

# **Preliminary observations of bulls-eye borer (*Phoracantha acanthocera*) on marri (*Corymbia calophylla*): A bellwether for effects of climate trends on ecosystem quality in forest of south-west Western Australia?**

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## **Abstract**

*Phoracantha acanthocera* (Coleoptera: Cerambycidae) is endemic to southern and eastern Australia where its larvae feed in the bark, cambium and sapwood of living *Eucalyptus* and *Corymbia* spp. Scars left in annual growth rings by cambial feeding insects have sometimes been used to derive historical incidence and population fluctuations for these insects. Previous studies have found that *P. acanthocera* populations may be responsive to host stress. Dendro-entomological data covering a hundred year time span collected from marri (*Corymbia calophylla*) boles during 1995 are appraised in the light of a continued warming and drying trend, and depletion of groundwater under jarrah forest in south-west Western Australia. There was no significant correlation between decadal mean annual rainfall and decadal gallery incidence. Decadal gallery incidence was significantly correlated with the frequency of consecutive year droughts. Decadal gallery incidence was also significantly correlated with decadal mean annual minimum temperature, in particular mean minimum temperatures in the months February to May. That *P. acanthocera* populations are apparently responsive to drought and temperature signals indicates dendro-entomology is a potentially useful tool in elucidating the role of climate shifts in controlling the population dynamics of cambium boring insects such as *P. acanthocera*.

## **Introduction**

In recent times dark red kino and insect damage have been regarded as features of interest in marri furniture grade timber because of their contrast with the paler timber. High frequencies of kino and insect gallery defects precluded the use of marri (*Corymbia calophylla*) as a timber of commerce from the earliest days of the Western Australian timber industry until the establishment of a woodchip export industry in 1976 (FDWA 1977). Marri can represent a substantial component of mixed stands within jarrah or karri dominated forests, to the extent that borer damage and kino defects in marri

were once regarded as important research priorities (Kessell 1922). Subsequently, Clark (1925) detailed the life history of the bulls-eye borer *Phoracantha acanthocera* and identified marri as a principal host in Western Australia. The commercially important jarrah (*Eucalyptus marginata*) and karri (*E. diversicolor*) also host *P. acanthocera* (McKenzie and Donnelly 1993, Abbott et al. 1991). In contrast to *P. semipunctata*, which opportunistically attacks severely stressed or dead eucalypts in south-west Western Australia, *P. acanthocera* attacks living trees (Wang 1995). However, *P. acanthocera* populations are possibly sensitive to stress in their hosts. Abbott et al. (1991) and Farr et al. (2000) found greater incidence of *P. acanthocera* damage in regenerating karri forest on lower quality sites in close proximity to mixed jarrah and marri forest and in small coupes where competition with adjacent mature forest was likely greater and source populations of *P. acanthocera* were present. It is unclear whether source-sink population dynamics or physiological changes imposed by competition for available soil water in regenerating stands were responsible for these higher incidences of *P. acanthocera* attack.

Scars left in annual growth rings by cambium feeding insects have sometimes been used to derive historical incidence and population fluctuations for these insects (Muzika and Guyette 2004, Haavik and Stephen 2010a,b). *P. acanthocera* larvae feeding in cambial tissue of marri induce permanent kino veins and scars in tree growth rings. Time series data, covering a hundred year time span, was appraised for seven marri boles in the light of a documented drying trend and depletion of groundwater under jarrah forest in southwest Western Australia (Kinal and Stoneman 2011), the potential threat of *P. acanthocera* to forest health (Maher et al. 2010), and the recent identification and emerging importance of kino inducing marri pathogens possibly responsive to environmental stress (Paap et al. 2008).

## Methods

Clark (1925) detailed the life history of *P. acanthocera* on marri. The insect has a 2 year life cycle with adults active in January and February in Western Australia. Eggs are laid in small cracks in the bark of host trees. On hatching, larvae feed on living bark tissue excavating a gallery upwards in a spiral direction, and inwards reaching the cambium and sapwood. Galleries consist of an erratic series of vertical and spiral stages in the cambium, sapwood and living bark. Excavation of the pupal chamber into heartwood with its distinctive external bulls-eye is completed in April and May of the second year and larvae occupy the chamber thereafter. Pupation occurs in October or November of the second year.

