Analysing the Effect of Drought on Net Primary Productivity of Tropical Rainforests in Queensland using MODIS Satellite Imagery

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ABSTRACT

The changing climate is characterised by increased frequency and severity of extreme weather events that include cyclones, drought, flooding, heatwaves and snowing. Such climatic patterns are predicted to have negative effects on tropical forests. Given the role played by these forests in hydrological cycle, carbon cycling and biodiversity, it is crucial to quantify these effects to ensure adequate monitoring and management of these forest ecosystems. The aim of this study was to analyse the effect of drought on the Net Primary Productivity (NPP) of tropical rainforests. The specific objectives were to a) determine existing trends of NPP over the study period, b) assess the relationship between NPP and climatic - biophysical factors, c) analyse the effect of drought on NPP, and d) evaluate inter-annual variation of NPP.

Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery, thematic data sets and climatic data sets were acquired and analysed using GIS techniques, image processing tools and statistical techniques. Correlation and regression analyses were used to establish relationship between NPP and climatic-biophysical factors. NPP had a positive trend over the study period even though there was a significant reduction of NPP in 2003 and 2006 as a result of drought events in 2002 and 2005, respectively. A significantly high r^2 (0.8) was achieved when comparing rainfall of current year and NPP of subsequent year. In this study, it was concluded that rainfall and drought had a lag effect on NPP. The interannual variation of NPP in this region was significantly ($P < 0.001$) influenced by the rainfall amount ($r = 0.8$), maximum temperature ($r = 0.8$), solar radiation ($r = 0.84$) and potential evaporation ($r = -0.61$). The influence of temperature was evident within distinct periods (cycles). The index representing soil water holding capacity in the B horizon was found to have a positive relationship ($r = 0.82$) with NPP. The other biophysical factors (slope, DEM, aspect and terrain wetness index) did not exhibit strong correlations with NPP, indicating a weak influence. The influence exerted by the interaction of biophysical and climatic factors on NPP requires more research.

KEYWORDS: Net Primary Productivity, tropical rainforests, drought, MODIS

1 INTRODUCTION

Tropical forests play a significant role in the carbon budget. They store significant amount of carbon in their woody biomass. The rate at which energy is converted into plant biomass is called Primary Productivity (Roy & Saugier, 2001). Net primary productivity (NPP) represents the net amount of carbon added to plant biomass per unit of space and time. Terrestrial NPP is the initial step in the carbon cycle. Studies have indicated that terrestrial ecosystems are becoming a major sink in the global carbon cycle (Houghton, 2007). A major contribution in sequestering carbon comes from tropical forests and they have become part of the mitigation strategy proposed by Intergovernmental Panel for Climate Change to address increasing carbon emissions (IPCC, 2007).

The role played by tropical forests seems to be threatened by changing climatic patterns. Changes in climate include predictions of increased frequency of extreme weather events such as cyclones, droughts, floods, heat waves and snowing (Whetton, 2003). Some studies have reported that extreme droughts, usually associated with El Nino Sothern Oscillation (ENSO), causes higher rates of tree mortality and increase forest flammability (Nepstad et al., 2004). However, contrasting observations have been made where excessive greening has been associated with drought in the Amazon tropical forests (Saleska et al., 2007). It is evident that the sensitivity of tropical forests to drought is poorly understood.

Climate change has been associated with increased frequency and severity of drought episodes (Salinger et al., 2000). Drought has been defined as a period of abnormally dry weather, sufficiently prolonged because of a lack of precipitation, causing serious hydrological imbalance and has connotations of a moisture deficiency with respect to water use requirements (McMahon and Arenas 1982). The deficiencies have impacts on both surface and groundwater resources and leading to reductions in water supply and quality, reduced ecosystem productivity, diminished hydro-electric power generation, disturbed riparian and wetland habitats, and reduced opportunities for some recreation activities (Riebsame et al., 1991).

In Australia, drought is defined as a condition when the rainfall over a three-month period is in the lowest decile (i.e. lowest 10%) of what has been recorded for that region in the past (BoM, 2011a). The worst drought in the past ten years occurred in 2002 with the Australian average rainfall of 472mm. It was the fourth lowest on record since 1902 where it was 317mm (BoM, 2011a). Drought has been identified as a precursor of forest fires, thus generating more carbon emissions. This is downplaying forests' role in the mitigation strategy to reduce carbon concentration. The prediction of increased frequency of extreme weather events such as drought will continue altering species abundance, composition and dominance, and reducing favourable habitats to the point of extinction in some cases (Thomas et al., 2004).

It has been argued that measuring and quantifying Net Primary Productivity (NPP) is one of several methods to monitor response of tropical rainforests to the recurring extreme weather events (Cramer et al., 1999). The variation of NPP driven by global change has been one of the most important aspects in climate-vegetation studies. Understanding the suite of factors influencing NPP is one of the main interests for scholars in this field. This will allow development of models that will predict variation of NPP with changing climate.

