1984; Oct-Dec 1986; Feb 1988; Jan 1990; May 1990; July 1990; Sept – Dec 1990)	39	4.6%	 CDA, ARS Highlands Agric College NWS
Kundiawa Composite			May 1950-Nov 1950, April 1952-Dec 1952, Dec 1953-	48	21%	

- Kerowagi (90001, 200052) - Kundiawa (90002, 200182) - Minj sdo (75004, 200240)	-5.54, 144.51 -6.01, 144.58 -5.54, 144.41	1550 1530 1600	Dec 1985, April 1990-Jun 1993, Jan 1995-Feb 1998 Missing values (Jan-Apr 1950; Dec 1950-Mar 1952, Jan 1953-Nov 1953, Aug-Sept 1984; Dec 1984; Aug-Dec 1985; Jan 1986-Mar 1990, Jul 1993-Dec 1994; Mar-Dec 1998).			CDA, NWS CDA, NWS CDA, NWS
Tambul Composite - Tambul pp (75010, 200348) - Tambul haes (75022)	-5.53, 143.57 na	2320 Na	Feb 1957-Jan 1973, Oct 1974-Dec 1991; Jul 2004-Jan 2009 Missing values (Jan 1957; Dec 1966; Oct-Nov 1972; Feb 1973-Sep 1974; Jan 1978; Aug-Dec 1978; May-Sept 1979;Nov 1980; Dec 1981; Apr 1983; June-Dec 1984; Jan-Apr 1989;Jan-June 1991;Jan 1992-June 2004; Feb-Dec 2009).	52	35%	CDA, NWS NARI HAES
Tari Composite			June 1952-Nov 1982, Jan	48	13.8%	

- Kugu (4km E of Tari), SHP - Tari SDHQ (70002, 200256) - Tari 1 SDHQ - Tari 2 (70024)	na -5.52, 142.55 -5.87, 142.92 5.50, 142.57	na 1670 1670 1670	1988-Dec 2000 Missing values (Jan-May 1952; Aug 1953; Mar 19568; May-Dec 1970; Dec 1972; Apr-June 1981; Dec 1982-Dec 1987).			AWS CDA, NWS GHCN NWS
Mendi Composite - Mendi WO (70038) - Mendi DHQ (70005, 200339)	 6.15, 143.67 6.09, 143.39	 1750 1750	May 1951-Jun 2006 Missing values: (Jan-Apr 1951; Dec 1953; Jan 1954; Feb 1968; May 1968; Apr-Aug 1969; Oct – Dec 1969; Jan-Feb 1970; Apr 1970; May-July 1971; July 1992; Dec 1992; Oct-Dec 1997; Dec 1998; Dec 2000; July-Dec 2006.)	55	5.5%	 CDA, NWS CDA, NWS
Wabag Composite with Amapyaka (05012, 200265)	5.29, 143.43	2080	April 1950-Dec 1969, March 1987-Dec 1997, Jun 2000-Mar 2002, Jan-Sep 2003; Jan 2005; Jul-Aug 2005	55	39.7%	

			Missing values (Jan-Mar 1950; Jan-Feb 1970; Apr-Aug 1970; Aug 1970-Nov 1971; Mar-Apr 1972; June 1972-Dec 1981; Aug 1982-Apr 1984; July 1984-Feb 1987; Dec 1987-Jan 1988; Dec 1988-Jan 1989; Dec 1989-Jan 1990; Sept-Oct 1994; Dec 1994; Jan 1998-May 2000; Apr-Dec 2002; Oct 2003-Dec 2004; Feb-June 2005; Sept-Dec 2005)			
Henganofi (25006, 200312)	6.15, 145.38	1570	Oct 1955-Feb 1982; April 1984-June 1986 Missing values: Jan-Sept 1955; Mar 1970; Nov 1970; Mar-Apr 1971; Oct 1972; Mar-Dec 1973; July 1975; June 1978; May- June 1970; Mar 1982-Mar 1984; June 1985; July – Dec 1986.	31	15.6%	

Appendix 3. Reported food shortages in the Papua New Guinea highlands, 1910 to 2009

Year	Time of year	Province /District	Extent	Cause	Notes	Source
1911-1914		Aiyura area, EHP	WS			Bourke 1988
1930s and 1940s	early		WS WS	Frost and drought	An informant born about 1923 recalled two major shortages; Oral accounts report numerous deaths as a direct result of food shortages in 1941 in Enga Province	Bourke 1988
1937		Kainantu				Bourke 1988
1938-39		Kainantu		Drought		Bourke 1988
1940		Kainantu				Bourke 1988
1955	JASOND	SHP				Bourke 1988
1962	JASOND	EHP Kainantu, SHP	WS	Waterlogging in SHP	This food shortage may be due to excess rainfall during tuber initiation phase (see Table 7.2 p 178, 181). Tambul Feb 62 - 425mm. Mendi Aug 62 - 410mm, Sept 62 - 386mm and Oct - 428 mm	Bourke 1988 Bourke 1988 p174-80
1964-65		Kainantu, Henganofi		Water surplus then drought		Bourke 1988 (p 184)
1965-66	JASONDJFM	SHP	WS	Water surplus then drought 1965 JJASON Frost	Tari Nov 64 – 679 mm, Mendi Mar 65 – 405 mm, Aug-Nov 64 - above average rainfall Mendi and Tari	Bourke 1988 (p 196)
1967-68	JASONDJFM	SHP		Water surplus Jul-Aug 67; Planting rate cycles	Mendi Jul 67 - 370mm, Aug 67 - 351mm	Bourke 1988 (p 224)
1970-71	JASONDJFM	SHP		Water surplus MJJASON 1970	Mendi May 70 - 384, Jun 70 - 218, Jul 70 - 342, Aug 70 - 280, Sept 70 - 345, Oct 70 - 435mm, Nov 70 - 363mm	Bourke 1988
1972-73	JASONDJFM	Enga, SHP, WHP	WS	Water surplus, Frost - Severe at high alt; Drought; Climate	Major food shortage; Large scale food relief operation till May 73; It is possible that this food	Bourke 1988 (p 224)