During 1995, time-series *P. acanthocera* and kino damage data was collected from butt and mid bole discs used in a study of defects in milled jarrah and marri timber (Wills et al. 1995). Ten pairs of butt and mid-bole discs were obtained from a load of marri logs from coupe 105 in Wilga forest block (33.725°S, 116.174°E). The coupe, of about 15 ha, was harvested in summer (January or February) 1995. Seven mid-bole discs were used in the present

analysis. In 1915, the seven trees were saplings or small pole sized trees (Abbott and Loneragan 1986), with height and diameter growth rates typical of growth rates in conditions of competition in jarrah forest (Abbott and Loneragan 1986, Hingston *et al.* 1990, Whitford 2002) (Table 1). The harvest history of the coupe prior to 1995 was inferred from surrounding unlogged forest from measurements of the DBHOB above the union with the stump of stems of unsuppressed jarrah stump coppice using the age-diameter algorithms of Abbott and Loneragan (1982, 1986) derived from coppice of known age. Selective harvesting in the coupe occurred at least four times at about 22 to 30 year intervals prior to the more intensive harvest of 1995 (Table 2). Fires were probably of lower frequency but greater intensity between 1895 and 1940 (encased scar ca. 1922, Table 2) compared to post-1940, conforming to the findings of Burrows *et al.* (1995). Mid-bole discs were used in the present analysis to minimize the effects on kino formation of changes in anthropogenic influences on fire intensity and frequency (Burrows *et al.* 1995). Since 1976 road access to the coupe was restricted to Disease Risk Area entry permit holders and the coupe is accessed by a seldom-used track.

Mid-bole discs were obtained from between 4.0 and 6.1 m above the bole butts. Sawn faces of discs were planed using an electric plane. Annual growth rings are formed in *Eucalyptus* and *Corymbia* species in southwest Australian forests in response to seasonal changes in soil moisture availability (Abbott and Loneragan 1986, Rayner 1992, Burrows 1995, Whitford 2002). The annual rings in marri discs were sometimes discontinuous or exhibited localized areas of false rings. An age sequence of rings was established for each disc, approximately along the longest radius by counting from visual inspection under 10X magnification. Distinctive rings and kino veins were used to traverse between the best resolvable radial sequences within discs. Using distinctive rings and kino veins as a cross reference, the age sequence within discs, in decade intervals, was determined for the longest and shortest radii, and the bisector of the largest angle subtended by these. Age sequences were allocated *pro rata* along the radial length where sections of the age sequence could not be precisely determined for the sampling radius due to the high density of rings, particularly on short radii. By selecting these three radii, sampling radii were situated independently of damage.

Sampling along radii was akin to repeated sampling for damage features at three fixed sample points on each bole across the same period of time. The frequency of intersections with kino veins with and without an intimately associated insect gallery, insect galleries without intimately associated kino, voids and rotted wood were recorded where they intersected these three radii within decade intervals. Where insect galleries intersect the cambium a kino vein or callus is usually induced, allowing the age of the gallery to be determined. Not all kino is associated with insect galleries, and larvae can also excavate beneath the cambium and not induce a kino or callus response and these galleries cannot be aged. Radial dimensions of the decadal intervals, rot, voids and encased fire scar features were recorded. Attractiveness of boles to ovipositing *P. acanthocera* females was assumed to be independent of tree diameter. It was assumed there was independence

between the disc circumference and extent of individual kino veins. Occurrences within decades from the three different radii within a disc were averaged to derive an occurrence value for each decade for each tree. Ten year intervals between 1895 and 1994 were used to ensure all intervals were represented in the 7 mid-bole discs and the rainfall record. The occurrence values for each decade used for regression analysis were calculated as the mean of the occurrence values from the 7 discs.

Annual rainfall records between 1895 and 1994 were obtained from the Bureau of Meteorology for two rainfall stations: Greenbushes (9552, 33.86°S, 116.06°E) and Bridgetown (9510, 33.96°S, 116.14°E), 20 km SW and 26 km S of the coupe. Nearest rainfall station to the coupe was Wilga (9671, 33.69°S, 116.21°E), 6 km to the NE. Rainfall records for Wilga were limited. Mean annual rainfall for Wilga for the period 1895-1994 was estimated to be 826 mm with a standard deviation of 152.29, using conversion factors of 0.87 and 0.99 on Greenbushes and Bridgetown 1895-1994 averages respectively.

Rainfall trends were compared with trends in damage features. Annual rainfall for Bridgetown and Greenbushes was normalized using mean annual rainfall and standard deviation between 1895 and 1994. Normalized data were averaged within years across the two stations and the resulting means averaged within 10 year intervals. Damage in each decade was regressed against mean rainfall anomaly for those decades using least squares regression, and significance of a non-zero slope was tested using ANOVA.

May to September rainfall for each station was normalized using mean May to September rainfall and standard deviation between 1895 and 1994. Normalized data were averaged within years across the two stations. The effect of two consecutive years of drought was investigated by summing for each decade the number of times May to September rainfall fell below particular anomaly thresholds in two consecutive years. Thresholds ranged from 0.2 to 0.7 standard deviations below long term mean in 0.1 standard deviation increments. The number of galleries in each decade was regressed against the number of consecutive year droughts for each threshold value using least squares regression, and significance of a non-zero slope was tested using ANOVA.