The launch of MODIS in 1999 has provided an array of data outputs that give useful information in the monitoring of certain phenomenon in our planet, including monitoring biophysical aspects of vegetation (Zhao et al., 2004). The operational MODIS Production Efficiency Model (MOD17) on the Terra satellite is used to generate a composite of 8-day near-real-time vegetation primary production (Heinsch et al., 2003; Zhao et al., 2005). MOD17 is based on the radiation use efficiency logic which state that the NPP of well-watered and fertilized annual crop plants is linearly related to the absorbed photosynthetically active radiation (APAR) (Monteith, 1972). The study by Zhao et al. showed that tower-based and MODIS estimates of annual GPP compare favourably for most biomes, although MODIS GPP overestimates tower-based calculations by 20%–30%.

There are several factors that influence net primary productivity. Studies have shown that forests growing on soils with relatively high fertility and moisture content will have high productivity (Field et al., 1995; Delucia et al., 2007). These factors have an indirect impact on the process of photosynthesis. Different vegetations react differently to changing seasons and rainfall patterns (Huete et al., 2006). Some plants have better coping strategies during drought periods, thus minimising the negative impact on net primary productivity. It has been argued that the effects of climatic factors on NPP are sometimes delayed in certain biomes due to interaction of climatic and physical factors. The current study is exploring the lag-effect concept in tropical forests ecosystems.

The response of tropical rainforests to drought has been a subject of debate in the past few years. Some have shown that tropical forests green up during drought implying an increase of net primary productivity during the drought episodes (Saleska et al., 2007). However, recent studies (Samanta et al., 2010) have refuted these results indicating that only 11- 12 % of the forests greened up during the 2005 drought in the Amazon; 28-29% showed browning or no change; and the rest of the forest could not be categorised due to poor quality of the data used.

A study by Nemani et al. (2003) which explored variation of NPP between 1982 and 1999 showed a positive trend in NPP in spite of the occurrence of drought episodes within the study period. The increase was attributed to global warming and increasing concentration of CO^2. Recently, a study by Zhao et al. (2010) reported a decline in NPP between 2000 and 2009 as a result of drought episodes. However, their finding has caused alarm in some quarters (Sherwood and Craig, 2011). The ongoing debate indicates that the sensitivity of tropical rainforests to drought episodes is still poorly understood. The debate has motivated the current study.

The aim of the study was to analyse the effect of drought on the Net Primary Productivity (NPP) of tropical rainforests. The specific objectives were to a) determine existing trends of NPP over the study period, b) assess the relationship between NPP and climatic - biophysical factors, c) analyse the effect of drought on NPP, and d) evaluate inter-annual variation of NPP. MODIS satellite imagery (2000-2006), thematic data sets, climatic data sets and other relevant data sets were acquired and analysed using GIS techniques, image processing tools and statistical techniques.

2 DATA AND METHODS

The study was confined to the tropical rainforests found in Queensland, Australia, within a biome region known as the Wet Tropics. The Wet Tropics Bioregion covers approximately two million hectares. Two main sites were identified, namely Daintree National Park and Wooroonooran National Park which are relatively close to Cairns, one of the major cities in Australia (Figure 1). Both national parks are listed under the World Heritage Area. The rainforests in these areas are closed forests characterised by dense foliage in the upper layers (> 70% foliage cover), with vines, epiphytes and mosses form a conspicuous and important element of the structure (Department of the Environment and Water Resources, 2007). The main reason for selecting protected areas as a study area was to minimise the influence of potential disturbance (e.g. forest clearing) during the study period (2000-2006).

The mean annual rainfall in Cairns is about 2,200 mm. However, rainfall is highly variable in the wet tropics ranging from 1,200 mm to 6,000 mm. The area has a distinct wet and dry season with most of the rainfall received during the summer months. The mean minimum temperature is about 18^{o}C while mean maximum temperature is approximately 31^{o}C. Daintree National Park is about 100 km from Cairns. It has been described as one of the oldest forests in the world. It has about 57,000 ha of tropical rainforest. On the other hand, Wooroonooran National Park is located about 25km from Cairns. The two highest mountains in Australia are located within the Wooroonooran National Park boundary. It has about 115 000 ha of tropical forest.

The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (1km spatial resolution) was downloaded from the NASA MODIS Land Science team website for the period 2000 to 2006. In this study, the MOD 17A3, version 4.8 GPP/NPP product was used and it is designed for the study of the net amount of carbon fixed in vegetation by the photosynthesis process. Each pixel of the MODIS NPP product is expressed as grams of carbon per m^2 per year ($gC/m^2/yr$). In the production of MOD 17A3, corrections for gases and clouds are implemented. The MODIS GPP product showed seasonal variation that was generally consistent with the in situ observations (Turner et al., 2006). Validation at “stage 3” has been achieved for the global and net primary production products. The global annual estimates of GPP and NPP are within 10.4% and 9.0% of average published results, respectively (http://landval.gsfc.nasa.gov).

