Interannual Precipitation and Temperature Variability Near Mt. Panié Wilderness Reserve and its Connection to Kauri (Agathis montana) Die-Back

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Chapter 7

Interannual precipitation and temperature variability near Mt. Panié wilderness reserve and its connection to kauri (*Agathis montana*) die-back

Analyse du régime des précipitations et des températures près de la réserve de nature sauvage du Mont Panié en lien avec le dépérissement du kaori *Agathis montana*

Joseph H. Casola and François M. Tron

SUMMARY

The microendemic and long-living Mt. Panié kauri (*Agathis montana*) currently encounters a significant and recent die-back with 18.1% mature trees already dead (DBH>10cm) and 27.6% of mature live trees in poor health condition. A number of factors have been identified as potentially contributing to this dieback, including drought, pathogens, insects and erosion related to the invasive feral pig growing population. This paper examines recent local precipitation and temperature variability, comparing it to longer-term record and discusses the relevance of the drought stress factor for Mt. Panié vegetation. Overall, the last 20 years were relatively dry, but still within the historical range of precipitation variability. The period between 2003 and 2007 was particularly dry, reflecting the influence of larger-scale climate variability related to El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) on rainfall in the region. We also note a warming trend over the last several decades, which may potentially exacerbate the impacts of drought stress on vegetation in the ecosystem. It is thought that the kauri die-back may be an easily detectable symptom of a wider conservation issue on this remarkable mountain ecosystem.

RÉSUMÉ

Le kaori microendémique du Mont Panié (*Agathis montana*) presente un dépérissement récent et significatif avec 18.1% des arbres matures (DBH>10cm) morts et 27.6% des arbres matures dépérissants. Les facteurs de dépérissement préliminairement identifiés incluent des ravageurs, des pathogènes, l'érosion causée par les cochons féraux et des épisodes de sécheresse. L'analyse d'un jeu de données à long terme révèle que les 20 dernières années apparaissent relativement sèches, plus particulièrement de 2003 à 2007, en relation avec El Niño et l'oscillation pacifique interdécennale. La tendance au réchauffement constatée sur ces dernières décennies peut par ailleurs exacerber les effets de sécheresses sur la végétation. Ces facteurs climatiques de stress peuvent se cumuler et renforcer les effets de la perturbation du sol et de l'érosion liées aux cochons féraux, espèce exotique envahissante, dont les populations sont réputées s'accroître localement depuis une vingtaine d'années. Le dépérissement observé du kaori du Mont Panié pourrait être un symptôme aisément détectable d'un problème de conservation plus vaste de ce remarquable écosystème de montagne.

PRECIPITATION DATA AND THE MONTHLY CLIMATOLOGY OF PRECIPITATION

The precipitation data were taken from daily records at two meteorological stations, Galarino (*Météo France Station ID #98824002; latitude 20°31'S, longitude 164°46'E, elevation 4m*) and Hienghène (*Météo France Station ID # 98807001; latitude 20°41'S, longitude 164°57'E, elevation 22m*), respectively located at about 10 and 20 km from Mt. Panié summit (see Figure 1, page 26). The data records begin in August 1959 and January 1959 for Galarino and Hienghène respectively. For this analysis, observations up until December 2010 were used.

The daily data was summed for each month. The mean monthly climatology for the period for each station is shown in Figure 2, along with the standard deviation for each month. The graphs in Figure 2 show that the region receives most of its rainfall between December and April. They also demonstrate that the Galarino station (top panel) is considerably wetter than the Hienghène station (bottom panel) despite their relatively close geographic proximity and comparable elevations. The greater rainfall in Galarino reflects orographic enhancement of precipitation occurring on the eastern flanks of Mt. Panié: since the prevailing winds are from the east, the areas between the mountains range and the coast receive relatively more precipitation as air masses are forced to ascend, leading to cloud formation and condensation.

For all of the monthly averages, the interannual variability (i.e., year-to-year; the differences among the averages for a particular month) is relatively large, based on a comparison of the standard deviation to the mean (i.e., the values of the dashed lines to solid lines in Figure 2). Essentially, for any particular month, the historical record of rainfall is "noisy"; values less than 50% of the mean and values 50% greater than the mean typically fall within one standard deviation of the mean.

The plots have been organized into a "water year," beginning in August and ending in July, as this display maintains continuity through the wet season. Subsequent discussions of annual rainfall totals are also calculated for the period August-July. In this paper, "the water year of 2010," actually refers to the period of August 2009-July 2010.