Mean annual minimum and mean monthly minimum temperature records between 1905 and 1994 were obtained from the Bureau of Meteorology for 3 stations: Donnybrook (9534, 33.57°S, 115.82°E), Bridgetown (9510, 33.96°S, 116.14°E) and Katanning (10579, 33.69°S, 117.56°E). Mean annual and monthly minimum temperatures for each station were normalized using mean of annual or monthly mean minimum temperature and standard deviation between 1905 and 1994. Normalized data were averaged within years across the three stations and the resulting means averaged within 10 year intervals. Damage in each decade was regressed against mean temperature anomaly for those decades using least squares regression, and significance of a non-zero slope was tested using ANOVA.

## Results

### *Long-term trends in rainfall, minimum temperature, and drought frequency*

Trends in rainfall and minimum temperature are evident across the 20th century (Fig. 1A, 1B). Notable wet periods occurred in the decades between 1915 and 1934, and dry decades occurred after 1965 (Fig. 1A). Decadal average minimum temperatures were cooler between 1905 and 1954 and decadal minimum temperature was on average warmer after 1964 (Fig. 1B). A trend to increasing frequency of drought in two consecutive years is evident after 1945. These droughts also increased in intensity (Fig. 2).

### *Long-term trends in kino and galleries*

Trends in non-gallery kino and galleries are evident across the 20th century (Fig. 3A, 3B). The decade centred on 1910 showed a low occurrence rate of non-gallery kino arcs, trending upwards until 1934. No trend in non-gallery kino occurrence was evident after 1934 (Fig. 3A). Gallery occurrence tended to increase after 1945 (Fig. 3B).

### *Rainfall and kino, and rainfall and galleries.*

There was no significant correlation between decadal rainfall anomaly and non-gallery kino or gallery incidence (Table 3). The fluctuation across the wet period between 1915 and 1934, and the dry period from 1965-1994 was not correlated with gallery or non-gallery kino incidence. The number of galleries was positively correlated with the number of consecutive year droughts in each decade below a threshold anomaly of -0.3, and the number of consecutive year droughts below a threshold anomaly of -0.4 in each decade explained 81% of the variation in gallery incidence (Fig. 4). An anomaly of 0.4 corresponds to a 9% difference from long term average May to September rainfall.

### *Minimum temperature and kino, and temperature and galleries*

There was no significant correlation between mean minimum temperature and incidence of non-gallery kino arcs. Decadal gallery incidence had a significant positive correlation with decadal mean minimum temperature anomaly (Table 3.).

Decadal gallery incidence had a significant positive correlation with decadal mean minimum temperature anomaly for the months February to May (Fig. 5). Decadal mean minimum temperature anomaly in March and April explained 69% and 67% of variation in decadal incidence of *P. acanthocera* galleries. These months correspond to periods of early larval development, and initiation and construction of pupal chambers in the two year life cycle of *P. acanthocera*.

## Discussion

### *Limitations of the data*

Ring discontinuities and eccentric diameter growth make aging large marri difficult based on visual counts, though eccentric growth was less of a

problem on mid-bole discs. In the present case, growth ring widths were not cross referenced with an independent covariate such as annual rainfall (Cullen and Grierson 2008), ring ages against  $^{14}\text{C}$  atomic bomb pulses (Pearson *et al.* 2011), or fire scars against recorded fires (Rayner 1992, Burrows *et al.* 1995), to check fidelity of growth ring age determination. Despite this, visual counts are likely to be sufficiently accurate for the coarse resolution and relatively short hundred-year sequence used for this data set (Rayner 1992). Perhaps the greatest limitation of the data is that it is derived from a small sample drawn from a single coupe.

Dendrochronological studies of the red oak borer *Enaphalodes rufulus*, an endemic North American Cerambycid, indicated infestation rates varied with height in the bole. Maximum differentiation between attack intensity classes was at 1 to 4 m of height in boles (Fierke and Stephen 2010). Attack rates of *P. acanthocera* vary with height in bole in marri with most likely position for galleries between 2 and 3 m bole height, showing clear differentiation between tree dominance classes in rates of attack between 0 and 8 m bole height (Farr *et al.* 2000). Wills *et al.* (1995), with the same boles used in the present analysis, found no systematic variation with height in marri or jarrah boles in gallery frequency in sawn boards. Lack of effect of bole height might reflect the known smaller effect of bole height at low rates of infestation. However, at the sampled heights in the present analysis there would still be sufficient sensitivity to long term changes in frequencies of *P. acanthocera* galleries.