				extreme exacerbated by low in planting cycle in SHP, which were in turn initiated by very wet periods in early 1970	aid averted increases in death rates. Mendi Feb 72 - 369, Mar 72 - 387mm; Tambul Mar 72 - 383mm, Apr 72 - 351; Tari Feb 72 - 407, Mar 72 - 362mm, Apr 72 - 246	
1978-79	JASONDJF	Upa SHP		Water surplus, Drought	Selling small tubers, Mendi May-Oct 77 water surplus, Aug 77 - 557mm	Bourke 1988
1980-81	SONDJFMA	Upa SHP, WHP, Enga	WS	Frost – high alt; Waterlogging SHP Water surplus EHP	Rise in price of SP at Upa Village; Extremely high water surplus at Mendi July-Aug 80 (p 181-3,192); reports of hairy tubers in SHP support waterlogging;	Bourke 1988
1982-83	ASONDJF	EHP, SHP, Chimba, WHP, Enga	WS	Drought/frost; High alt more severe; Late 1981-early 1982 was an extended period of water surplus Aiyura, Goroka, Mendi (p 183, 186)	Food inadequate in EHP till June 83; Rise in price of SP from 10 to 20 toea/kg compared to last year; claim of unsuccessful request for food aid at Upa; Climatic extreme does not usually affect planting rate of SP, but very wet period in early 1982 in EHP was an exception (p226)	Bourke 1988
1984-85	JJASONDJFM	EHP, Chimba, SHP	WS	Water surplus; Severe; Exceptionally wet weather in late 1983 to mid 1984 in SHP provides partial explanation for food shortage in 1984; Planting rate cycles SHP, EHP and Chimbu (p224); Low in planting cycle exacerbated by climate extreme in SHP. Water surplus for extended period May 83-Jul 84 at Mendi and Oct 83-Dec 83 at	Cash from sales of coffee muted impact; Food intake was limited but no indication that food intake was seriously reduced; intake of imported food rose; intake of pigs reduced. Mendi JFMAMJ 1984 - 327, 376, 308, 302, 311, 363 Minor drought in JFM 1984 where rainfall at Aiyura, Mt Hagen, Kundiawa, Goroka all below average.	Bourke 1988 (p 192, 224) SCOPIC

				Goroka and Dec 83 at Kundiawa		
1987-88	AMJJASOND	EHP, SHP, WHP	WS	Water surplus from Apr 87-Jun 87 at Tambul; Drought	Aiyura SPI drought rank 4; Mendi SPI drought rank 8; Aiyura Jan 87 374 mm; no prior water surplus evident at Mendi	SCOPIC
1990	FMAMJ	EHP, SHP			Mendi SPI drought rank 4	SCOPIC
1991-96		Islands and Coastal			Long period of drought; severe in places; Wewak, Madang and Misima either SPI drought rank 1 or 2	SCOPIC
1992	SOND	EHP, Chimba, Enga		Water surplus Oct 91-Jun 92 in EHP & Chimba and Apr 92-Jul 92 Enga		SCOPIC
1993	MJJASON	EHP, SHP, WHP, Chimba, Enga			Minor drought in highlands	SCOPIC
1997-98	AMJJASONDJFMA	EHP, WHP, Enga, SHP, Chimba	WS	Water surplus July-Nov 1996; Drought/frost; Severe	Major international food aid effort; 1.2M people or 40% of rural population in PNG in a severe and life threatening food shortage – many others were affected less severely; Mendi Jan 97 302, Feb 97 305mm – v wet ASO 96; Tari Sept 96 345 mm Oct 350 mm; Misima Mar 97 756 mm – v wet SOND 96;	Allen and Bourke 1997ab SCOPIC
2001-02	SONDJF	EHP		Water surplus Apr-Jul 01; Drought	Goroka rainfall low, SPI drought rank 3	SCOPIC
2002-03	JASONDJFM	SHP		Water surplus Apr-Jun 02; Drought	Mendi low rainfall JASO, Mendi SPI drought rank 6; Mendi Sept 01 - 401mm, Oct 01 - 396mm	SCOPIC
2004-05	ASONDJFMAM	SHP		Water surplus Feb-Mar 04; Drought	Mendi SPI drought rank 10; Mendi Dec 03 - 256mm, Jan 04 - 281mm, Feb 2004 - 395mm	SCOPIC
2006-07	ONDJFMAMJJ	WHP		Water surplus Jan-Jun 06; Drought followed		SCOPIC

EHP – Eastern Highlands Province, SHP - Southern Highlands Province; WHP - Western Highlands Province; WS – widespread; SPI – Standard Precipitation Index; SCOPIC indicates a drought but not necessarily a food shortage.

Footnote - The apparent increase in the frequency of food shortages closer to the present is most likely to reflect greater availability of data and better reporting rather than an increase in food shortages over time.