DATA GAPS AND THE TIMESERIES OF ANNUAL PRECIPITATION

Time series of annual precipitation for Galarino and Hienghène for the water years 1960 through 2010 are shown in Figure 3. Since data were missing for numerous months within the records, a method for filling in the gaps within each record was devised.

Galarino was missing data (i.e., there were no observations of precipitation for any days during the month) for 21 months between August 1959 and July 2010. Hienghène was missing data for 36 months for the same period. Galarino was missing data for 19 days during July 2010. Hienghène was missing data for 13 days in September 2010. Both stations had partial records (10 days missing data for Galarino; 8 days missing data for Hienghène) for June 2010. All other months had data for all days.

Since the monthly precipitation totals for the two stations[1] are highly correlated ($R^2 = 0.73$) with one another, linear regression was used to establish a prediction equation for each station. The two prediction equations are:

$$G_{Pred} = 1.2026*(H_{Obs}) + 87.87\text{ mm} \quad (1)$$

$$H_{Pred} = 0.611*(G_{Obs}) - 4.01\text{mm} \quad (2)$$

Where G_{Pred} and G_{Obs} represent the predicted and observed monthly precipitation at Galarino, respectively; and H_{Pred} and H_{Obs} represent the predicted and observed monthly precipitation at Hienghène, respectively.

The regression equations were used to estimate the monthly precipitation values for the missing months. Values could not be estimated for October 1992 and June 2010, since those months lacked data for both stations. The annual totals for these months appear as asterisks (*) in Figure 3, since they only include 11 months of data, and are under-estimates. These two years were not used in any subsequent analyses of interannual variability (e.g., calculation of annual mean or standard deviations), and are shown in Figure 3 for illustrative purposes only.

DISCUSSION OF INTERANNUAL PRECIPITATION VARIABILITY

Characterization of interannual variability

As was the case for the monthly precipitation (Figure 2), the time series of annual precipitation (Figure 3) demonstrates large interannual variability in rainfall for the both stations. Figure 3 further demonstrates the relatively large difference between precipitation at Galarino, which has a mean annual precipitation of over 3700 mm, compared to the precipitation at Hienghène, which has a mean annual precipitation of just below 2300 mm. Some of the driest years at Galarino

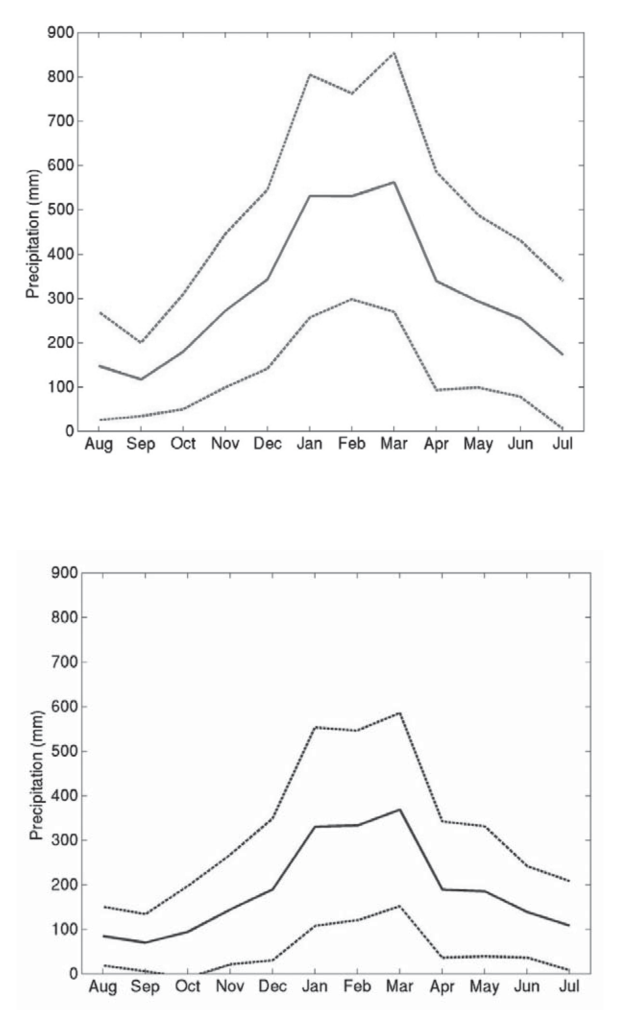

Figure 2: Monthly mean precipitation (bold) and +/- 1 standard deviation (dashed), based on data representing 1959–2010 at the Galarino station (top panel) and the Hienghène station (bottom panel)

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[1] The correlation was performed on the 558 months within the record in which both stations had data.

exhibit rainfall that is approximately equivalent to the long-term mean of precipitation at Hienghène.

