Available Online at SAINS TANAH Website: http://jurnal.uns.ac.id/tanah
SAINS TANAH – Journal of Soil Science and Agroclimatology, 16(2), 2019, 229-253
REVIEW

CURRENT evidence AND FUTURE PROJECTIONS: A COMPARATIVE ANALYSIS OF THE IMPACTS OF CLIMATE CHANGE ON CRITICAL CLIMATE-SENSITIVE AREAS OF PAPUA NEW GUINEA

Patrick S. Michael*

Department of Agriculture, PNG University of Technology, MP411, Papua New Guinea

Submitted : 2019-11-20   Accepted: 2019-12-02

ABSTRACT

Climate change is a global concern arising from spatial or temporal changes in precipitation, temperature and greenhouse gases. The impacts of this on critical climate-sensitive areas are largely on land, marine resources, forestry and agriculture, and their biodiversity and ecosystems. In Papua New Guinea (PNG), the mainstay (85%) of the rural people is on land and agriculture, compared to resources obtained from the marine areas and forest. Productivity on land depends on climatic factors and a compromised climate affects land, which in turn affects forestry, agriculture and the marine environment (resources and ecosystems). Because of this, a lot of resources have been invested in climate change to understand the impacts; however, much is yet to be achieved, especially in the developing nations. In PNG, understanding the types of changes in climate that will be experienced is important to be resilient, to mitigate and to adapt. In this review, the potential impact of global climate change on climate of PNG and the impact of the new (future) climate on land, marine and forest resources and their biodiversity and ecosystems are analyzed. Moreover, the impacts on crop agriculture are discussed. Analysis of available data shows that the temporal and spatial changes in precipitation and temperature projections of the future climate are within current optimum crop production ranges, at least up to 2090. Since most staple and plantation crops in PNG are C_3 plants, an increase in CO_2 levels will have a fertilizing effect on productivity. The plastic effects on certain crops may benefit some farmers as temperature, precipitation and CO_2 levels change.

Keywords*:* Agriculture, Climate change, Critical impact areas, PNG, Precipitation, Temperature

How to Cite: Patrick S. Michael. (2019). Current Evidence and Future Projections: A Comparative Analysis of the Impacts of Climate Change on Critical Climate-Sensitive Areas of Papua New Guinea. Sains Tanah Journal of Soil Science and Agroclimatology, 16(2): 229-253 (doi: 10.20961/stjssa.v16i2.35712)

Permalink/DOI: http://dx.doi.org/10.20961/stjssa.v16i2.35712

INTRODUCTION

The impact of climate change on the environment is overwhelming. The major impacts include changes in temperature, rainfall, CO_2 levels and sea-level rise (Mawdsley, O'Malley, & Ojima, 2009). The increase in temperature is caused by the accumulation of greenhouse gases (e.g., carbon dioxide, nitrous oxide, and methane) in the atmosphere that trap irradiation from the earth (IPCC, 2013; Morice, Kennedy, Rayner, & Jones, 2012). The increase in temperature, in turn, is melting the ice sheets in Greenland and West Antarctic (Gardner et al., 2013), raising the sea level. The critical impact areas of increase in precipitation, high temperature, and rise in sea level are on terrestrial and

---

* *Corresponding Author:*
Email: patrick.michael@pnguot.ac.pg

aquatic resources, civic infrastructure, population and agriculture (Lawler, 2009). The severity on the global scale of the impact areas is widely reported, but the available data cannot be extrapolated to the country level even using data from within a region. For example, crop yield data from the Pacific region cannot be used widely to predict the impacts of the projected climate change on agriculture of PNG (Figure 1 shows the provinces) or that of PNG compared to another in the same region because of the seasonal variability. Most of the individual provinces made references to are shown on this map. The elevation of each province can be estimated from Figure 2. These types of scenarios make country-specific data more important compared to regional or global to assess the impacts of climate change (Leakey, 2009).

The Intergovernmental Panel on Climate Change (IPCC) pointed out that the attributes of climate used based on global or regional climate models are the least accurate measure of projected climate and render interpretation difficult (IPCC, 2007a). In PNG (Figure 1), the Office of Climate Change and Development has made significant progress to prepare for impacts of climate change on critical climate-sensitive areas (population, biodiversity, forestry, environment, land, agriculture, and economic development (GDP)) by developing mitigation and adaptation strategies. Despite these ongoing efforts, PNG is yet to fully strategize countermeasures to climate change, especially in the agriculture sector. This review aims to document the current climate, the changes based on the projections and the impacts on critical climate-sensitive areas. The mainstay of the rural livelihood (85%) is plant agriculture (crops), therefore the impacts on this sector are discussed on its own.

Figure 1. PNG is located 6°31'50.66"S and 143°59'55.0"E of the equator (Koczberski et al., 2018)

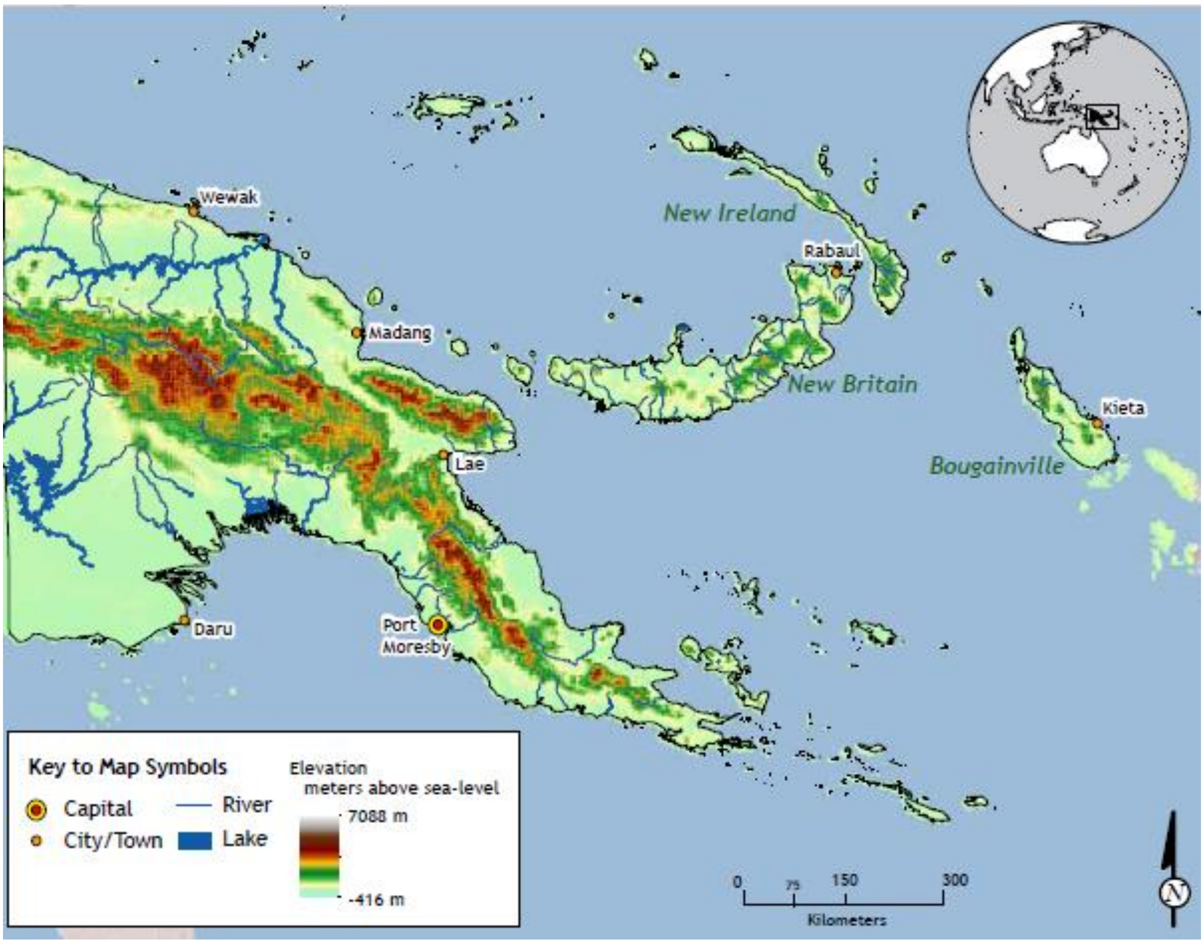

Figure 2. The elevations (above sea level) of PNG

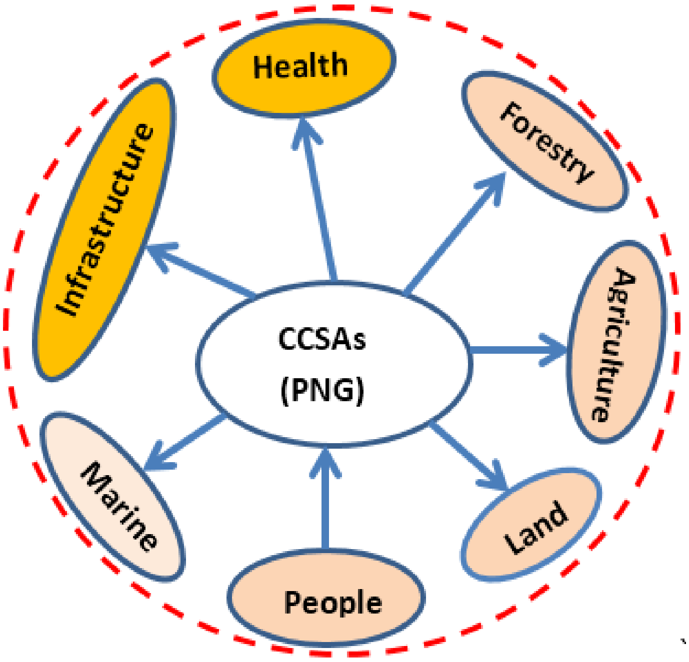

Figure 3. Critical climate-sensitive areas (CCSAs) of PNG. The interconnections are shown by the circular broken line. The CCSAs are directly affected by anthropogenic activities (arrowhead pointing directly towards the CCSAs).

METHODOLOGY

Survey on relevant literature (journal, book, online publications, press media, etc.) containing information and data on climate and climate change impacts of PNG environment from within the last 10 years was conducted. The main environmental components included land, forestry, marine, and aquatic resources, health, and agriculture. The target climatic factors considered are current rainfall, temperature, and carbon dioxide (CO_2) levels. The environmental factors considered are the mainstay of more than 85% of rural PNG that are most climate-sensitive. The productivity of land, forestry, marine, and aquatic resources are dependent on the climatic factors, and rainfall, temperature, and CO_2 level are the main ones, particularly for crop agriculture (Boehm et al., 2016; Mittler, 2006). Figure 3 shows these important environmental factors and points out that the main changes faced by them are anthropogenic.

The data and information collected from the literature were handled systematically. Initially, the current climate (precipitation, temperature, and CO_2 levels) and its changes expected were discussed. Secondly, the information collected was synthesized and changes in precipitation, temperature, and CO_2 levels of the future climate compared. Thirdly, based on the information gathered, land, forestry, marine, and aquatic resources, health and infrastructure and agriculture have been highlighted as critical climate-sensitive areas.