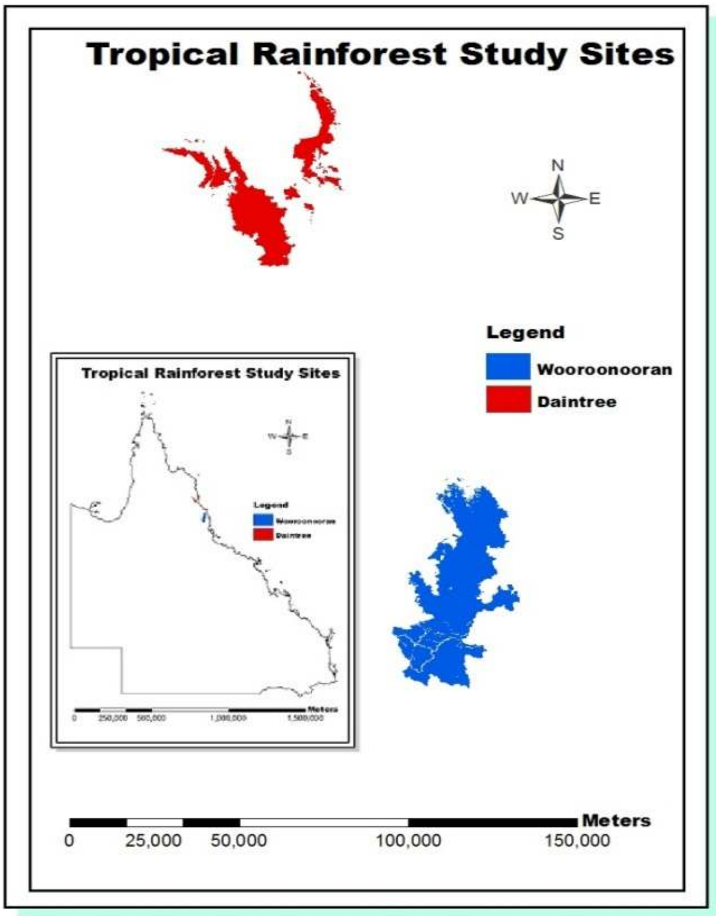


Figure 1: Study sites for tropical rainforests in Queensland

Thematic map data sets were acquired from the following data custodians or agencies:

- Queensland Department of Environment and Resource Management (regional ecosystems map, national park and reserves boundary, land use, DEM, locality, geology, land use, land cover, foliage projective cover, etc.);
- Australia's Bureau of Meteorology (mean annual rainfall, mean maximum annual temperature); and
- CSIRO (available soil water holding capacity, incoming solar radiation, and potential evaporation).

The pre-processing step included mosaicing within the ERDAS IMAGINE software, combining the four MODIS image tiles into a big digital image covering Queensland. The Queensland boundary map layer was used to clip the mosaic image to eliminate areas outside Queensland. The image was further clipped by the national park boundary map to focus on the wet tropics bioregion. All other GIS datasets were geo-referenced and clipped to a common map projection (Geocentric Datum of Australia 1994) using ArcGIS 10.

The "sample" tool within ArcGIS was used to extract pixels values from these raster maps. The generated tables were exported to Excel for statistical analysis. Regression and correlations analysis were used as statistical tools to investigate relationships between NPP and climatic factors. The t-test was used to compare NPP of drought years and NPP of non-drought years. There has been a suggestion by Steele et al. (2005) that effects of drought may be delayed. This was incorporated in the analysis by comparing NPP of a drought year with NPP of the subsequent year.

3 RESULTS AND DISCUSSION

3.1 NPP Trend

The results showed a positive trend in NPP from 2000 to 2006 even though there was a drop in 2003 and 2006. This trend was illustrated by the fitted line on the NPP graph (Figure 2). The obtained results are similar to a conclusion reached by Nemani et al. (2003). Their study investigated the trend of NPP between 1982 and 1999, and concluded that recent climatic changes have enhanced plant growth in northern mid-latitudes and high latitudes. The enhanced plant growth resulted in an increase of 6% NPP globally. The largest increase occurred in tropical ecosystems. Several factors were attributed to the positive trend, including the increase in carbon dioxide concentration which has been described as having fertilization effect (Norby et al., 2005).