Absolute populations in the stand were not measured. Necessary requirements to estimate absolute populations would be measurement of borer populations on a stem surface area basis, knowledge of changes in the basal area, bole heights and species composition of stand, and a larger sample size.

#### *Changes in incidence of galleries and kino*

Decreases in average annual rainfall in the latter part of the 20<sup>th</sup> century have led to depletion of groundwater under, and decreases in stream flow from, jarrah forest in south-west Western Australia. This depletion is even evident in harvested treatments which reduced forest density (Kinal and Stoneman 2011). Paap *et al.* (2008) considered declining rainfall and associated changes in hydrology in southwest W.A. to be a possible contributing or predisposing factor in the emergence of marri decline attributable to canker disease caused by *Quambalaria coyrecup*. The disease is associated with extensive perennial cankers leading to girdling of affected marri stems (Paap *et al.* 2008). In sampled boles in the present study there was no effect of changes in rainfall on kino incidence, particularly in response to diminishing rainfall in the latter decades of the 20<sup>th</sup> century. There was a notable low incidence of non-gallery kino in 1905-1914 prior to the wet decades 1915-1934, and there was no clear signal in the dendrochronology that indicated emergence of a kino inducing stem pathogen at this site prior to 1995.

*P. acanthocera* was present in marri in the Wilga coupe throughout the 20<sup>th</sup> century. There was no evidence in this stand of large fluctuations in *P.*

*acanthocera* populations in response to disturbance by selective harvesting throughout the 20<sup>th</sup> century or fluctuating decadal mean rainfall across the 20<sup>th</sup> century. Marri's relatively conservative water use strategy (Szota *et al.* 2011) and access to soil moisture deep in the profile (Farrington *et al.* 1996) may reduce the effects of year to year variation in rainfall. That average stream flow increases from thinned jarrah forest are less than predicted (Kinal and Stoneman 2011) may indicate a role in buffering of vegetation from immediate physiological effects of declining rainfall by soil water expected to have contributed to groundwater tables and stream flow. Attempts using isotope tracing to measure the extent to which jarrah forest species directly access groundwater tables have been limited by uniform deuterium profiles in the unsaturated and groundwater zones of jarrah forest soils (Farrington *et al.* 1996).

The frequency of consecutive year droughts explained up to 81% of variation in decadal *P. acanthocera* gallery incidence. In the congeneric *P. semipunctata*, larval survival is known to be sensitive to moisture content of host tissue (Hanks *et al.* 1999). *P. semipunctata* outbreak is usually associated with drought stressed and dying or dead trees, conditions which alter bark moisture content. High populations of *P. acanthocera* found in karri regrowth stands in small gap felled coupes in previous studies (Abbott *et al.* 1991, Farr *et al.* 2000) might also be attributable to changes in tree susceptibility or suitability to *P. acanthocera* arising from changes to tree physiological status due to within-stand competition for soil moisture. Response to drought frequency in the present study lends support to the hypothesis that *P. acanthocera* larvae are also responsive to the physiological status of their hosts.

Decadal incidence of *P. acanthocera* galleries in the seven marri trees of the sample from the Wilga coupe was also correlated with decadal trends in mean annual minimum temperature and trends in mean minimum temperature for particular months. Long term trends in mean minimum temperature for March and April explain about 70% of variation in decadal incidence of galleries. These months correspond to life cycle periods of early larval development, and initiation and construction of bulls-eyes and pupation chambers.

Studies of red oak borer in North America demonstrate the potential for complex interactions of the roles of climate, host condition and stand dynamics over long periods of time to affect Cerambycid populations normally of minor importance in living host trees (Haavik *et al.* 2011). Early dendrochronological investigation of red oak borer outbreak in North America found that borer wound abundance was not correlated with mean maximum temperature or annual precipitation but was related to annual mean temperature and annual mean minimum temperature (Muzika and Guyette 2004). Subsequent studies provide evidence of the role of drought in particular months on per capita population growth rates (Haavik and Stephen 2010b), using the Palmer Drought Severity Index which uses precipitation and temperature among other inputs. Within-stand competition also affects larval and tree mortality outcomes (Haavik and Stephen 2010a). The earlier observations might reflect the influence of temperature on survival and

fecundity of red oak borer (Galford 1974) in early stages of outbreak development. Temperature exposure can affect larval development rates for Cerambycidae, with early instars showing greatest responses to increasing temperature (Keena and Moore 2010). Temperature exposure can also affect pupal dormancy period and adult weight (Hanks *et al.* 1991), all of which may impinge on survival or fecundity in natural populations of Cerambycidae.