The impacts on plant agriculture, production, and management are discussed separately and the need for this has been pointed out. The essence is that recent literature on climate change and PNG's ability to identify, observe and monitor the stresses that influence CCSAs are established. The general time horizon is from the recent past to the period between 2030 - 2090, although longer-term (to 2100) are considered. The main reason for these periods is that the shorter time is within the planning horizon and longer makes planning unrealistic and unattainable.

CURRENT CLIMATE

The PNG climate is monsoonal and tropical, characterized by high relative humidity (70-90%) and temperature with seasons based on two monsoons. The northwest monsoon occurs from December to March and the southwest from May to October, each year. The climate is one of the wettest in the world and rainfall often exceeds 250 cm in many areas (Figure 4). The wet season occurs from November to April and dry season from May to October, respectively. The average temperature for the coastal plains, inland and mountain areas, and the higher mountain areas are 28°C, 26°C, and 23°C, respectively. The higher mountain areas are cooler and lowlands are warmer. The annual variation in rainfall is shown in Figure 4. Most places, except some parts of the southern region and northeast and southeast of Bougainville, receive rainfall over 100 cm.

The climate is influenced by the trade winds, movement of the South Pacific Convergence Zone (SPCZ, a zone of high-pressure rainfall that moves across the Pacific south of the equator), the Intertropical Convergence Zone (ICZ) and the Southern Oscillations (El Niño and La Niña) as shown in Figure 5. The El Niño years are drier resulting in prolong droughts and La Niña years are wetter with flood events. During the El Niño events, monsoon season starts and causes places like Port Moresby to be cooler than normal and warmer than normal in the La Niña years.

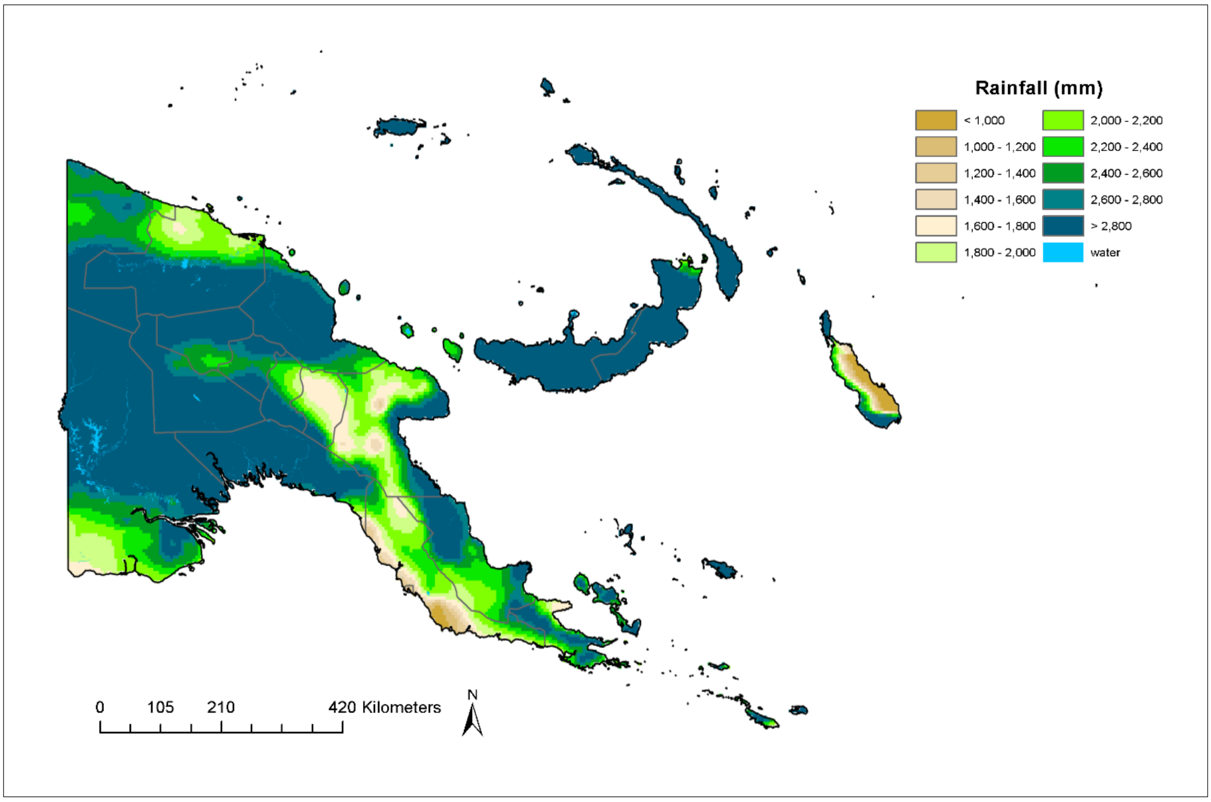

Figure 4. Average annual precipitation (rainfall) of PNG

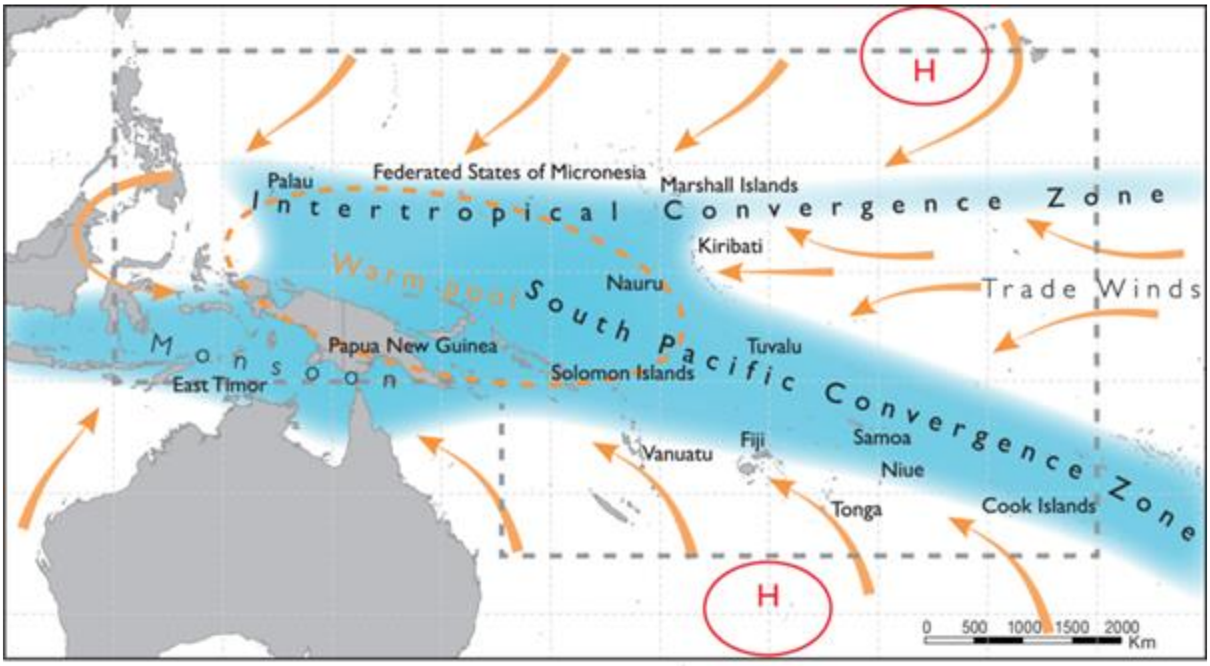

Figure 5. The major climate features of PNG. The surface winds are indicated by the arrows, the bands of rainfall convergence zones are shown by the blue shading, the West Pacific Warm Pool is shown by dash oval and the typical positions of moving high-pressure systems are shown by Pacific Australia Climate Change Science and Adaptation Programme (PACCSAP, 2011).

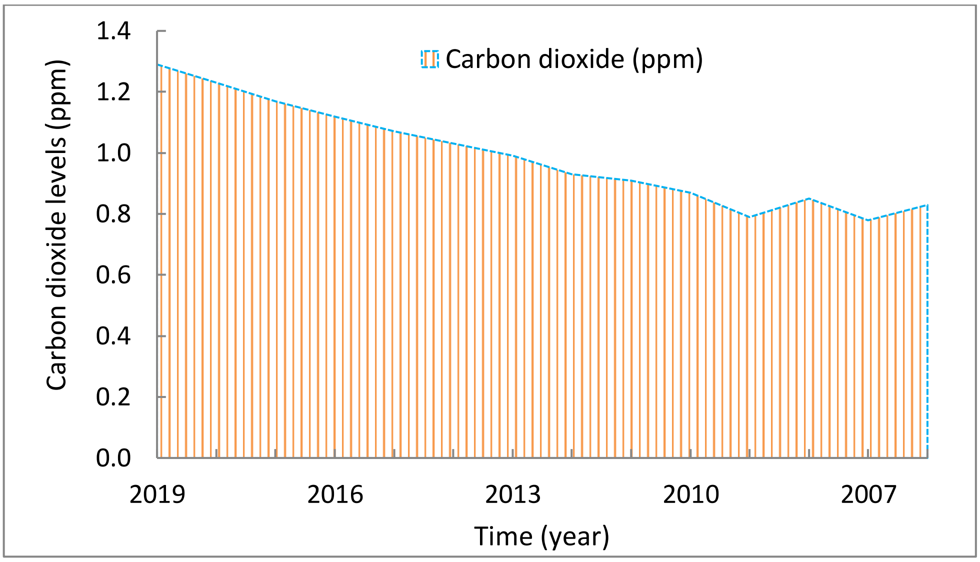

Figure 6. The current carbon dioxide emission trend of PNG (Knoema.com, 2018)

Recent changes in CO_2 levels are shown in Figure 6. Over the last 12 years (2007 - 2019), emission was increasing at a rate of 7.1%, with 1.3 ppm (CO_2) emission in 2019 (Knoema.com, 2018). The global and PNG emission and associated changes in temperature projections are given in Table 1. Under the lowest and the highest emission scenarios, the CO_2 level is projected to increase from 380 to 1000 ppm (IPCC, 2013), resulting in a temperature increase of 0.3 - 2.6°C and 0.9 - 6.8°C, respectively for the two emission scenarios by 2100.

FUTURE CLIMATE

The average annual temperature and precipitation are given in Table 1. Compared to the current climate described previously, the predictions of (PACCSAP, 2011) indicate that the future climate of PNG will be warmer and wetter due to climate change impacts. Rainfall is projected to change by ± 25%, the temperature will increase by 1.4 - 3.1°C and sea level will rise by 19 - 85 cm. Surface temperature is projected to increase by 1.0 - 4.2°C, resulting in sea surface temperature increase of 1.0 - 3.0°C. The ocean is projected to be acidified by 0.3 - 0.4 pH units, as more CO_2 dissolves in the sea. As per the regional projection, the rate of change in the maximum and minimum temperatures will be 0.2 - 1.4°C and 0.2 - 1.7°C in the western and eastern half of PNG per decade.