Figure 3 illustrates the relatively high correlation between the two stations. As mentioned previously, this relationship was exploited to develop the prediction equations for filling missing data. In general, both stations are experiencing the same relatively wet years and dry years. This correlation validates the use of the variability of rainfall observed at the stations as a proxy for the variability of the rainfall occurring within the Mt. Panié wilderness reserve, including for the mountain cloud forest above 1000 m where the kauris live. Essentially, the region as a whole is experiencing the same *relative* wet and dry years, even though local factors, such as elevation and aspect (the direction a slope faces), may enhance and or reduce the total amount of precipitation falling in one location compared to another location.

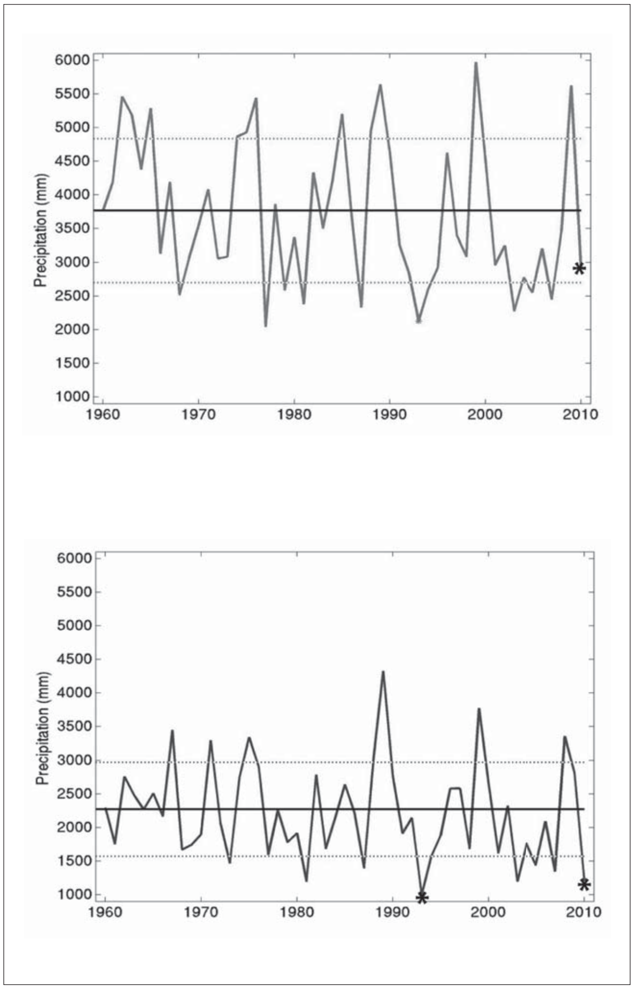

Figure 3: Annual timeseries precipitation during the water year (August–July) for 1960–2010 at Galarino (top panel) and Hienghène (bottom panel). The respective means for the period are shown by the bold horizontal lines. The thin dashed lines show the mean values +/- 1 standards deviation. Asterisks represent years in which months are missing (water year 1993 and 2010) – these two values are underestimates of the annual precipitation.

Of particular interest within the last 20 years of the station records is the relatively dry period experienced between August 2002 and July 2007. At Galarino, the mean of these five water years was approximately 2650 mm (about 70% of the long-term mean), and only one year experienced more than 3000 mm of rainfall (over 70% of the years between 1960–2009 exceeded 3000 mm, see Figure 4). At Hienghène, the mean was approximately 1570 mm for these water years (also about 70% of the long-term mean) and only one year experienced more than 2000 mm of rainfall (over 60% of the years between 1960–2009 exceeded 2000 mm, see Figure 4). There was a similar dry period occurring between August 1976 and July 1981; however, the mean values for those periods were slightly wetter than 2002–2007 period. To put this in perspective of the full record, Figure 4 shows the relative frequency[2] of rainfall amounts of different magnitudes for each of the stations.