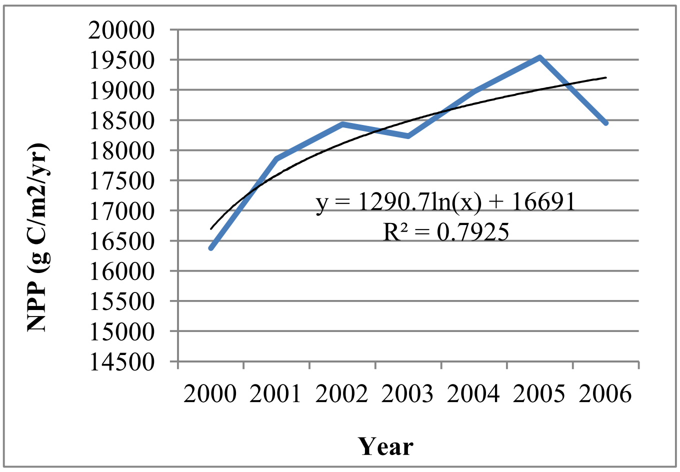


Figure 2: NPP trend between 2000 and 2006

However, recent studies have reported a gradual change of the global trend observed by Nemani et al. (2003). The change was attributed to increased frequency of drought events (Zhao & Running, 2010). In their study, Zhao and Running observed a reduction in the global NPP of 0.55 pentagrams of carbon over the period 2000-2009. The drought episodes that induced the reduction occurred in 2002 and 2005. The positive trend observed in the current study may be due to regional differences in the intensity and frequency of drought events. The drought year in the wet tropics had an annual rainfall of 1591 mm, yet in other regions of the world the drought threshold was around 500 mm annually. Therefore, the difference in the severity of the drought may be the explanation for the different trend. Given the prediction of increased occurrence of drought episodes in Australia in the next 50 years (CSIRO, 2001; IPCC, 2001), a steady decline in NPP may be expected

3.2 NPP and Rainfall

NPP ranged from 16,373 gC/m^2/yr in 2000 to 18,448 gC/m^2/yr in 2006 (Figure 3). The lowest NPP in the year 2000 surprisingly corresponded to the wettest rainfall of 4307 mm in the same year. According to the reports from Bureau of Meteorology, the year 2000 was Australia's second wettest year on record (http://www.bom.gov.au /info/leaflets/nino-nina.pdf). The rainfall decreased, reaching the lowest rainfall in 2002 of 1,591 mm. Unexpectadly, the NPP in the same year (2002) increased, reaching 18,426 gC/m^2/yr.

El Nino conditions within the study period occurred in 2002-2003 and 2004-2005. These conditions resulted to a severe drought in 2002 and a mild drought in 2005. The expectation was to have a reduced NPP in 2002. The rainfall increased in 2003 while NPP reduced in the same year. A similar trend was observed from 2004 to 2005 where rainfall reduced by 1,076 mm while NPP increased by 566 gC/m2/yr in 2005. Again, the NPP reduced the subsequent year (2006) even though rainfall increased. The drop in rainfall seems to have lag effect on NPP where the negative effects of reduced rainfall amount are realized in the subsequent year.

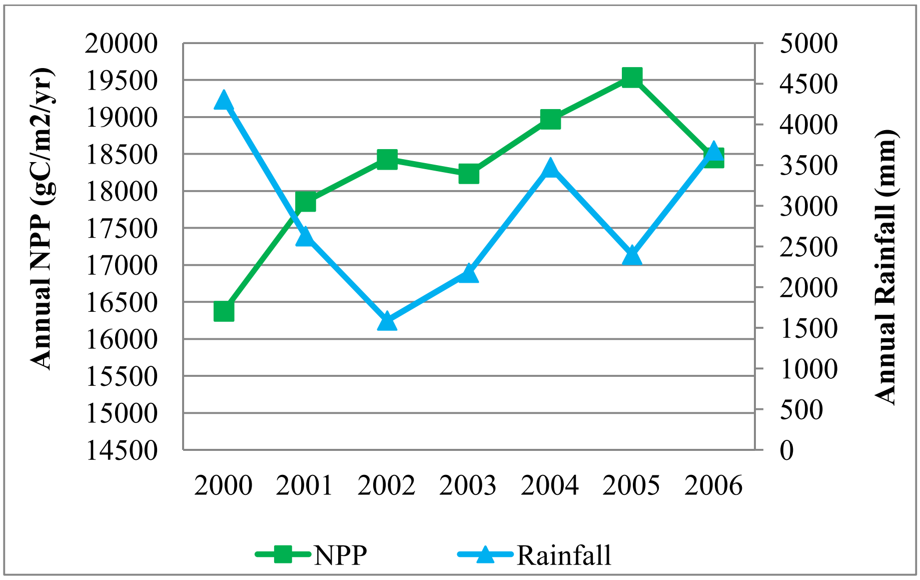
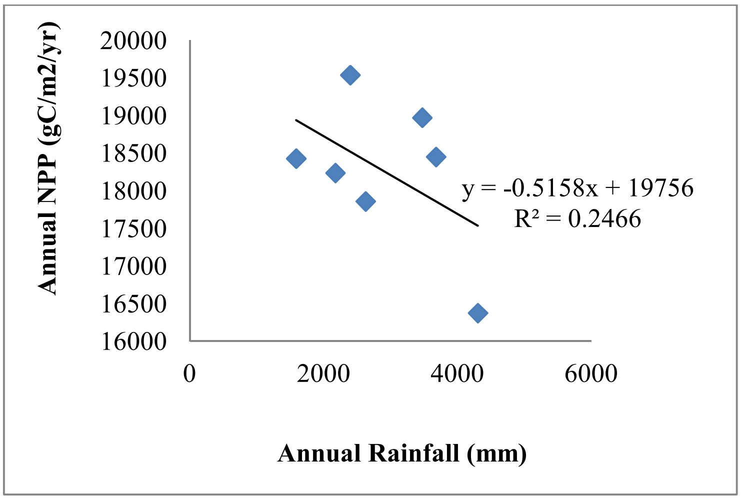