These changes will continue for the foreseeable future due to the increasing emissions of greenhouse gases (Canadell & Raupach, 2008; Rahmstorf et al., 2007) in CO_2 levels (Figure 6). If the high emission scenario continues as pointed out by Pacific Australia Climate Change Science and Adaptation Programme (PACCSAP, 2011), PNG will be warmer by 0.5 - 1.1°C by 2030, 1.0 - 2.0°C by 2050 and 2.1 - 4.2°C by 2070. This means that the average annual temperature for the coastal plains, inland, and the higher mountain areas will be 30.1 - 32.2°C, 28.1 - 30.2°C and 25.1 - 37.2°C, respectively by 2070.

In 2090, the increase in temperature at low, medium and high emission scenarios will be 29 - 30.2 °C, 29.6 - 31.2 °C and 30.2 - 31.4°C, respectively, implying that spatial and temporal variability in temperature will be small (increase by nearly 1 - 2 °C) compared to the current variability. This supports that the mean annual temperature will be around 30±2°C throughout. The increase is estimated to be at the rate of 0.24 - 0.32°C from 2030 to 2050 and 0.34 - 0.46 °C from 2055 to 2090, a steady increase in temperature over the next 60 years. This implies an increasing rate of 0.08 - 0.10°C per decade, which is consistent with the current global projection of 0.11 °C per decade (Figure 7). This might further increase under a high emission scenario.

The annual and seasonal rainfall is projected to increase consistently with an intensification of the monsoon and convergence of the inter-tropical zones. Figure 8 shows that most of the areas (Figure 1 for the elevations) will be wetter and warmer. If the trend continues, East and West New Britain and New Ireland Province (Figure 1) receiving >280 cm of rain per year under the current climate will receive up to 1000 cm a year (Figure 8A) by 2100; the North Solomon Province will receive even more rain than now.

Table 1. Average annual air temperature and precipitation projections for PNG under three emission scenarios over three time periods.

Scenarios	**Temperature (°C)**			**Precipitation (cm)**		
	2030	**2055**	**2090**	**2030**	**2055**	**2090**
Low emissions	0.3 - 1.1	0.6 - 1.6	1.0 - 2.2	4 - 14	10 - 26	17 - 46
Medium emissions	0.4 - 1.2	1.0 - 2.0	1.6 - 3.2	5 - 14	9 - 30	20 - 58
High emissions	0.4 - 1.0	1.1 - 1.9	2.2 - 3.4	4 - 15	10 - 29	22 - 60

The values are the differences between the lowest and highest average annual temperature ranges (PACCSAP, 2011)

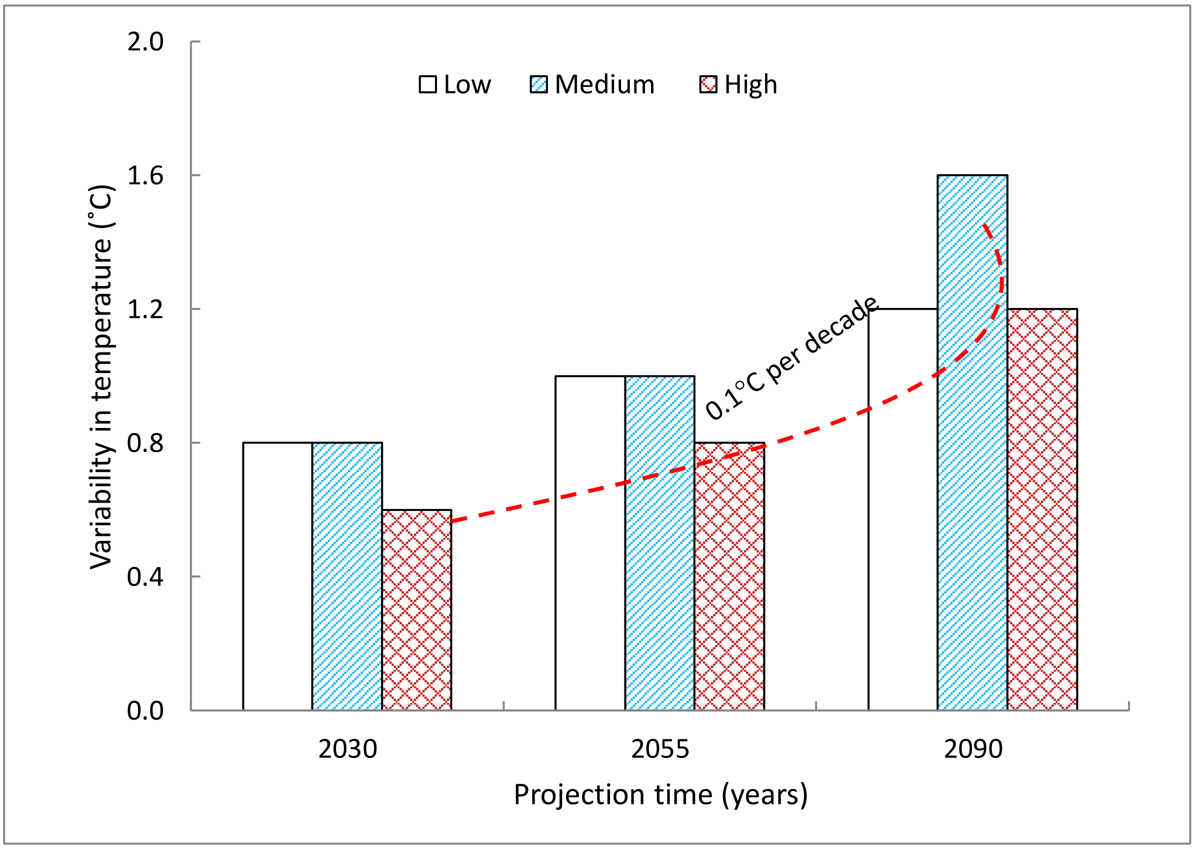

Figure 7. Variability in temperature projections (an increase of 0.10°C per decade) during the 2030-2090 period under three emission scenarios.

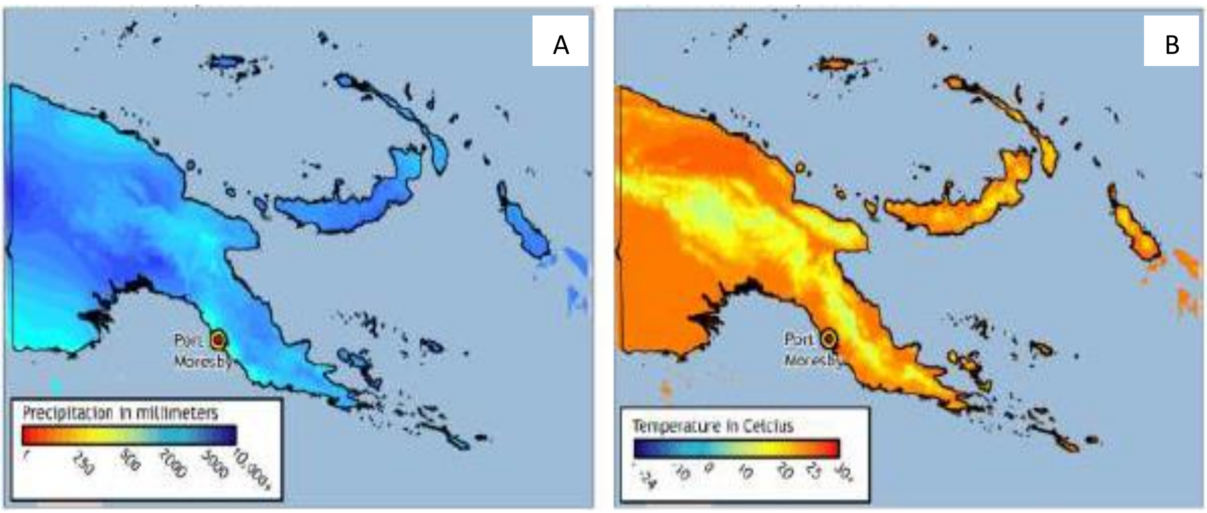

Figure 8. Total annual precipitation and temperature of PNG A) precipitation in millimeter (250, 500, 2000, 5000, and 1000 mm) B) temperature in celcius (-24, -10, 0, 10, 20, 25, and 30˚C)

In the lower and upper central highland provinces (elevation range of 1000 - 1500 m, Figure 1), a similar increase in rainfall (26 - 76 cm) is expected; total rainfall is 500 - 1000 cm per annum (Figure 8A). A future climate with these changes in precipitation will affect most of the CCSAs (Figure 3). Table 5 provides the rainfall requirement for most crops (100 - 300 cm), making the projected increase in rainfall a threat to crop production.

CRITICAL CLIMATE-SENSITIVE AREAS

The impacts of the future climate on the CCSAs except agriculture are discussed in this section. The land is an important non-renewable resource with a lot of benefits. Most of the CCSAs (Figure 3) are sourced from the land. The land provides clean water, soil for trees and plants of the forest and agricultural production. The status of the aquatic environment from which natural food sources, as well as amenities for socio-economic development obtained, is in part dependent on the land. A compromised terrestrial environment directly affects its marine and aquatic environments. Even infrastructure (e.g., roads and bridges) are installed on the land. These make land an important natural resource available to man. A summary of the losses that will occur on all the CCSAs (Figure 3) is presented in Figure 9.

Land: PNG is ca. 48 million ha of which 97% is customary and 3% is alienated (that is, 2% state land and 1% private) (Lakau, 1991). The types of land are shown in Figure 10A and land cover in Figure 10B. The livelihoods of the small people depend on the customary land, whilst economic activity and urban development, including public amenities and infrastructure, are on the alienated land (freehold and leasehold). In the light of global climate change, the question is how the future climate will impact land, taking into consideration only 1% of the land is fertile (Figure 10A) and vulnerable to extreme climatic events. An increase in temperature will result in terrestrial water sources drying up; although the high temperature will change local hydrological cycles, leading to more rain (IPCC, 2007b). The high temperature will result in a loss of water from the inundated land. The land is highly erodible (54%) and under inundation (17%). There is a high indication that increases in precipitation will result in flooding and inundation, landslides and erosion, causing damage to public amenities and infrastructure (e.g., flooding of food gardens and washing away of bridges and roads) (Robbins & Petterson, 2015). These events will not only affect land but have a significant impact on public health. In the cooler highlands (22°C), for example, an increase in temperature is causing malaria, which is an important health issue. Similarly, contaminated water sources for communal use as a result of flooding are a potent source of health concern (Obradovich & Fowler, 2017).