Physical drivers of interannual variability

New Caledonia's rainfall is heavily influenced by the El Niño-Southern Oscillation (ENSO), which is a phenomenon that affects atmospheric and oceanic circulations at the global scale. In addition to ENSO, which has a period of approximately 2–7 years (i.e., within the span of 2–7 years, it is typical for both an El Niño and a La Niña event to occur), the Pacific Ocean basin is subject to climate oscillations on multi-decadal time scales. This latter oscillatory behavior has been named the Interdecadal Pacific Oscillation (IPO) [2, 3].

During El Niño events, areas of heavy precipitation in the South Pacific in the austral summer and fall tend to shift to the northeast of their mean locations, leading to wet anomalies along the equator, around and east of the international dateline, and dry anomalies to the west, extending northward from eastern Australia to the Southeast Asia. For New Caledonia, El Niño events are typically associated with below-average rainfall; while La Niña events are associated with above-average rainfall [2,3].

The IPO also has an important influence on the location of rainfall in the tropical Pacific [4, 5]. Its negative phase, which was prevalent during the period 1946–1977 [4] is considered to have influenced precipitation patterns in the southwestern Pacific Ocean in a fashion similar to La Niña [5]. Conversely, its positive phase, which has been prevalent since 1977, is considered to displace areas of maximum rainfall in the tropical western Pacific toward the northeast, somewhat similar to an El Niño event. It has also been suggested that the IPO interacts with ENSO, such that El Niño

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[2] It appears that the annual rainfall does not follow a normal distribution – both distributions exhibit a "long tail" with respect to extremely wet years, and a comparatively higher frequency of events less than one standard deviation drier than the mean value. Given the shape of the distribution, and the role of decadal variability in the regional climate (explained in section 4.2), no significance testing was performed on the annual or multi-year rainfall anomalies.

Table 1: Average annual rainfall estimates (in mm) for specified subsets of water years

	1960–2009	1960–1976	1977–2010	1990–2009	2003–2007
Galarino	3767	4127	3576	3492	2654
Hienghène	2272	2402	2203	2184	1570

The first column shows the average for the entire period. The second and third columns show the averages for the years before and after the change in sign of the IPO phase. The last two columns show averages for the last twenty years during which significant kauri die-back was observed, and the particularly dry period from 2003–2007. As noted in the text, no significance testing was performed on the anomalies, since there are periods of dryness similar to 2003–3007 within the climate record. The averages are presented to support the argument that the 2003–2007 period can be considered relatively dry and that the kauri were likely subject to drought conditions. Note: water years 1992 and 2010 were excluded from all totals, since those years had incomplete data.