Changes in *P. acanthocera* populations across the 20<sup>th</sup> century, and the incidence of *P. acanthocera* in karri regrowth stands in small gap felled coupes and coupes within mixed species forest in previous studies (Abbott *et al.* 1991, Farr *et al.* 2000), indicate several possible drivers to *P. acanthocera* population increase. *P. acanthocera* might be sensitive to changes in microclimate within the stands, as a result of gross changes in stand architecture and tree species composition. High populations may be related to changes in tree susceptibility or suitability to *P. acanthocera* arising from changes to tree physiological status as a result of within stand competition or climate shifts affecting available soil moisture. In addition, source-sink population dynamics as affected by host attractiveness, stand area to perimeter ratio and proximity to source populations may also be important. In the present investigation, populations of *P. acanthocera* on marri were apparently responsive to temperature and/or drought signals, indicating dendro-entomology is a potentially useful tool in elucidating the role of climate shifts in controlling the population dynamics of *P. acanthocera*. The technique is also applicable to study of the effect of stand growth dynamics on *P. acanthocera* populations.

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Table 1. Dimensions, ages and estimated growth rates of sampled marri boles and discs. Discs used in regression analyses marked with \*.

Bole No.	Height above stump (m)	Estimated age (ring count to 1995)	Diameter under bark 1995 (mm)	Estimated height increment to mid-bole disc (m year <sup>-1</sup> )	Estimated Diameter under bark in 1915 (mm)	Estimated d.u.b. increment (mm year <sup>-1</sup> )
1	0.1	180	1026			5.7
2	0.1	163	692			4.2
3	0.1	118	580			4.9
4	0.1	157	652			4.2
5	0.1	120	515			4.3
6	0.1	105	505			4.8
7	0.1	149	590			4.0
8	0.1	114	615			5.4
9	0.1	114	595			5.2
10	0.1	150	455			3.0
						Mean 4.6 SEM 0.25
1*	4.5	160	844	0.23	454	5.3
2*	5.7	133	540	0.19	287	4.1
3	4.9	90	415	0.18	70	4.6
4*	5.0	125	555	0.16	187	4.4
5	6.1	95+ (termite void)	415		65	
6	6.0	79	385	0.23	0	4.9
7*	5.5	123	470	0.21	205	3.8
8*	4.0	105	550	0.44	245	5.2
9*	4.2	103	497	0.38	110	4.8
10*	5.9	140	345	0.59	158	2.5
				Mean 0.29 SEM 0.05		Mean 4.4 SEM 0.29

Table 2. Inferred harvest history and recorded fires for Wilga coupe 105 for sampled decades up to 1995. No recorded fire data are available before 1940.

Decade	Estimated year of harvest	Years of recorded fires	Encased fire scars (estimated year)
1985-1994	1985	1986	
1975-1984		1981	
1965-1974		1965, 1973	
1955-1964	1963	1955, 1961	
1945-1954			
1935-1944		1940	
1925-1934	1933	n.d.	
1915-1924		n.d.	1922
1905-1914	c. 1908	n.d.	
1895-1904		n.d.	

Table 3. Coefficients of determination-  $r^2$ , with  $P$  of F values in parentheses, for comparisons of *P. acanthocera* galleries per decade, non-gallery kino arcs per decade, decadal mean annual rainfall anomaly, and decadal mean annual minimum temperature anomaly. Galleries per decade =  $0.094$  (Decadal mean annual minimum temp. anomaly) +  $0.095$ .

y	x		
	Rainfall anomaly	Min. Temp. anomaly	Galleries
Min. Temp. anomaly	0.32 (0.12)		
Galleries	0.17 (0.24)	<b>0.49</b> <b>(0.04)</b>	
Non-gallery kino arcs	0.09 (0.41)	0.10 (0.41)	0.06 (0.49)