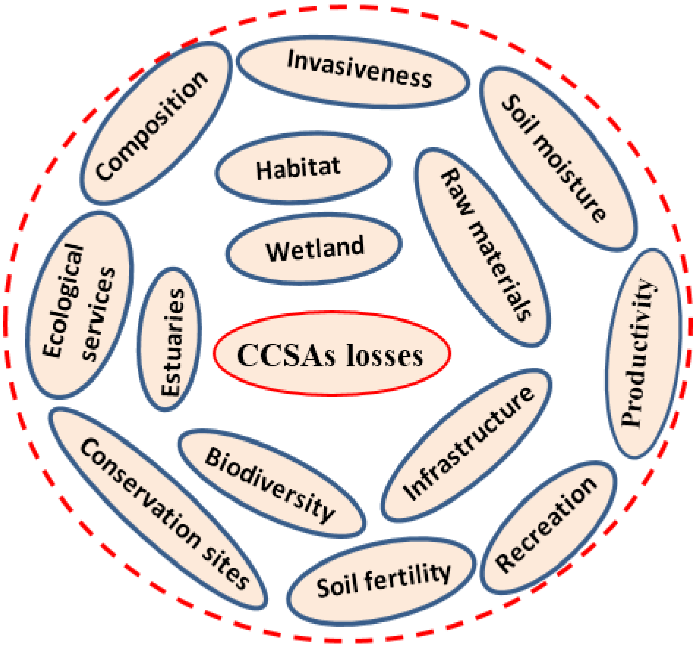

Figure 9. Critical climate-sensitive areas that would result in losses as a result of climate change stresses on terrestrial and aquatic environments. Invasiveness relates primarily to the evolution of pests that cannot be controlled conventionally.

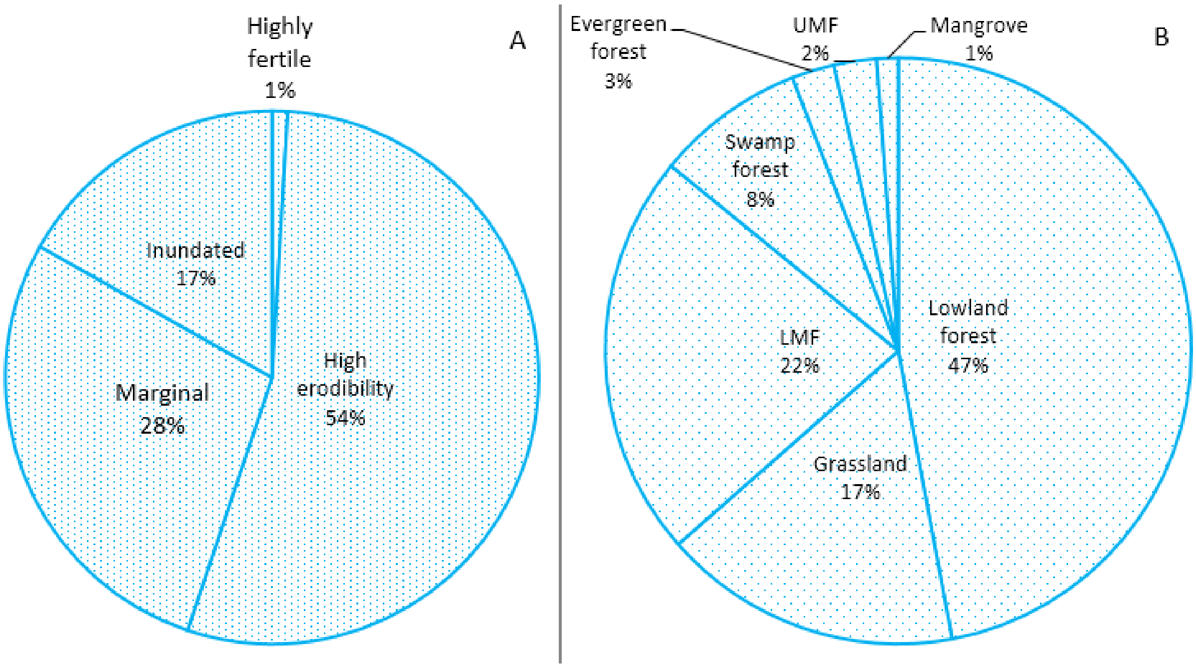

Figure 10. Land (A) and land cover (B) of PNG (Wickham et al., 2010). UMF and LMF are upper montane forest and lower montane forest, respectively.

PNG has one of the 10 largest rainforests; it is one of the 20 most biologically diverse nations in the world and home to 5 - 7% of the global biodiversity (Naser, 2014). This biological hotspot has been continuously under threat because of the increasing population, urbanization, land clearing, logging, and degradation of land ecosystems (Haberle, 2007). The changes in temperature and rainfall, including relative humidity, will greatly affect the richness in land biodiversity. The current biodiversity exists as a result of co-evolutionary processes and the mechanisms developed to co-exist through spatial and temporal variability in climate over time. The tolerance to endure and survive the future climate stresses will bring significant changes to the land biota, as it will take quite a long time to adapt. Changes in soil microbial composition will occur as these stresses take tall on the land, affecting soil ecosystem and the ecological services, the most important being decomposition of dead organic matter and cycling of soil nutrients, necessary for land productivity and sustainable use.

Decline in the general soil fertility because of low microbial composition (Kapal, Taraken, & Sirabis, 2010), contamination of water sources, drought and frost event and landslide are other notable phenomena anticipated to accelerate the impacts induced by the future climate on land resources and biota (Kaluwin, Ashton, & Saulei, 2000). Loss of biodiversity on land because of events associated with drought and frost (e.g., widespread fires and loss of plants) is already evident (Wickham et al., 2010). Rural people depend on the land and its resources that are limited in nature. Therefore, any kind of change in soil fertility, soil moisture, soil temperature, and even other ecological services pose serious threats to rural livelihood, land use, and management.

Forestry: Forest covers 70% (ca. 36 million ha) of the total land area and provides important biological resources and ecological services, which are dependent on its complexity (e.g., rainforest versus savannah grassland). Some of these ecological services are not limited to water quality, wildlife habitat diversity, biodiversity conservation, raw materials for food, houses and medicine, air quality, and climate regulation. One illustrative loss of ecological services is the decline in many pollinators around the world (Klein et al., 2007). Loss of pollinators means loss of plants (and crops) in the forests, and can often lead to malnutrition as a result of reduced fruits and vegetable supply and consumption (Frumkin & Haines, 2019). Dead plant matter alone as a result of changes in the composition is important to the whole forest ecosystem, as organic matters are potent sources of forest soil nutrients, soil moisture, and microbial diversity and ecology. At present, habitat loss is high, with more than 55 ha of forest cleared each year for agriculture, logging and infrastructure development (Shearman, Ash, MacKey, Bryan, & Lokes, 2009), leading endangered species (e.g., tree-kangaroo; *Dendrolagus Goodfellow*) to extinction (Chen, Hill, Ohlemüller, Roy, & Thomas, 2011) and disturbance of species composition.

The composition and productivity of the forest will be affected if the current rate of clearing continues in the future climate (Haberle, 2007). Tree productivity and composition are dependent on soil nutrients, water, temperature, and radiation. A future climate with changes in these key abiotic factors will immensely affect forest productivity and composition, making some plant species to expand and others to contract. Under a different climate, forest fire, an outbreak of invasive pests and pathogenic organisms (Bale et al., 2002) would become a common problem, which is difficult to manage

(Carroll, 2007; Westerling, Hidalgo, Cayan, & Swetnam, 2006). For example, climate affects insect populations through effects on the host, influencing mass attacks when diversity is limited to a few species (Logan, Régnière, & Powell, 2003). Change in precipitation is expected to affect productivity and species composition as the main driver of physiological growth and development. Water requirements by different plant species vary but any change is detrimental for the growth and productivity of plants. The summary of losses anticipated in addition to build up of invasive pests (weeds and diseases causing pathogens) is shown in Figure 9.

Marine and aquatic resources: The coastal environment is home to dugong, dolphins, whales, birds, sharks, crocodiles, turtles and nearly 300 corals and over 3000 fish species. This richness of flora and fauna (McGranahan, Balk, & Anderson, 2007) will be threatened by future climate change, particularly from the rise in sea level, sea acidification and high sea surface temperature (Occhipinti-Ambrogi, 2007). In the last 15 years, the rise in the global sea level was 0.36 cm per year (Katsman et al., 2011). The International Climate Change Adaptation Initiative (ICCAI) pointed out that sea level in PNG was rising by 0.7 cm per year since 1993 (Hunnam, 2013), twice the global projection (Merrifield, Merrifield, & Mitchum, 2009). In the next ten years from 2090 (i.e. by 2100), the sea level is projected to rise by 19 - 58 cm. Based on that, 19.4 - 59.5 cm rise is projected by 2100 (Table 2), bringing several stresses to the marine ecosystems and their biodiversity (Brierley & Kingsford, 2009).

On estimation, 17% of PNG land is inundated (Figure 10A) and 1% is mangrove (Figure 10B), indicating rising sea level will increase inundation and lead to loss of important mangrove and wetland ecosystems already with a significant amount of water (Naser, 2014; Waycott et al., 2009). There is already evidence of coral reef damage, floodplains salinization and salinity intrusion into freshwater systems, destroying delta, estuary, and access to freshwater (SOPAC, 2007). When water resources are inundated (same as land) and flooded, contamination is possible, leading to scarcity (Lund, Zhu, Tanaka, & Jenkins, 2006) and the incidence of water-borne diseases (typhoid, dysentery, and diarrhea) (IPCC, 2007a), affecting public health. Sea level rise is eroding coastlines, beaches, roads or scared sites (Bird, 1996) (e.g., along the Central coastlines and in West and East Sepik Provinces; Figure 1), making once dry land now underwater.

Ocean acidification is expected to increase destroying marine and aquatic ecosystems as more and more CO_2 dissolves and mixes with seawater (Hunnam, 2013). Coral bleaching caused by CO_2 dissolved in water and high temperature has been reported in PNG waters (Davies, Dunne, & Brown, 1997). A warmer climate (30.2 - 31.4°C in highlands by 2100 means increase temperature of water sources and modified precipitation patterns (IPCC, 2007a). The lakes, streams and the main rivers (Fly, Kikori, Sepik, Markham, and Purari), which support important natural resources (e.g., breeding sites for fishes and sea mammals), and floodplain ecosystems depend on temperature and precipitation. A future climate with increasing temperature and rainfall will surely result in drought and flood events affecting the availability of natural resources and losses of freshwater biodiversity and ecological services (Heino, Virkkala, & Toivonen, 2009). Availability for domestic, industrial, transport, agriculture, and energy need maybe scare under the future climate as sources become limited.

Table 2. Sea level rise projections for PNG for three emission scenarios (Hunnam, 2013).