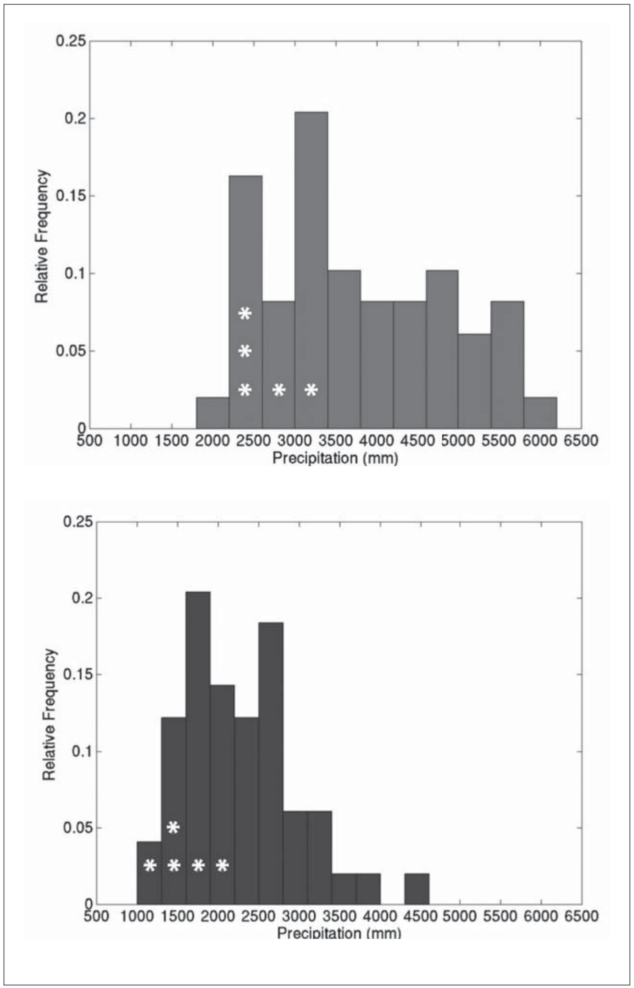

Figure 4: Histograms of annual precipitation for the water years 1960–2009. 1960–2009 at Galarino (top panel) and Hienghène (bottom panel). Asterisks indicates the bins that correspond to the annual precipitation for each of the years 2003–2007 for each station (i.e., each asterisk represents one year from the 5-year period). The years 1993 and 2010 were not included in the analysis since those years did not have data for all months. Bin widths for Galarino are 400mm; bin width for Hienghène 300mm.

events may be more frequent during the positive phase of the IPO [4].

Table 1 shows a summary of average rainfall values for various subsets of years, showing how the recent dry period (2003–2007) and the last twenty years (1990–2009) compare to the record as a whole, and to the period prior to 1977.

Comparison of rainfall variability to the southern oscillation index and assessment of recent dry period (water years 2003–2007)

The Southern Oscillation Index (SOI) is one measure of the atmospheric circulation in the tropical Pacific. The SOI is based on the difference in sea level pressure between Darwin, Australia and Tahiti, French Polynesia. In simple terms, negative values of the SOI correspond to weaker-than-normal trade winds and positive values of the SOI correspond to stronger-than-normal trade winds. Negative (positive) SOI values are typical for an El Niño (La Niña) event, as well as the positive (negative) phase of the IPO.

Using values of the monthly SOI from the Australian Bureau of Meteorology (ftp://ftp.bom.gov.au/anon/home/ncc/www/sco/soi/soiplaintext.html), a timeseries for the wet-season (November-April) mean SOI was calculated. This timeseries explained a relatively large portion of the interannual variance in both the Galarino (R^2 = 0.30) and Hienghène (R^2 = 0.40) station records.

Closer examination of the 2003–2007 water years shows that weak to moderate El Niño events affected water years 2003 and 2007 (Table 2). Within this period, four of the five years exhibited negative SOI values during the wet season. No La Niña events occurred during this period. However, none of these years exhibited particularly large El Niño events, based on the magnitude of the SOI values. For example, the SOI values for the 1982–1983 and the 1997–1998 El Niño events were larger than any of the years from 2002–2007 by a factor of two. This discrepancy is consistent with the findings of Nicet and Delcroix [3]: the SOI often matches the direction of the annual precipitation anomalies, but the Index does not always capture the relative magnitude of the precipitation anomalies. It is also consistent with the impacts of ENSO on rainfall in the region, as shown by the dry conditions experienced in Australia during the two El Niño events (Table 2). In other words, the SOI can be related to the occurrence of a relatively wet or dry year will occur, but may not indicate the magnitude of the wet or dry anomalies.

Even though the SOI may not be a precise predictor for annual precipitation, its ability to explain a large portion of the variance, and to reliably indicate the sign of the precipitation anomalies demonstrates the strong influence of ENSO and the IPO on rainfall in New Caledonia and around Mt. Panié.

The above analysis demonstrates that:

- The occurrence of an El Niño event typically reduces rainfall around Mt. Panié.[3] The positive phase of the IPO also appears to suppress rainfall in the region
- The recent dryness from 2003–2007 appears to be the product of the above – a string of El Niño-like conditions occurring while the IPO presumably remains in its positive phase. However, the annual rainfall totals during this period are not outside of the range of historical variability (i.e., there have been other dry years and similar periods of dry years). Climate change does not appear to be playing a detectable role in the regional rainfall, based solely on observations from these two stations.
- Although drought may have contributed to the Mt. Panié kauri die-back, conservation concerns related to droughts should be discussed in regards to species and ecosystem vulnerability and resilience capacity. Drought is essentially a contributing stressor, acting alongside, and likely synergistically with other environmental stressors.

TEMPERATURE DATA AND RECENT WARMING

Since heat-stress can also interact with drought to affect vegetation, it would have been ideal to present an analysis of the temperature variability for the region for the period 1960–2009 to accompany the discussion of the precipitation records. Unfortunately, the Galarino station lacks temperature data, and the Hienghène one is also missing some data during the period.