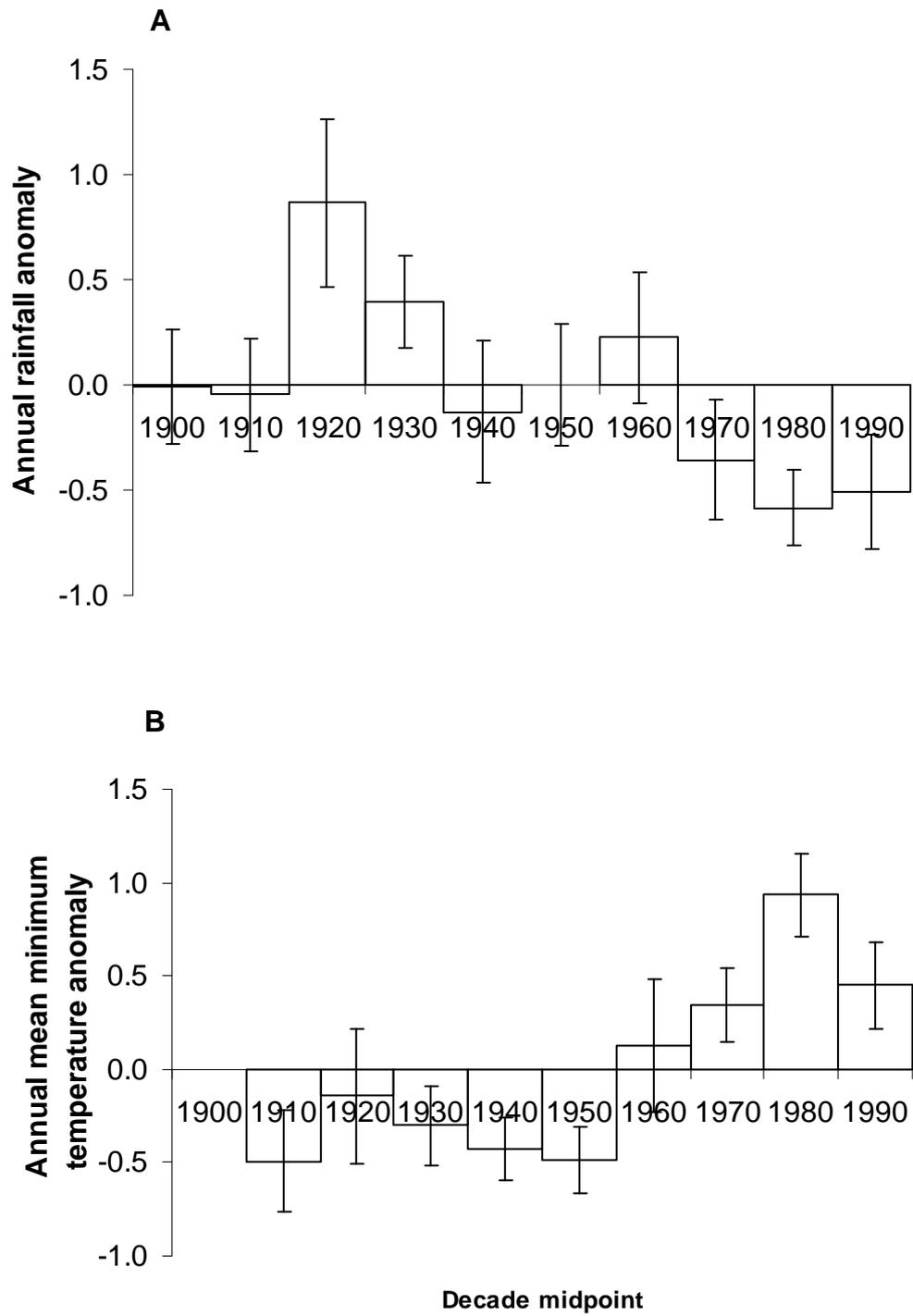


Fig. 1 A, B. Mean annual rainfall anomaly for each decade 1895-1994, and annual mean minimum temperature anomaly for each decade 1905-1994. Error bars are S.E.M.

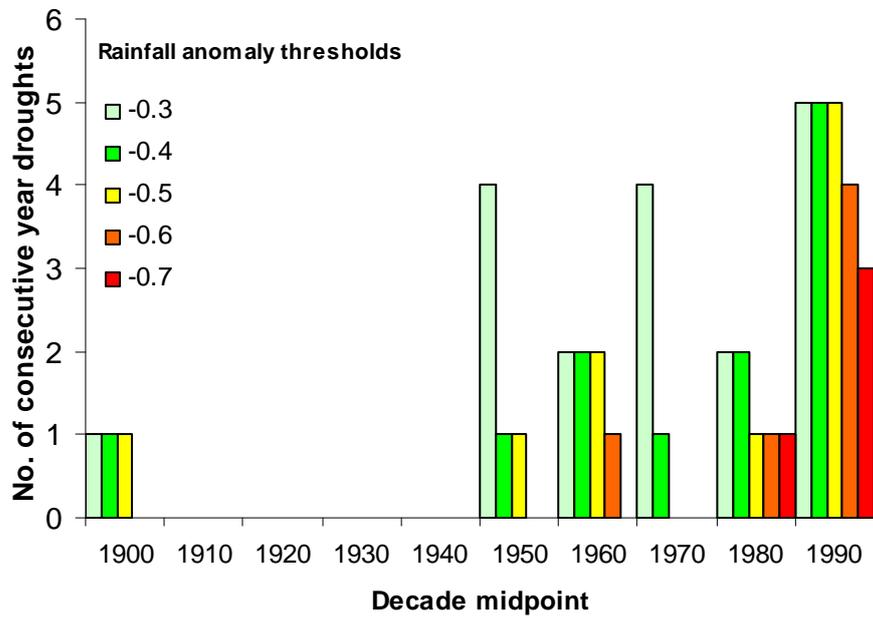


Fig. 2. Frequencies of two consecutive years of drought below particular rainfall anomaly thresholds in each decade 1895-1994.