Scenarios	Sea level rise (cm)			
	2030	2055	2090	2100
Low emissions	0.4 - 1.4	1.0 - 2.6	1.7 - 4.6	19.4 - 58.4
Medium emissions	0.5 - 1.4	0.9 - 3.0	2.0 - 5.8	19.5 - 59.4
High emissions	0.4 - 1.5	1.0 - 2.9	2.2 - 6.0	19.4 - 59.5

Health: The impact of changes in precipitation, temperature and CO_2 levels of the future climate on the health of people basically comes from the CCSAs (Figure 3), particularly land, forestry, marine resources, and agriculture. As precipitation increases, flood events and landslides including potentially toxic chemicals from the land, forest, marine, and cropland will end up in water sources used by people, increasing the incidents of water-borne diseases. Animals and plants are also expected to die as a result of drowning due to excess water or from high-temperature stresses. The decomposed or partially decomposed materials of animal and plant origin are potent sources of disease-causing pathogens, including pollution of air quality due to odor. Like the land, forestry is expected to face a similar fate. As the climate changes, the productivity of forest resources is expected to be affected. Changes in the composition of biodiversity (both flora and fauna) will result in loss of plant food sources (and nutritional quality), compromising the health of the consumers. The nutritional quality of agricultural produce from a compromised farm environment poses threats to human health. As the temperature changes, a pattern of disease incidence may occur, for example, malaria a disease of the lowland now becoming common in the highlands (Bourke, 2018). High CO_2 levels may reduce the nutritional quality of crops as reported in wheat (Soba et al., 2019), which is a serious concern for nutritional security and poor health.

When the sea level rises and inundates the lowlands, mangroves, floodplains and estuaries, the marine ecosystems will loss natural resources and biodiversity that people have access to as a result of coral reef bleaching, the saltwater intrusion of estuaries, flooding of floodplains and inundation of mangroves or displacement of flora and fauna. These events would not only result in loss of the marine ecosystems but affect the livelihoods, resulting in poor health, malnutrition and possible loss of lives. Contaminated marine resources are known as vehicles to fish foodborne bacterial and parasitic infections (Brown & Dorn, 1977). Bad odor and foul smell from organic matter decomposition would occur, resulting in air pollution. The nutritional status of food sources (e.g., crops) is affected by environmental factors that can impact the health and wellbeing of people (McMichael, 2013). Saltwater intrusion and salinization into freshwater systems are a potent source of freshwater contamination, and can often result in ill-health effects (Khan et al., 2014).

IMPACTS ON AGRICULTURE

Agriculture is a mainstay of rural livelihood (85%) and Gross Domestic Production (GDP) (30%) and is the most climate-sensitive sector; it is compounded by the rainfed crop agriculture in PNG. The optimum variability in temperature and rainfall under current production systems are given in Tables 3 and Table 4, respectively. Figure 11 shows a common staple in subsistence food gardens and Figure 12 shows plantation crops in commercial plantations. The staples, most of which are root and tuber crops, are grown in a subsistence and mixed good gardens. On the other hand, plantation crops are sole crops on intensive plantations. The productivity of all these crops is determined by climatic factors and is vulnerable to climate change (Lloyd, Sari Kovats, & Chalabi, 2011).

Sweet potato (*Ipomoea batatas* L.) is the staple of the high altitude areas of the highlands region and many coastal areas. Potato, taro, and banana or mixes of these are often consumed with sweet potato. In the lowlands and coastal plains, taro (*Colocasia esculenta* L.), sago (*Metroxylon sagu* Rottb.), yam (*Dioscorea* spp.), and cassava (*Manihot esculenta* L.) are the staples and these are also grown and consumed solely or together with Chinese taro (*Xanthosoma sagittifollium* L.) and banana (*Musa* spp.). In all the provinces, a small number of minor crops are also consumed which are not reviewed here. The rural livelihood depends on these staples and most importantly produced on marginal land (28%, Figure 8A) in mixed food gardens using family labor, making them key strategic crops of the future climate. Under the future climate, sustainability and nutritional security of the staples are in question as factors that support sustainable production (e.g., soil fertility and moisture) may be affected and the incidence of invasive pests may arise. Like the staples, plantation crops (Figure 12) being grown under a sole cropping system may face the same fate as climate changes.

The adaptation temperature and rainfall (optimum temperature and rainfall range) of the staples (Figure 10) and plantation (Figure 12) crops under current farming systems are given in Tables 4 and Table 5. Except for sugarcane and oil palm, all the staples and plantation crops are C_3 plants and are perennial herb, vine, grass or tree. Compared to the future temperature projections, the adaptation temperature requirement in Table 3 seems to indicate that the stress of the future temperature may turn out to be a problem, though the variability would be small. The adaptation temperature range of all the crops is 15 to 35°C (Table 4) and its projection is 29 to 31.4°C by 2090 (Table 1). Comparatively, the projections are small, closer to the current optimum ranges under which crops are grown.

Table 3. Temperature adaptation and photosynthetic pathways of staple and plantation crops

Crop	**Temperature (°C)**			**Crop adaptation**
Staples	Maximum	Minimum	Pathway*	Growth characteristics
Sweet potato	35	18	C_3	Perennial shrub
Taro	30	21	C_3	Perennial herb
Yam	30	25	C_3	Perennial herbaceous vine
Cassava	30	28	C_3	Perennial shrub
Chinese taro	30	21	C_3	Perennial herb
Banana	27	16	C_3	Perennial herb
Plantation				
Rubber	34	15	C_3	Perennial tree
Oil palm	33	22	C_4	Perennial tree
Tea	21	29	C_3	Perennial herb
Cocoa	80	65	C_3	Perennial tree
Sugarcane	26	20	C_4	Perennial grass
Vanilla	32	21	C_3	Perennial vine
Coffee	32	20	C_3	Perennial tree
Coconut	32	20	C_3	Perennial tree

*Carbon fixation and photosynthetic pathway of the plants.

The C_4 plants (e.g., sugar cane and oil palm) are suited to the climate of high temperature and limited water (Osborne & Freckleton, 2009), whereas in C_3 plants, high temperature and water limitation stresses are compromised due to photorespiration (Hill, Belesky, & Stringer, 1998). More than 85% of higher plants are C_3 plants, and high temperature, in general, is a common problem for most plants (e.g., the evergreen rainforest). An increase in temperature severely affects subsistence staple crop production. So, it may require to change the farming systems (e.g., need for irrigation) under the future climate. As the high temperature lowers soil moisture, the need for water to sustain the productivity of the C_3 crops will set in. Almost all crop production in PNG is rainfed; therefore increase in precipitation and its impact will be small, apart from topsoil erosion from excessive flooding and massive landslide with increasing precipitation.

Plants' response to CO_2 levels is well studied (e.g., Brown, 1999; Sage & Kubien, 2003). Most C_3 plants lack the mechanism to concentrate CO_2 levels in the leaves and depend on atmospheric availability (Norby, Wullschleger, Gunderson, Johnson, & Ceulemans, 1999). Therefore, the projected increase in CO_2 levels (Table 2) will boost photosynthetic activities and have a fertilizing effect on productivity (biomass and yield). In the event water stress sets in (which is unlikely for the next 70 years, Table 1), photosynthetic activities will be affected and the fertilizing effect under elevated CO_2 levels maybe for a shorter period due to acclimatization depression of photosynthesis (Makino & Tadahiko, 1999). On the other hand, the C_4 crops have the capacity to increase CO_2 levels in the leaves (even when photosynthetic pathway mechanisms are inactive), making an increase in atmospheric CO_2 levels do not affect productivity. This means water stress does not affect crop productivity as moisture loss is minimized from the surface of leaves (Simpson, 2016). This makes C_4 plantation crops (oil palm and sugarcane) strategic crops of the future climate under water stress, but the product of these cannot be eaten. Instead, the cash earned can be used to address food and nutritional security of the future climate to support livelihood.

Table 4. Optimum rainfall requirement (cm) for production of the staple and plantation crops of PNG and the current rainfall (cm) distribution under which the crops are grown.

Crop	**[a]Production requirement**		**Current in PNG**	
Staples	Maximum	Minimum	Maximum	Minimum
Sweet potato	20	18	280	100
Taro	30	21	280	260
Yam	30	25	280	240
Cassava	30	28	260	200
Chinese taro	30	21	280	260
Banana	27	16	260	240
Plantation				
Rubber	400	250	300	200
Oil palm	200	180	300	280
Tea	350	300	300	280
Cocoa	381	50	300	240
Sugarcane	350	120	300	260
Vanilla	30	20	280	240
Coffee	250	150	280	260
Coconut	320	130	280	120

CROP PRODUCTION AND MANAGEMENT

Agriculture in PNG occupies 6.6% (13.75 million ha) of total land areas. The current farming and crop production systems are based on the prevailing climatic conditions (Table 5). Under the future climate, the system of tillage, implement types, time of production and important other related activities of farming and crop production will be affected as temperature and precipitation increase or water stress sets in (Ziska & Runion, 2007). For instance, transplanting and harvesting are often done in the cooler part of the day and towards the onset of rain; but these types of practices may change under future climatic conditions (Masters & Norgrove, 2010). The types of farm machinery now used will be obsolete as the soil becomes too wet or too dry, requiring the design and development of new types of machinery. Spatial and temporal variation in precipitation may prolong the growing phase of crops, thereby delaying maturity and harvesting, leading to economic loss.

Crop production: The staples (Figure 11) sweet potato, cassava, yam, and banana are grown on well-drained soil. Sweet potato is a staple in many locations and grown under the climatic condition where the temperature rarely exceeds 31°C and is vulnerable to excessive soil moisture, which retards tuber initiation and reduces yield (Bourke, 1988). This implies that most of the rural growers will find it difficult to counter the significant increase in temperature and rainfall (Bourke, 2018). Cassava is a hardy crop and grown at areas that face dry and wet season each year, but an annual increase in rainfall by 25% or more would reduce yield (Bourke, 2018). Yam is a lowland crop and production is limited to areas that receive rainfall of between 100 cm and 250 cm per year. Quite recently, the crop has reached the lower highland areas (1500 m, Figure 2) and yet to be promoted in the cooler mountains. Production of this crop in areas of higher rainfall (>280 cm) and the lowlands when rainfall increases are yet to be seen. Banana is cultivated in areas that experience regular dry seasons as well as those that receive mildly seasonal rainfall distribution, and changes in temperature and rainfall by a few degrees Celsius or centimeters, respectively will not result in a significant reduction in yield.

The water-loving staples are sago, taro, Chinese taro and swamp taro (*Crytosperma merkusii* L.). Sago is a hard crop and an increase in rainfall or temperature will not have serious impacts on its production (Spencer, 1963). Similarly, Chinese and swamp taros are water-loving; therefore increase in rainfall under the future climate will not significantly affect production. Production of these crops, however, depends on moisture availability, and an increase in drought events related to change in temperature is a threat to its sustainable production and thus food security (Toyoda, 2018).