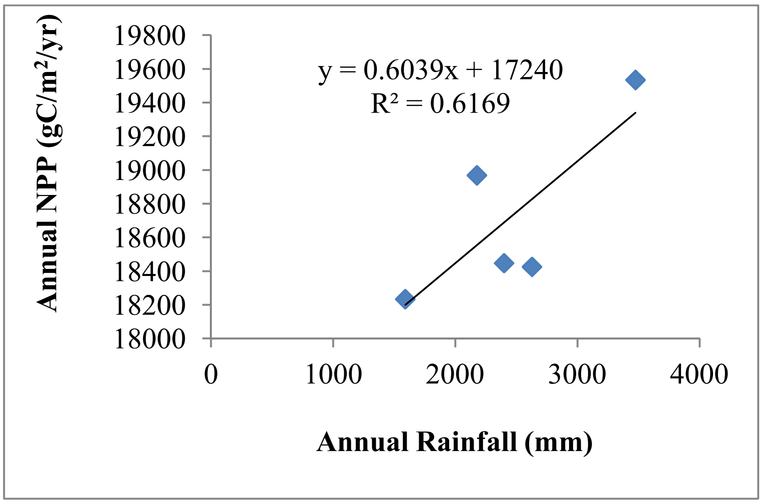
Figure 3: Variation of NPP and rainfall between year 2000 and 2006

3.3 Lag Effect of Rainfall

The lag effect was explored using regression analysis. The first step was comparing means of NPP and rainfall in the same year (i.e. without lag effect). The second step was comparing means of rainfall in the current year with means of NPP in the subsequent year (i.e. lag effect). Figure 4 (a) and (b) show results of the two conditions. The results showed that without lag effect, the relationship was poor with only 25% explained by the fitted regression equation. However, with the lag effect, the relationship improved with 62% explained by the equation. Individual years were compared on pixel basis to assess the lag effect, and it was discovered that the 2001 rainfall was significantly ($p< 0.001$) correlated to the 2002 NPP (Figure 5). The rainfall of 2002 (a drought year) was significantly correlated with 2003 NPP (Figure 6). There could be many factors related to this observation including the complexity of forest and canopy structure, reducing light penetration to the floor and thus reducing water loss through evaporation.



a) Comparison of annual NPP and annual rainfall without lag effect (r = -0.49)



b) Comparison of annual NPP and annual rainfall with lag effect (r = 0.79)