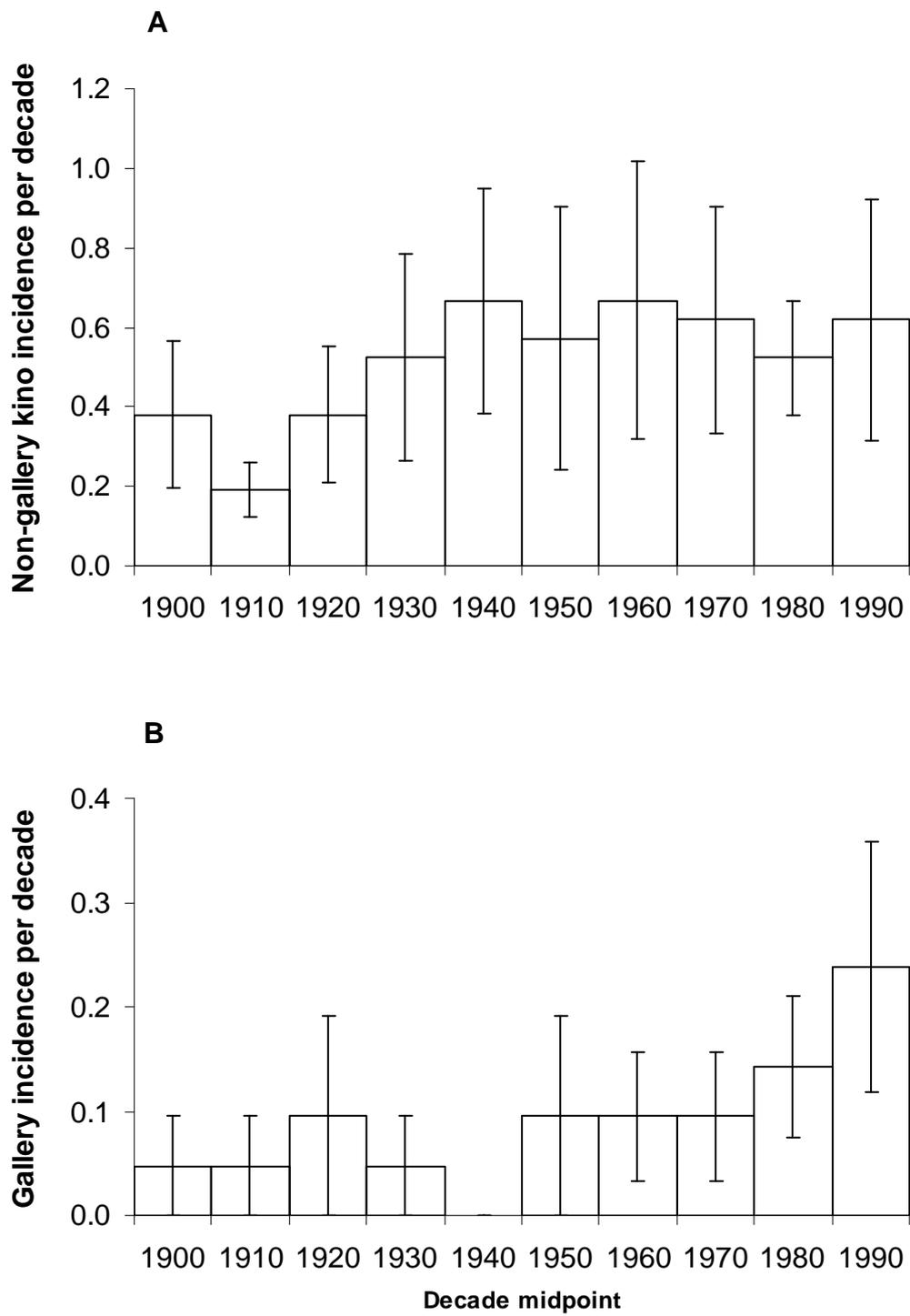


Fig. 3 A, B. Mid-bole non-gallery kino, and *P. acanthocera* gallery features for each decade 1895-1994. Error bars are S.E.M.