In the lowlands, coconut (*Cocos nucifera* L.), oil palm (*Elias guinensis* Jacq.), cocoa (*Theobroma cocoa*), rubber (*Hevea brasiliensis* L.), sugarcane (*Saccharum* sp.) and vanilla (*Vanilla* spp.) are grown (Figure 12). In the highlands, coffee (*Coffee* spp.) and tea (*Camellia sinensis*) productions are dominant. Coconut is grown along the coastlines and on the smaller islands. Therefore, a rise in sea level and saltwater intrusions are major concerns that may impact its production. The crop is tolerant to a certain level of temperature stress but excessive water leads to a decline in yield due to nutrient loss and waterlogging. Cocoa and oil palm are hardy crops and grown in areas of moderately high temperature and rainfall (Table 4 and Table 5). An increase in rainfall under the future climate (Table 1) may result in a reduction in yield although the current areas of production are under relatively high rainfall, 300 - 350 cm per year (Figure 8A). Rubber is a hot climate crop and grown from sea level up to 400 m with a temperature range of 23 - 30°C and a rainfall of 250 - 500 cm, indicating that an increase in rainfall or temperature will not be a significant problem (apart from prolonging drought events). The sugarcane production area (400 m) is located in an Inter-tropical Convergence Zone (Figure 4) receiving an average annual rainfall of 150 - 250 cm with a mean temperature of 26.7°C. Sustainable production of this crop will face a problem if the temperature increases by 4°C, which is unlikely under any projection between 2030 and 2090 (Table 1). The variability within this period is small, ranging from 0.6 to 1.6°C (1.0°C).

Coffee production is at 600 to 2100 m high lands (pre-montane to mid-montane, Table 5) with most plantations located at 1400 to 1800 m. Commercial production of this crop is undertaken at the higher altitude areas with sufficient rainfall (Table 4) and it is unlikely that an increase in rainfall will greatly impact its yield. The future climate, however, may become conducive to the frequent incidence of pests and diseases (Dukes & Mooney, 1999). Tea is grown at a temperature range of 15 - 30°C and under evenly distributed rainfall of 100 - 140 cm. Like coffee, an increase in temperature or rainfall will not have a significant impact on the yield of tea; however fungal diseases such as *Exobasidium vexans* may become prevalent. Vanilla is grown above 1500 m and the ideal growing conditions are 150 - 300 cm of rainfall and within a temperature range of 15 - 30°C. Production of vanilla is limited to the lowlands; however as the future climate becomes warmer, introduction in the highlands is possible. Anthracnose (*Colletotrichum* spp.) is a fungal disease of vanilla that is pronounced during humid periods. This disease might become more common as humidity becomes high under the future climate.

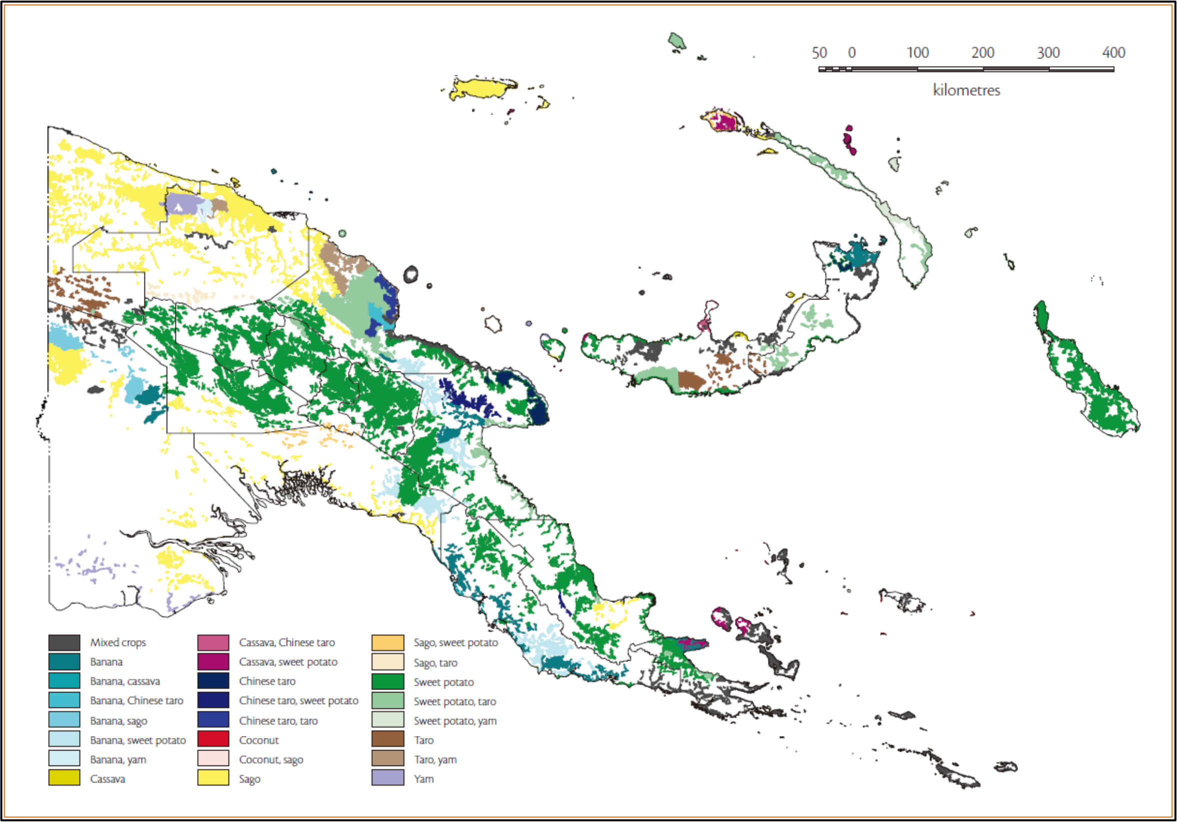

Figure 11. Important staples to the rural livelihood of PNG.

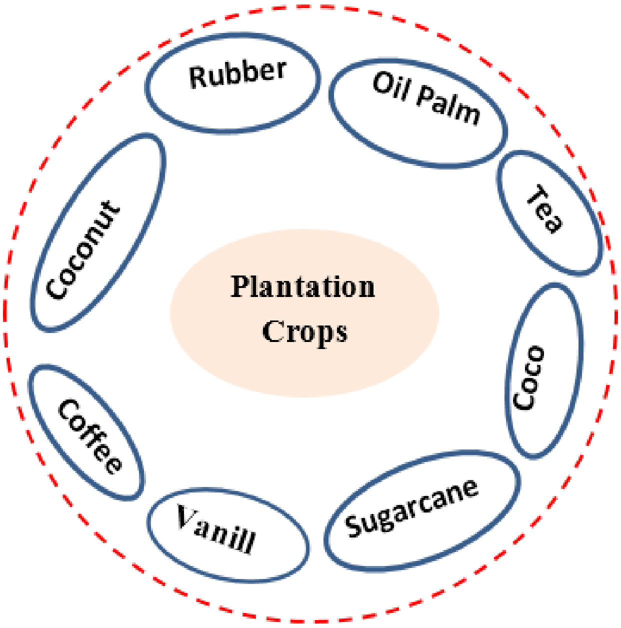

Figure 12. Future climate strategic plantation crops of PNG. Tea and coffee are grown on large-scale plantations in the lowlands as well as in the highlands.

Table 5. Agro-ecological zones based on temperature and rainfall (Mcalpine, Keig, & Short, 1975).

	Temperature (°C)		Meters above sea level
Zones	Maximum	Minimum	
Lowland	32	23	0-600
Pre-montane	29	18	600-1500
Lower montane	25	13	1500-1800
Mid-montane	22	11	1800-2700
Upper montane	11	4	2700-3300
Sub-alpine	<4	4	>3300
	Rainfall (cm)		
Dry-subhumid	150	100	
Subhumid	200	1500	
Humid	350	200	
Perhumid	>350	350	

Considering the data available, there is not much variability in the projected climatic factors (Table 1) and the crop's adaptation requirements (Table 4 and Table 5), indicating the future climate will not significantly reduce production, at least by 2090. The impacts of the environment on the production of the stables are relatively small because of the scale of production compared to the plantation crops. The plantation crops, however, are produced on large-scale and the impacts of the environment are huge. A good number of studies show oil palm plantation establishment alone and the events associated with it (e.g., wildfires) is one of the main reasons of rainforest loss globally (e.g., Frumkin & Haines, 2019; Nadal, Marquès, Mari, & Domingo, 2015; Newbold et al., 2016). Most of the plantation crops are produced as sole crops and on a large area of land, and most often this occurs with a certain degree of losses in biodiversity, soil moisture and nutrients, and even forest cover during Anthropocene (Newbold et al., 2016). These losses are permanent, unless managed, because of continuous production on the same piece of land and in such areas; the environments are often scalded by chemicals (Diamond et al., 2015), with implications on the climate. Regarding climate change, plantations involve single crops, therefore limited biodiversity and species composition. Carbon sequestration for coupling climate change mitigation from plantation crops are even reported to be variable, with oil palm containing the lowest carbon content of 45 t ha^{-1} (Budiadi & Ishii, 2010; Kongsager, Napier, & Mertz, 2013; Subramaniyan, Jothi, Shoba, & Murugesan, 2017). The cropland itself has a huge potential to sequester because the soil is carbon-depleted as a result of crop production (Di Vita, Pilato, Pecorino, Brun, & D'Amico, 2017). Removal of CO_2 levels from the atmosphere is not only important for global warming but to mitigate the negative impacts on crop nutrition.

Altitudinal Change: In PNG, every 1000 m increase in altitude results in a 5.2°C decrease in maximum and minimum temperature (Bourke, 2018). An increase in temperature would result in an increase in altitude at which most staples are grown. For instance, an increase in temperature by 1.2 °C by 2090 (Table 1) would result in staples to be grown above 200 m than their current location (Bourke, 2018). The lower limits of certain lowland crops, including coconut, *Marita* pandanus (*Pandanus conoideus*) and mango have increased, bearing at 300 m in the highlands. The most likely explanation for this is an increase in temperature. Similarly, the upper limit of highland crops has decreased. The banana that normally grows at 1700 m (at high altitude) is now growing at 9 m (Figure 13). This could mean the air temperature at the lowlands is getting cooler, maybe because of the increase in rainfall.

Figure 13. Banana (*Musa* sp.) that only grows and bears fruit at upper highlands (1667 m) is now growing at 9 m above sea level in Lae, 2019.

As pointed out previously, the dry season is experienced between April and October and the wet season between November and March. The changes in weather patterns make crops to have different tolerance to temperature extremes (Laing, Kretchmer, Zuluaga, & Jones, 1983; Wu, Yu, & Liou, 1974). The banana plants now growing at the lowlands may be just phenotypic plasticity in response to climate change (Gratani, Pesoli, Crescente, Aichner, & Larcher, 2000; Spencer, Teeri, & Wetzel, 1994). Meaning, the banana plants are responding to the variation in climatic factors by becoming more plastic than genetically variable (Via & Lande, 1987). Similarly, cocoa, a lowland crop is now striving in the highlands (Simbu, Figure 1) and producing heavy crops.