Figure 4: Comparing annual NPP and annual rainfall

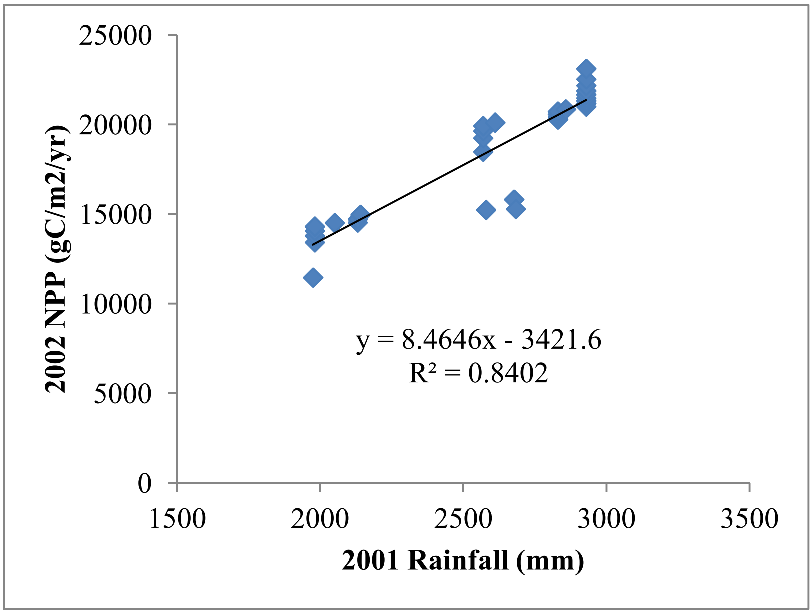


Figure 5: Comparing 2001 rainfall and 2002 NPP

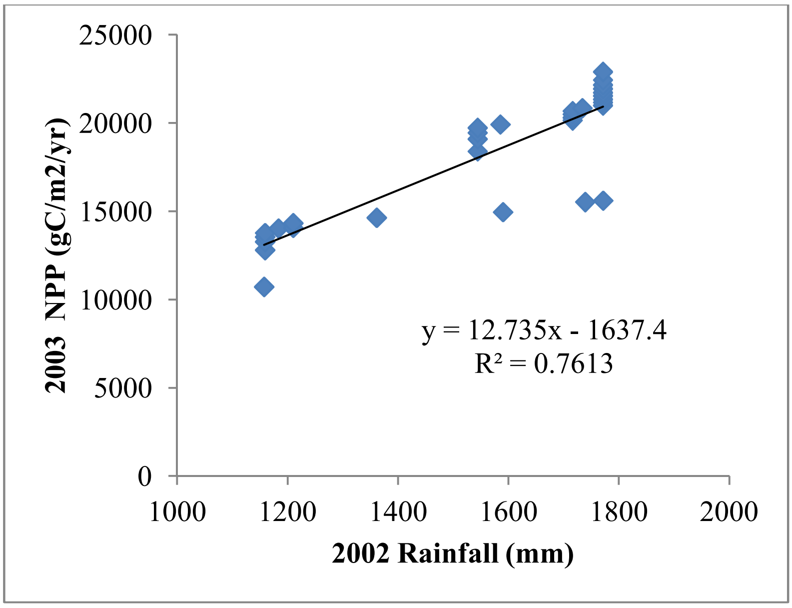


Figure 6: Comparing 2002 rainfall and 2003 NPP

3.4 The Lag Effect of Drought

The study has showed that effects of drought do not normally occur in the same year in which the episode occurs. The years 2002 and 2005 were drought years within the study period. For the rainforests in the study area, the NPP increased during 2002 which was one of the worst drought episodes in many parts of Australia. The observation was similar to that made by Saleska et al. (2007) who studied the effect of drought in Amazon forests in 2005.

The annual NPP in the year 2000 (wet year) was 18,426 gC/m^2/yr while in 2002 (drought year) it was 20,479 gC/m^2/yr. There was a significant ($P<0.001$) increase of NPP during the drought year by 2,053 gC/m^2/yr when compared to the wet year (Figure 7). The increase in NPP in 2002 was against expectation, as the rainfall significantly reduced due to El Nino conditions that brought severe drought over most parts of Australia.

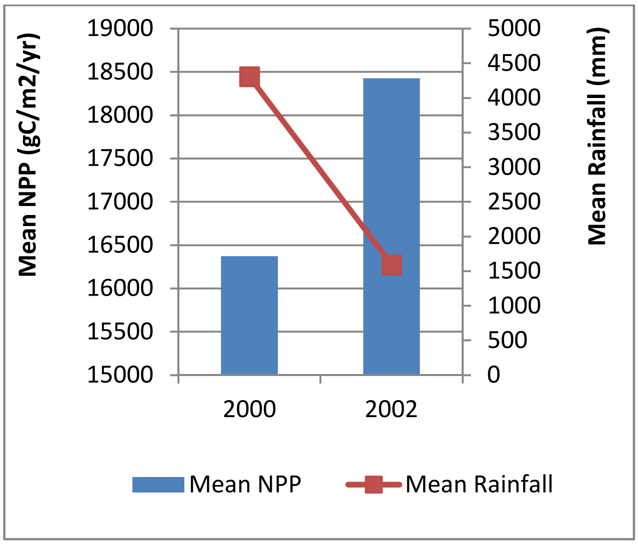


Figure 7: Comparing NPP of drought year and non-drought year

The debate surrounding the behaviour of tropical rainforest during drought conditions has resulted in proposals of assessing the effects in the long term rather than in the same year in which drought occurs. Figure 8 shows a comparison of NPP and rainfall between the drought year and the subsequent year. The NPP during the drought increased to 18,426 gC/ m^2/yr when rainfall reduced to 1,591 mm. In the subsequent year (2003), NPP significantly dropped ($P<0.001$) by 192 g C/ m^2/yr compared to 2002. This was in spite of the significant increase ($P<0.001$) in rainfall in 2003 of about 586 mm. This drop in NPP was associated with drought conditions of the previous year, indicating delayed effects of drought on the tropical rainforest.

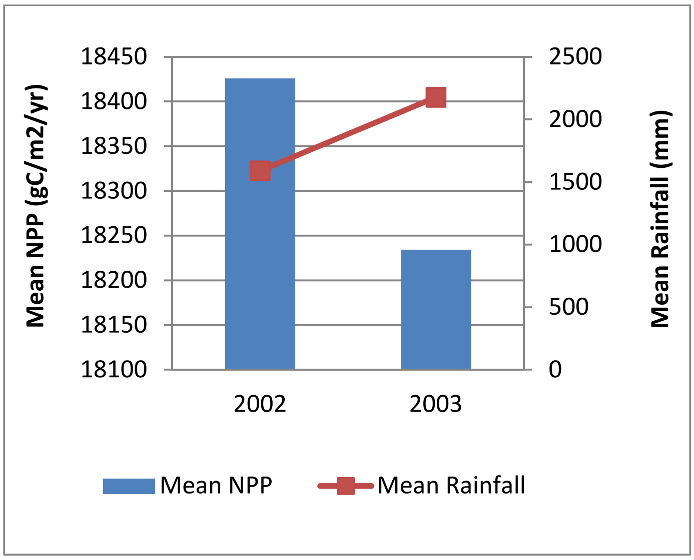


Figure 8: Comparing drought year and subsequent year

A trend similar to 2002 and 2003 was observed between 2005 and 2006. The NPP in 2005 increased even though rainfall significantly dropped by 1,076 mm from previous year. However, in the subsequent year (2006), NPP reduced significantly by 1,087 gC/m^2/yr ($P<0.001$) in spite of the significant increase in rainfall by 1,281 mm (Figure 9). The impact of reduced rainfall in 2005 was realised in the subsequent year.