We were able to obtain monthly temperature data for the period 1970–2009 from the Poindimié station (*Météo France Station ID # 98822001; latitude 20°56'S, longitude 164°20', elevation 13m*), which is located 70 km to the south of Mt. Panié and the related two meteorological stations. A plot of the mean temperatures for the water years 1971–2009 is shown in Figure 5. There is a clear warming trend – the rate of warming is approximately 0.25°C/decade, and the trend explains just over 50% of the variance of the time series. This warming rate is slightly greater than the globally averaged rate for the recent decades (0.15–0.20 °C/decade since the late 1970's [7]), but much less than rates observed at higher latitudes over land. The warming is likely a product of the influence of the IPO [4] and global-scale warming.

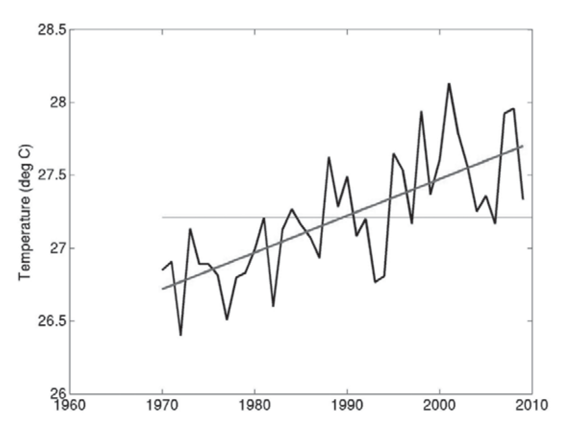

Figure 5: Mean annual temperature for water years 1971–2009 at Poindimié station. The mean for the entire period shown by the thin horizontal line; the sloped line shows the linear trend through the period (+0.25°C per decade).

Interestingly, the water years 2003–2007 were relatively cool compared to some of the other years in the 1990's and 2000's (see Figure 5). The role of heat-stress was unlikely to play a major role in worsening the 2003–2007 drought period. However, the strength of the warming trend does suggest that future conditions are likely to be warmer than past conditions, and in turn, future droughts could be accompanied by higher temperatures.[4]

DROUGHT AS A STRESSOR AND SECONDARY AGENT OF DIE-BACK

Over the past 10–20 years, significant die-back of the Mt. Panié kauri (*Agathis montana*) and a reduction of mosses have been observed within the higher altitudes of the Mt. Panié wilderness reserve [1]. A number of stressors have been identified as potentially contributing to this die-back, including drought, erosion related to invasive feral pigs, pathogens, and insects.

As this is the case of the die-back sensitive *Agathis australis* in New Zealand [9], *Agathis montana* has a mycorhized root system dominantly situated in the top soil ; it is therefore particularly vulnerable to changing climatic and edaphic conditions.

Given the recent sequence of relatively dry years, it is likely that drought may have contributed to the kauri die-back. Several of the frameworks for drought-disease

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[3] Recent work suggests that rainfall in New Caledonia could be sensitive to the spatial structure of the El Niño events, i.e., that precipitation in New Caledonia responds more strongly to sea surface temperature anomalies located in the Central Pacific Ocean, as opposed to those in the East Pacific that are associated with a "canonical" El Niño event [6].

[4] The interaction between warming and drought has been discussed as an important driver of vegetation die-off for the piñon pine (*Pinus edulis*), in the North American southwest [8]

Table 2: Recent ENSO events

Years of Event	Water Year Affected	Event Type	Notable Australian Impact
1991–1992	1992	El Niño	Extreme dry conditions through much of 1991, especially in New South Wales.
1994–1995	1995	El Niño	Dry conditions through much of 1994 and February-April 1995
1997–1998	1998	El Niño	Some areas of reduced rainfall in the southeastern portion of the continent, but effects were not as large-scale or severe as other El Nino events
1998–2001	1999–2001	La Niña	Strong wet anomalies across Australia for the period May 1998-March 2001; numerous tropical storms caused significant flooding
2002–2003	2003	El Niño	Major drought across much of the country
2006–2007	2007	El Niño	Large regions experienced rainfall in lowest decile (lowest 10% of events); some of the longest running brushfires in Victoria's history
2007–2008	2008	La Niña	Much of eastern Australia was relatively wet from June 2007 through February 2008
2008–2009	2009	La Niña	Wet anomalies across a large portion of Australia in November and December of 2008; early 2009 was quite dry, however
2009–2010	2010	El Niño	Widespread areas of below average rainfall across Western Australia, but weaker than previous El Nino events