Management of pests: In managed and unmanaged ecosystems, most weeds are C_4 plants and respond directly to CO_2 levels. The increase in CO_2 levels under the future climate (now 380 ppm, Vu, 2005) may stimulate the growth of these plants and would require different management systems (Sage and Kubien, 2003). This will become common under high temperatures and reduced soil moisture conditions (Patterson, 1993). Generally, CO_2 stimulates C_3 photosynthesis but the projected high temperature and water stress will impede, making C_4 weeds to become invasive at the expense of C_3 plants, even in unmanaged areas (e.g., savannah grassland) (Patterson, 1995). Weed invasion affects farming systems and management of weeds under the future climate may be expensive (Ziska & Runion, 2007). Reproduction and spread of common weeds like crabgrass (*Digitaria sanguinalis*), pigweed (*Chenopodium album*) and C_4 itch grass (*Rottboellia cochinchinensis*) may change (Lejeune, Griffin, Reynolds, & Saxton, 1994; Lencse & Griffin, 1991) under managed and unmanaged ecosystems. In other words, all types of weeds suppressed by low temperature or precipitation will surge under the future climate (Hussner, Van De Weyer, Gross, & Hilt, 2010). An increase in precipitation and temperature facilitates the spread of pests and disease, e.g., crops under excessive water stress are prone to virus attack and under drought stress are unable to complete with drought-tolerant weeds for soil moisture and nutrients (Simpson, 2016). Insects are poikilothermic and an increase in temperature results in population increase, which is difficult to manage (Cammell & Knight, 1992). Change in climate will affect the natural enemies of pests and modify diversity, resulting in a surge of particular pests (Zvereva & Kozlov, 2010). The metabolic rate of insect pests increases as temperature increases, causing them to consume more, which may become common under higher temperatures.

CONCLUSIONS

Precipitation, temperature and CO_2 levels are examples of important climatic factors that affect land, marine, forest resources, agriculture, and their biodiversity and ecosystems. These CCSAs experience a wide range of anthropogenic and natural stresses, including pollution and contamination, floods and landslides, drought and wildfires, pests and pathogens, and invasive species. The changes in climatic factors exacerbate these stresses through changes in precipitation, temperature and CO_2 levels affecting the CCSAs, which in turn affect rural livelihood and survival. Changes in soil moisture and fertility affect land resources, productivity, and biodiversity; contamination, landslides and flood events affect water resources and promote water-borne diseases; and drought events and wildfires destroy forest resources and its biodiversity. Saltwater intrusion, salinization, acidification, and inundation affect mangroves, estuaries, flood plains, coastlines, and important marine resources as sea level rises. Evolution of invasive pests and diseases, loss of topsoil and contaminated water sources will affect agriculture and sustainable production of the staple and plantation crops, and the mainstay of the people of PNG. This review documented the current climate, changes expected based on projections and impact on critical areas including staple and plantation crops of PNG. As resources (land, marine, forest, and agriculture) use will continue to compound the stresses of the future climate, local strategies to mitigate and to adapt the changes are needed. In agriculture, having known the types of crops and climatic requirements, strategic directions that include smart-agriculture; research, development, and extension are "survival tools" forward for PNG under the future climate. The altitudinal change of crops to different agro-climatic zones as a result of climate change will provide more challenges for crop production in the future.

ACKNOWLEDGMENT

There is no conflict of interest related to this work. Works of literature on PNG climate were collated by Malice Michael, Alice Pokon, and Pamawi Meko Michael. The author is grateful for the input of the anonymous reviewers.

REFERENCES

Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., … Whittaker, J. B. (2002). Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Global Change Biology*, *8*(1), 1–6. https://doi.org/10.1046/j.1365-2486.2002.00451.x

Bird, E. C. F. (1996). Coastal Erosion and Rising Sea-Level. In J. D. Milliman & B. U. Haq (Eds.), *Sea-Level Rise and Coastal Subsidence: Causes, Consequences, and Strategies* (2nd ed., pp. 87–103). Dordrecht: Springer. https://doi.org/10.1007/978-94-015-8719-8_5

Boehm, R., Cash, S. B., Anderson, B. T., Ahmed, S., Griffin, T. S., Robbat, A., … Orians, C. M. (2016). Association between empirically estimated monsoon dynamics and otherweather factors and historical tea yields in China: Results from a yield response model. *Climate*, *4*(2), 20. https://doi.org/10.3390/cli4020020

Bourke, R Michael. (1988). *Taim hangre: variation in subsistence food supply in the Papua New Guinea highlands*. *Department of Human Geography*. Australian National University. https://doi.org/10.25911/5d739086d9691

Bourke, Richard Michael. (2018). Impact of climate change on agriculture in Papua New Guinea. In A. R. Quartermain (Ed.), *Climate Change: Our Environment, Livelihoods, and Sustainabilit* (pp. 35–50). Papua New Guinea: University of Goroka.

Brierley, A. S., & Kingsford, M. J. (2009). Impacts of Climate Change on Marine Organisms and Ecosystems. *Current Biology*, *19*(14), R602–R614. https://doi.org/10.1016/j.cub.2009.05.046

Brown, L. D., & Dorn, C. R. (1977). Fish, Shellfish, and Human Health. *Journal of Food Protection*, *40*(10), 712–717. https://doi.org/10.4315/0362-028x-40.10.712

Brown, R. H. (1999). Agronomic Implications of C4 Photosynthesis. In R. F. Sage & R. K. Monson (Eds.), *C4 Plant Biology* (pp. 473–507). Cambridge, Massachusetts: Academic Press. https://doi.org/10.1016/B978-012614440-6/50015-X

Budiadi, & Ishii, H. T. (2010). Comparison of carbon sequestration between multiple-crop, single-crop, and monoculture agroforestry systems of Melaleuca in Java, Indonesia. *Journal of Tropical Forest Science*, *22*(4), 378–388.

Cammell, M. E., & Knight, J. D. (1992). Effects of Climatic Change on the Population Dynamics of Crop Pests. *Advances in Ecological Research*, *22*, 117–162. https://doi.org/10.1016/S0065-

2504(08)60135-X

Canadell, J. G., & Raupach, M. R. (2008). Managing forests for climate change mitigation. *Science*, *320*(5882), 1456–1457. https://doi.org/10.1126/science.1155458

Carroll, S. P. (2007). Natives adapting to invasive species: Ecology, genes, and the sustainability of conservation. *Ecological Research*, *22*(6), 892–901. https://doi.org/10.1007/s11284-007-0352-5

Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, *333*(6045), 1024–2016. https://doi.org/10.1126/science.1206432

Davies, J. M., Dunne, R. P., & Brown, B. E. (1997). Coral bleaching and elevated sea-water temperature in Milne Bay Province, Papua New Guinea, 1996. *Marine and Freshwater Research*, *48*(6), 513–516. https://doi.org/10.1071/MF96128

Di Vita, G., Pilato, M., Pecorino, B., Brun, F., & D'Amico, M. (2017). A review of the role of vegetal ecosystems in CO2 capture. *Sustainability (Switzerland)*, *9*, 1840. https://doi.org/10.3390/su9101840

Diamond, M. L., de Wit, C. A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., … Zetzsch, C. (2015). Exploring the planetary boundary for chemical pollution. *Environment International*, *78*, 8–15. https://doi.org/10.1016/j.envint.2015.02.001

Dukes, J. S., & Mooney, H. A. (1999). Does global change increase the success of biological invaders? *Trends in Ecology and Evolution*, *14*(4), 135–139. https://doi.org/10.1016/S0169-5347(98)01554-7

Frumkin, H., & Haines, A. (2019). Global Environmental Change and Noncommunicable Disease Risks. *Annual Review of Public Health*, *40*, 261–282. https://doi.org/10.1146/annurev-publhealth-040218-043706

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., … Paul, F. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, *340*(6134), 852–857. https://doi.org/10.1126/science.1234532

Gratani, L., Pesoli, P., Crescente, M. F., Aichner, K., & Larcher, W. (2000). Photosynthesis as a temperature indicator in Quercus ilex L. *Global and Planetary Change*, *24*(2), 153–163. https://doi.org/10.1016/S0921-8181(99)00061-2

Haberle, S. G. (2007). Prehistoric human impact on rainforest biodiversity in highland New Guinea. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1478), 219–228. https://doi.org/10.1098/rstb.2006.1981

Heino, J., Virkkala, R., & Toivonen, H. (2009). Climate change and freshwater biodiversity: Detected patterns, future trends, and adaptations in northern regions. *Biological Reviews*, *84*(1), 39–54. https://doi.org/10.1111/j.1469-185X.2008.00060.x

Hill, N. S., Belesky, D. P., & Stringer, W. C. (1998). Encroachment of endophyte-infected on endophyte-free tall fescue. *Annals of Botany*, *81*(4), 483–488. https://doi.org/10.1006/anbo.1998.0583

Hunnam, P. (2013). *Review of The International Climate Change Adaptation Initiative Pacific Programs in Climate Science and Adaptation Planning 2008-2013: Pasific Climate Change Science Program Pacific Adaptation Strategy Assistance Program Pasific-Australia Climate Change*. *The International Climate Change Adaptation Initiative Pacific Programs in Climate Science and Adaptation Planning*. Honiara, Solomon Islands.

Hussner, A., Van De Weyer, K., Gross, E. M., & Hilt, S. (2010). Comments on increasing number and abundance of non-indigenous aquatic macrophyte species in Germany. *Weed Research*, *50*(6), 519–526. https://doi.org/10.1111/j.1365-3180.2010.00812.x

IPCC. (2007a). *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson, Eds.). Cambridge: Cambridge University Press.

IPCC. (2007b). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, … H. L. Miller, Eds.). Cambridge, UK, and New York, USA: Cambridge University Press.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (S. T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley, Eds.). Cambridge, UK, and New York, USA: Cambridge University Press.

Kaluwin, C., Ashton, J., & Saulei, S. (2000). *Papua New Guinea Initial national communication under the United Nations Framework Convention on Climate Change*. Port Moresby.

Kapal, D. B., Taraken, I. T., & Sirabis, W. (2010). Soil fertility management options in sweet potato based cropping systems in the highlands of Papua New Guinea. In R. Gilkes & N. Prakongkep (Eds.), *19th World Congress of Soil Science, Soil Solutions for a Changing World* (pp. 144–146). Brisbane, Australia: International Union of Soil Sciences.

Katsman, C. A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., … Weisse, R. (2011). Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta-the Netherlands as an example. *Climatic Change*, *109*(3–4), 617–645. https://doi.org/10.1007/s10584-011-0037-5

Khan, A. E., Scheelbeek, P. F. D., Shilpi, A. B., Chan, Q., Mojumder, S. K., Rahman, A., … Vineis, P. (2014). Salinity in drinking water and the risk of (pre)eclampsia and gestational hypertension in coastal Bangladesh: A case-control study. *PLoS ONE*, *9*(9), e108715. https://doi.org/10.1371/jouemrnal.pone.0108715

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, *274*, 303–313. https://doi.org/10.1098/rspb.2006.3721

Knoema.com. (2018). Papua New Guinea CO2 emissions, 1970-2018 - knoema.com.