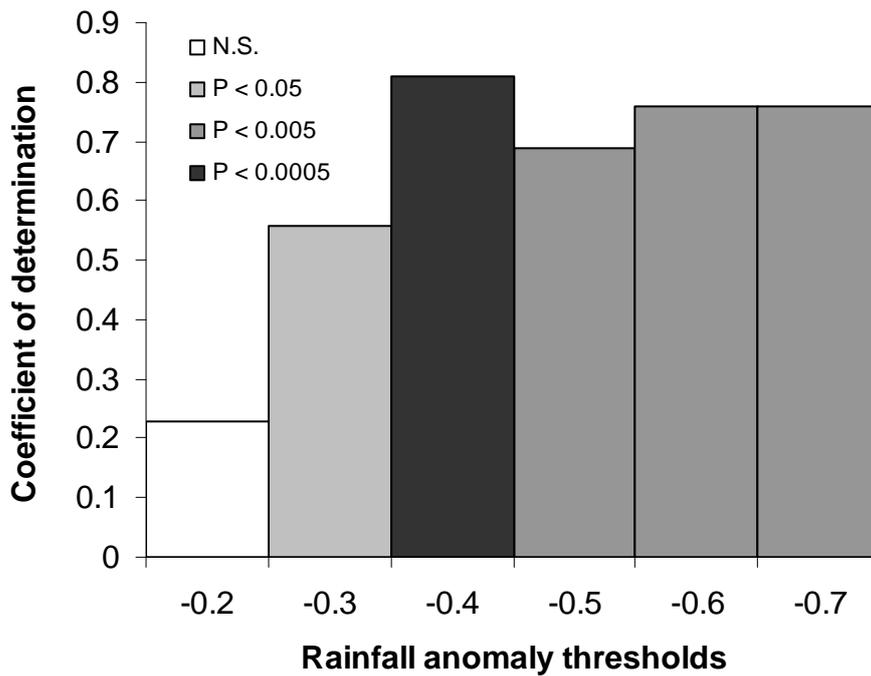


Fig. 4. Coefficients of determination-  $r^2$ , with  $P$  of F values denoted by shading of bars, for regressions of *P. acanthocera* galleries per decade against decadal frequencies of two consecutive years of drought below particular rainfall anomaly thresholds. Regression equation for rainfall anomaly thresholds of -0.4: Galleries per decade = 0.038 (No. of consecutive year droughts) + 0.045.

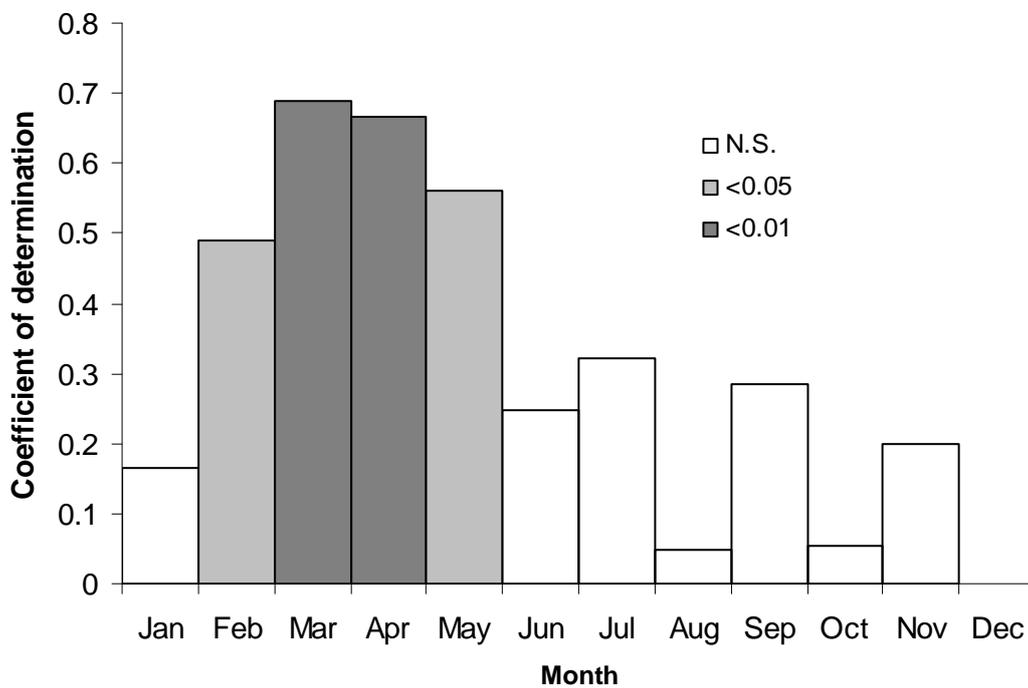


Fig. 5. Coefficients of determination-  $r^2$ , with  $P$  of F values denoted by shading of bars, for regressions of *P. acanthocera* galleries per decade against decadal mean monthly minimum temperature anomaly for each month. Regression equation for March: Galleries per decade = 0.132 (Decadal mean March minimum temp. anomaly) + 0.094.