The classifications of the years and descriptions are taken directly from the Bureau of Meteorology, Australia [14]. These can be found online (El Niño http://www.bom.gov.au/climate/enso/enlist/; La Niña http://www.bom.gov.au/climate/enso/lnlist/). As noted on the Bureau of Meteorology's website, there are several ways to determine and classify an ENSO event using measures of sea surface temperature (such as the Oceanic Niño Index) or the atmospheric circulation (such as the SOI). These different measures may provide a different picture of when the above events began or ended and their relative magnitudes. The table includes events that had a substantial impact on Australian rainfall and/or were of relatively large magnitude based on the oceanic and atmospheric indices.

interaction presented by Desprez-Loustau et al. [10] appear applicable to the case of the Mt. Panié kauri:

- *Direct effect of drought on pathogens* – Although many pathogens, especially fungal pathogens, require moisture to be spread effectively, they are also capable of thriving at water potentials well below their optimal value.
- *Drought and tree predisposition* – Drought-stressed trees undergo metabolic changes that improve conditions for pathogen establishment and growth, or that inhibit the maintenance of biophysical resistance (e.g., production of enzymes that kill fungus).
- *Drought in a multiple stress context* – Combinations of stressors can act synergistically, magnifying the cumulative impact experienced by trees. This framework can also be extended beyond just drought-disease interaction. For example, the effects and interactions associated with drought and fungal pathogens are likely enhanced by soil disturbances and erosion ; all of them can be related to feral pig foraging on Mt. Panié.[5]

In the coming decades, the distribution of particular vegetation types is also expected to shift according to changes in temperature and precipitation regimes [11]. In some cases this will likely involve gradual transformation to new ecosystem types, such as transformation of the Amazon rainforest to seasonal forest or savannah in Brazil [12].

CONCLUSIONS

We present some conclusions based on the analyses and discussion presented above.

- *Local precipitation in Mt. Panié region is subject to considerable interannual and decadal variability*. Analysis of the precipitation records show that the dry period experienced between August 2002 and July 2007 was relatively long in duration and large in magnitude, although not entirely unprecedented. Its duration and intensity illustrate how climate variability, associated with ENSO and the IPO can affect precipitation in New Caledonia. In particular, the positive phase of the IPO combined with El Niño conditions, can enhance the probability and perhaps the duration of droughts chances.
- *Drought is likely to have played a role in the recently observed kauri die-back.* The recent dry period from 2002–2007 is likely to have caused stress to the Mt. Panié kauri and the wider cloud mountain ecosystem. However, we contend that the recent drought should be considered as a secondary factor that exacerbated the impacts of feral pigs. This

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[5] The multiple stress framework is not entirely distinct from a predisposition mechanism; however, the sequence relating a particular predisposing factor to the ultimate outcome is less stringent. In a multiple stress context, any of the stresses could theoretically function as a predisposing factor (not just drought). Furthermore, the predisposing factor may also act to enhance or reinforce effects of other stressors; it is not simply an initiating factor.

is further supported by a kauri die-back that started well before 2002, as witnessed by the local guides.

- *It may be possible to use recent observations or forecast information about precipitation as part of an adaptive management scheme.* The potential for drought in the southwest Pacific region, and the particular difficulty associated with making decisions in the context of large interannual and multi-decadal variability, has been recognized by water managers [13]. Although conservationists may not have the same tools as water managers, there are several steps that could be taken to help prepare or cope with potential precipitation deficits:
    - Management resources could be devoted to protecting portions of the forest with relatively healthy trees, which may be found on the eastern face (windward and therefore more rainy) of Mt. Panié. Focusing on areas likely to receive more precipitation and less likely to be affected by drought represents one way to "climate-proof" conservation efforts.
    - Recognition of the phase of the IPO and use of ENSO forecasts, the latter of which may be useful 6 months in advance of an ENSO event, may provide prognostic information about future drought. Such information may help guide some sort of triage process, or the timing of management or monitoring activities (e.g., surveys that would be taken before and after the wet season, or protective measures, such as culling the pig population, prior to an anticipated drought)
    - Establish a meteorological monitoring plan in the cloud mountain forest where the kauri lives. This data could contribute to the monitoring efforts associated with conservation management.
    - To facilitate the above steps, partnerships could be forged with local and regional meteorological organizations or research institutes. The understanding of climate variability and the ability to make seasonal and annual forecasts are dynamic and improving; members of the meteorological community may be able to assist conservation planners in translating the latest available information for use in conservation planning.

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