Koczberski, G., Curry, G. N., Bue, V., Germis, E., Nake, S., & Tilden, G. M. (2018). Diffusing Risk and Building Resilience through Innovation: Reciprocal Exchange Relationships, Livelihood Vulnerability and Food Security amongst Smallholder Farmers in Papua New Guinea. *Human Ecology*, *46*(6), 801–814. https://doi.org/10.1007/s10745-018-0032-9

Kongsager, R., Napier, J., & Mertz, O. (2013). The carbon sequestration potential of tree crop plantations. *Mitigation and Adaptation Strategies for Global Change*, *18*(8), 1197–1213. https://doi.org/10.1007/s11027-012-9417-z

Laing, D. R., Kretchmer, P. J., Zuluaga, S., & Jones, P. G. (1983). Field beans. In *Potential Productivity of Field Crops Under Different Environments* (pp. 227–248). Manila, Philippines: International Rice Research Institute.

Lakau, A. A. L. (1991). *State acquisition of customary land for public purposes*. Lae, Papua New Guinea: Dept. of Surveying and Land Studies, Papua New Guinea University of Technology.

Lawler, J. J. (2009). Climate change adaptation strategies for resource management and conservation planning. *Annals of the New*

York Academy of Sciences, *1162*, 79–98. https://doi.org/10.1111/j.1749-6632.2009.04147.x

Leakey, A. D. B. (2009). Rising atmospheric carbon dioxide concentration and the future of C 4 crops for food and fuel. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1666), 2333–2343. https://doi.org/10.1098/rspb.2008.1517

Lejeune, K. R., Griffin, J. L., Reynolds, D. B., & Saxton, A. M. (1994). Itchgrass (Rottboellia cochinchinensis) Interference in Soybean (Glycine max). *Weed Technology*, *8*(4), 733–737. https://doi.org/10.2307/3988188

Lencse, R. J., & Griffin, J. L. (1991). Itchgrass (Rottboellia cochinchinensis) Interference in Sugarcane (Saccharum sp.). *Weed Technology*, *5*(2), 396–399. https://doi.org/10.1017/s0890037x0002830x

Lloyd, S. J., Sari Kovats, R., & Chalabi, Z. (2011). Climate change, crop yields, and undernutrition: Development of a model to quantify the impact of climate scenarios on child undernutrition. *Environmental Health Perspectives*, *119*(12), 1817–1823. https://doi.org/10.1289/ehp.1003311

Logan, J. A., Régnière, J., & Powell, J. A. (2003). Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment*, *1*(3), 130–137. https://doi.org/10.1890/1540-9295(2003)001[0130:ATIOGW]2.0.CO;2

Lund, J. R., Zhu, T., Tanaka, S. K., & Jenkins, M. W. (2006). Water Resources Impacts. In J. B. Smith & R. Mendelsohn (Eds.), *The Impact of Climate Change on Regional Systems A Comprehensive Analysis of California* (p. 165 - 187). Massachusetts, USA: Edward Elgar Publishing. https://doi.org/10.4337/9781847203120

Makino, A., & Tadahiko, M. (1999). Photosynthesis and plant growth at elevated levels of CO2. *Plant and Cell Physiology*, *40*(10), 999–1006. https://doi.org/10.1093/oxfordjournals.pcp.a029493

Masters, G., & Norgrove, L. (2010). *Climate Change and Invasive Alien Species* (1 No. 1). *CABI Working Paper 1*. Oxfordshire.

Mawdsley, J. R., O'Malley, R., & Ojima, D. S. (2009). A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*, *23*(8), 1080–1089. https://doi.org/10.1111/j.1523-1739.2009.01264.x

Mcalpine, J., Keig, G., & Short, K. (1975). *Climatic tables for Papua New Guinea. Technical Paper No. 37*. Canberra, Australia.

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, *19*(1), 17–37. https://doi.org/10.1177/0956247807076960

McMichael, A. J. (2013). Globalization, climate change, and human health. *New England Journal of Medicine*, *368*, 1335–1343. https://doi.org/10.1056/NEJMra1109341

Merrifield, M. A., Merrifield, S. T., & Mitchum, G. T. (2009). An anomalous recent acceleration of global sea level rise. *Journal of Climate*, *22*, 5772–5781. https://doi.org/10.1175/2009JCLI2985.1

Mittler, R. (2006). Abiotic stress, the field environment and stress combination. *Trends in Plant Science*, *11*(1), 15–19. https://doi.org/10.1016/j.tplants.2005.11.002

Morice, C. P., Kennedy, J. J., Rayner, N. A., & Jones, P. D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research Atmospheres*, *117*, D08101. https://doi.org/10.1029/2011JD017187

Nadal, M., Marquès, M., Mari, M., & Domingo, J. L. (2015). Climate change and environmental concentrations of POPs: A review. *Environmental Research*, *143*(A), 177–185. https://doi.org/10.1016/j.envres.2015.1

0.012

Naser, H. A. (2014). Marine Ecosystem Diversity in the Arabian Gulf: Threats and Conservation. In *Biodiversity - The Dynamic Balance of the Planet*. https://doi.org/10.5772/57425

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., … Purvis, A. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science*, *353*(6296), 288–291. https://doi.org/10.1126/science.aaf2201

Norby, R. J., Wullschleger, S. D., Gunderson, C. A., Johnson, D. W., & Ceulemans, R. (1999). Tree responses to rising CO2 in field experiments: Implications for the future forest. *Plant, Cell and Environment*, *22*(6), 683–714. https://doi.org/10.1046/j.1365-3040.1999.00391.x

Obradovich, N., & Fowler, J. H. (2017). Climate change may alter human physical activity patterns. *Nature Human Behaviour*, *1*, 0097. https://doi.org/10.1038/s41562-017-0097

Occhipinti-Ambrogi, A. (2007). Global change and marine communities: Alien species and climate change. *Marine Pollution Bulletin*, *55*(7–9), 342–352. https://doi.org/10.1016/j.marpolbul.2006.11.014

Osborne, C. P., & Freckleton, R. P. (2009). Ecological selection pressures for C4 photosynthesis in the grasses. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1663), 1753–1760. https://doi.org/10.1098/rspb.2008.1762

PACCSAP. (2011). *Pacific-Australia Climate Change Science and Adaptation Planning Program: Current and future climate of Papua New Guinea*. Papua New Guinea. Retrieved from https://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/14_PACCSAP-PNG-11pp_WEB.pdf

Patterson, D. T. (1993). Implications of Global Climate Change for Impact of Weeds, Insects, and Plant Diseases. In *International Crop Science I* (pp. 273–280). Madison: Crop Science Society of America. https://doi.org/10.2135/1993.internationalcropscience.c42

Patterson, D. T. (1995). Weeds in a Changing Climate. *Weed Science*, *43*(4), 685–701. https://doi.org/10.1017/s0043174500081832

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E., & Somerville, R. C. J. (2007). Recent climate observations compared to projections. *Science*, *316*(5825), 709. https://doi.org/10.1126/science.1136843

Robbins, J. C., & Petterson, M. G. (2015). Landslide inventory development in data spare region: spatial and temporal characteristics in Papua New Guinea. *Natural Hazard and Earth System Sciences*, *3*, 4871–4917.

Sage, R. F., & Kubien, D. S. (2003). Quo vadis C4? An ecophysiological perspective on global change and the future of C4 plants. *Photosynthesis Research*, *77*(2–3), 209–225. https://doi.org/10.1023/A:1025882003661

Shearman, P. L., Ash, J., MacKey, B., Bryan, J. E., & Lokes, B. (2009). Forest conversion and degradation in Papua New Guinea 1972-2002. *Biotropica*, *41*(3), 379–390. https://doi.org/10.1111/j.1744-7429.2009.00495.x

Simpson, B. M. (2016). *Preparing Smallholder Farm Families to Adapt to Climate Change. Pocket Guide 1 Extension Practice for Agricultural Adaptation*. (G. Burpee & D. Pachico, Eds.). Baltimore, MD, USA: Catholic Relief Services.

Soba, D., Sinda, B. M., Fuertes-Mendizábal, T., Méndez-Espinoza, A. M., Gilard, F., González-Murua, C., … Aranjuelo, I. (2019). Metabolic Effects of Elevated CO2 on Wheat Grain Development and Composition. *Journal of Agricultural and Food Chemistry*, *67*(31), 8441–8451. https://doi.org/10.1021/acs.jafc.9b0159

4

SOPAC. (2007). *National Integrated Water Resource Management Diagnostic Report Papua New Guinea*. Suva, Fiji.

Spencer, J. E. (1963). The migration of rice from mainland Southeast Asia into Indonesia. In J. Barrau (Ed.), *Plants and the migrations of Pacific peoples; a symposium.* (pp. 83–89). Honolulu: Bishop Museum Press.

Spencer, W. E., Teeri, J., & Wetzel, R. G. (1994). Acclimation of photosynthetic phenotype to environmental heterogeneity. *Ecology*, *75*(2), 301–314. https://doi.org/10.2307/1939536

Subramaniyan, P., Jothi, L. J., Shoba, N., & Murugesan, S. (2017). Carbon sequestration in plantation crops. *International Journal of Scientific Development and Research*, *2*(5), 96–101.

Toyoda, Y. (2018). Life and livelihood in sago-growing areas. In H. Ehara, Y. Toyoda, & D. V. Johnson (Eds.), *Sago Palm: Multiple Contributions to Food Security and Sustainable Livelihoods* (pp. 31–42). Singapore: Springer. https://doi.org/10.1007/978-981-10-5269-9_3

Via, S., & Lande, R. (1987). Evolution of genetic variability in a spatially heterogeneous environment: Effects of genotype–environment interaction. *Genetical Research*, *49*(2), 147–156. https://doi.org/10.1017/S001667230002694X

Vu, J. C. V. (2005). Rising atmospheric CO2 and C4 photosynthesis. In *Handbook of Photosynthesis, Second Edition*. https://doi.org/10.1201/9781420027877

Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., … Williams, S. L. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.0905620106

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase Western U.S. forest wildfire activity. *Science*, *313*(5789), 940–943. https://doi.org/10.1126/science.1128834

Wickham, F., Kinch, J., Mitchell, D., Bongro, M., Alphonse, R., Sissiou, G., … Nicholls, S. (2010). *National capacity self assessment project: assessing the capacity of Papua New Guinea to implement the United Nations Convention on Biological Diversity (UNCBD), the United Nations Convention to Combat Desertification (UNCCD), and the United Nations Frame*. Papua New Guinea.

Wu, H. B.-F., Yu, T. T., & Liou, T.-D. (1974). Physiological and biochemical comparisons of sweet potato varieties sensitive (Tai-long 57) and insensitive (Red-tuber-tail) to chilling temperature. In R. L. Bieleski, A. R. Ferguson, & M. M. Creswell (Eds.), *Mechanisms of Regulation of Plant Growth* (pp. 483–486). New Zealand: Royal Society of New Zealand Bulletin 12.

Ziska, L., & Runion, G. (2007). Future weed, pest and disease problems for plants. In P. C. D. Newton, R. A. Carran, G. R. Edwards, & P. A. Niklaus (Eds.), *Agroecosystems in a Changing Climate* (pp. 261–287). Boca Raton, FL: CRC Press.

Zvereva, E. L., & Kozlov, M. V. (2010). Responses of terrestrial arthropods to air pollution: A meta-analysis. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-009-0138-0