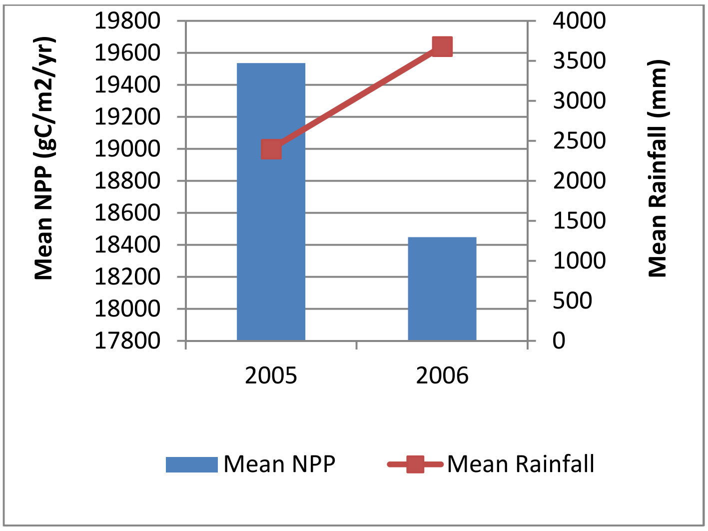


Figure 9: Comparing NPP between 2005 and 2006

It has been shown that in short time scales, climatic factors affect the physiological processes that control plant photosynthesis and growth (Christopher et al,. 1995). However, in some vegetation types the effects of climatic factors on NPP are not instantaneous, exerting delayed effects and serial correlation ageing (Steele et al., 2005; Peng et al., 2008). Drought is found to significantly affect ecosystem carbon exchange processes (Krishnan et al., 2006). Analysis of measured atmospheric carbon dioxide and satellite-derived measurements of temperature and the vegetation index suggests that nutrient effects on the carbon cycle can delay ecosystem response to changing climate by as much as two years (Braswell et al*.,* 1997). The current study show delayed effects of drought events. Therefore long term studies are essential to establish the effect of drought and other climatic and physical factors on NPP.

3.5 NPP and Other Climatic Factors

The overall correlation coefficients of all the climatic factors with NPP are shown on Figure 10. The interannual variation of NPP in this region was significantly ($P < 0.001$) influenced by rainfall amount ($r = 0.8$), maximum temperature ($r = 0.8$), incoming solar radiation ($r = 0.84$) and potential evaporation ($r = -0.61$). Similar results were obtained by Peng et al. (2008). The increasing temperature appears to reduce the cloud cover, subsequently increasing the photosynthesis activity in some regions within the Wet tropics.

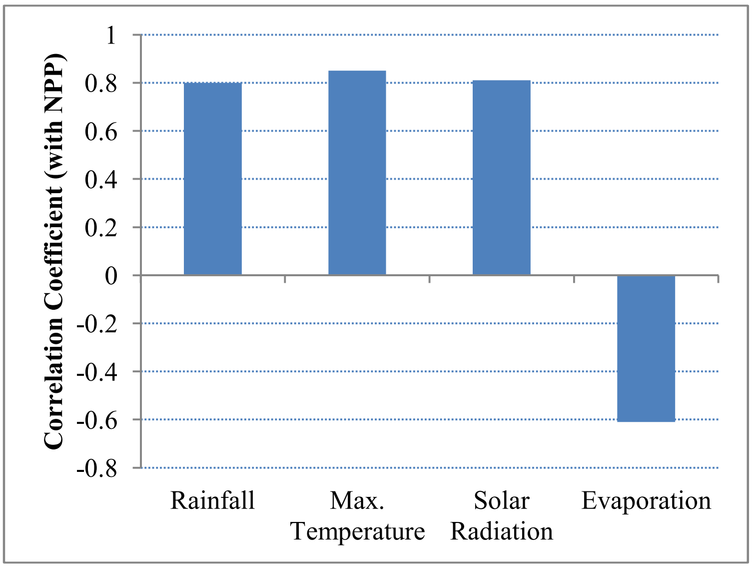


Figure 10: Correlation coefficient of climatic factors with NPP

3.6 NPP and Biophysical Factors

The overall correlation coefficients of all the biophysical factors are shown on Figure 11. The soil water 2 (r=0.82), which is an index for water holding capacity of the sub soil (B horizon), was found to have a significant influence on NPP. The tropical forests are made of tall trees with deep roots that extract moisture from deeper layers of the soil. Therefore, indices that indicate water availability in deep layers are likely to give best prediction of NPP (Eamus, 2003). Churkina and Running (2008) indicated that while soil moisture availability may be the most influential variable for setting the upper limit on NPP, multiple environmental factors may influence NPP in nonlinear and perhaps discontinuous ways. Therefore, areas observed to have high soil water holding capacity are likely to avail moisture for longer periods and thus enhance productivity.

Aspect (r=0.48), slope (r=-0.14), DEM (r=0.26) and terrain wetness index (r=0.37) were found to have weak to moderate correlation with NPP (Figure 11). Their influence on NPP was significant ($p<0.05$) in spite of the weak correlation. This indicated that their influence may be linked to other factors, and therefore their study requires assessing interaction of a suite of factors. A study by Chen et al. (2007) showed that topography has an effect on NPP, with greater effects observed near 1,350 m above the sea level. Their study further showed that an elevation increase of 100 m above this level reduces the average annual NPP by about 25 g C/m^2. Also, they discovered that there was a 5% change in NPP as a result of terrain aspect for forests located below 1,900 m as a result of its influence on incident solar radiation. However, in the current study the influence of biophysical factors did not reflect similar results. Their influence could be overshadowed by other factors that affect NPP.

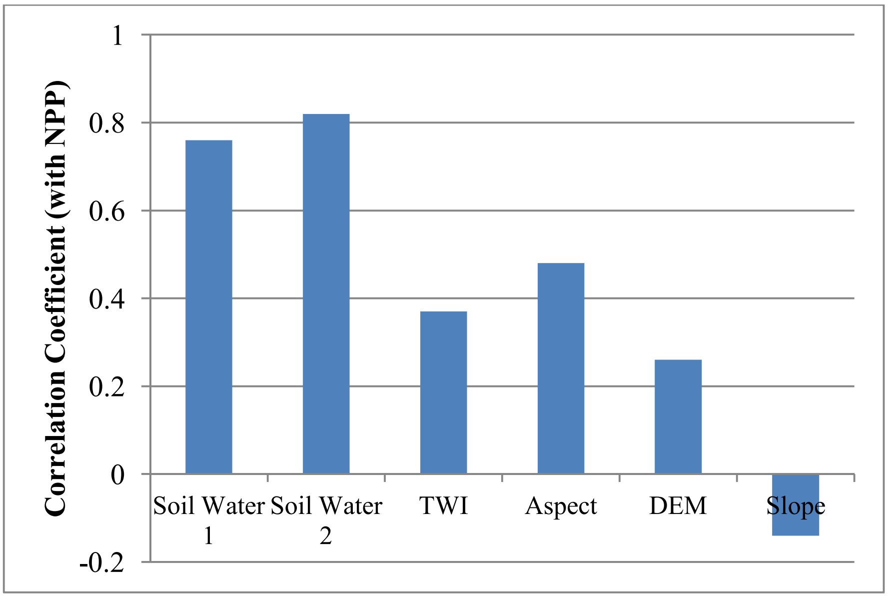


Figure 11: Overall correlation coefficient of Biophysical factors with NPP

4 CONCLUSION

The study has shown that significant drop in rainfall, including a drought event, has a lag effect on tropical rainforests. The effect of a drought episode in a particular year is delayed by one year as shown in this study. This was not tested in other vegetation types. Droughts episodes that occur over a period of more than one year consecutively may depict a different scenario in terms of the lag effect. Therefore studying just the year of drought event (i.e. 2002) may have led to a misleading conclusion that tropical forests are resilient to drought episodes.

The NPP in this region depicted a positive trend, a direct opposite to the recent global scenario where NPP is reported to decline due to frequent drought events. It is an indication that the severity of drought vary from region to region. The observed trend is likely to change given the prediction that frequency of severe drought will increase in the next 50 years in Australia. These predictions indicate future threats to the functions of forest ecosystems given the general negative impact of drought events on NPP.

The interannual variation of NPP in this region seems to be influenced by rainfall amount, maximum temperature, solar radiation and potential evaporation. This was depicted by strong correlation between these factors and NPP. There could be other environmental factors interacting with these factors in the processes driving NPP in the region. However due to time and resource limitation it was not possible to explore directly the influence of nutrients, soil pH, cloud cover, soil type, and plant species.

The index representing the soil water holding capacity in the sub soil was found to have a better positive relationship with NPP than the index representing the top soil. It provided an indication that tropical rainforests benefit more from water available in deeper layers as they generally have deep roots. Other physical factors which include slope, DEM, aspect and terrain wetness index did not exhibit strong correlations with NPP, indicating a weak influence.

Research assessing the effect of drought on tropical forests over longer time periods is essential in the future given the improved monitoring systems and availability of data sets. The challenge with the research establishing effects of past events dating backward to the 1900 is data availability. This future studies will enhance understanding the behaviour of these forest ecosystems in light of repeated episodes of different extreme weather events including drought.

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