Population size, habitat and conservation status of an Endangered species, *Macrozamia johnsonii* (Zamiaceae)

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***Abstract*:** *Macrozamia johnsonii* D. Jones & K. Hill is a locally endemic cycad (family Zamiaceae) with a restricted occurrence in north-eastern New South Wales and currently listed as Endangered. Based on recent field surveys, its mean population size is estimated as approximately 3.5 million mature plants, with the lower bound of the 95% confidence interval at 1.9 million mature plants. Thirty percent of the population occurs in a formal reserve. *Macrozamia johnsonii* occurs in grassy eucalypt forest, shrubby wet sclerophyll forest and in rainforest. It occurs most frequently on steeply sloping sites with high moisture index. There are no immediate significant threats to the species although timber harvesting is judged to be a potential longer term threat to part of the population. The conservation status of *Macrozamia johnsonii* is assessed using IUCN criteria and thresholds, using population size and extent data from this study and a plausible range of values based on available circumstantial evidence for parameters for which quantitative estimates are not available. Based on this assessment, we regard the conservation status of *Macrozamia johnsonii* to be in the category of Least Concern, and that its current listing as an Endangered species under the NSW *Threatened Species Conservation Act (1995*) needs to be revised.

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Introduction

In recent decades there has been increasing interest in compiling lists of threatened species for both practical conservation management and legislative purposes. In Australia, there is both Commonwealth (*Environmental Protection and Biodiversity Conservation Act 1999*) and State (e.g. for NSW, *Threatened Species Conservation Act 1995*) legislation which lists threatened taxa (species and infra-specific taxa) in various threat categories. These lists have a major role in determining conservation and natural resource management priorities in a very wide range of circumstances. Recently, explicit guidelines for assessment, largely modelled on the IUCN categories and criteria (IUCN 2001) have been developed. However, at least in NSW, current lists include a majority of species for which assessment criteria and thresholds have not been explicitly documented, and until very recently, there has been no public record of the details of assessment of a taxon against specific criteria. All listed species need to be assessed against IUCN criteria and assessments periodically reviewed using the same criteria, to ensure that all species are assessed consistently and that changes in status can be tracked.

Cycads as a group have a disproportionately high number of threatened species. About 60% of all cycad species were assessed as threatened by Osborne (1995), but this was revised to 52% by Donaldson (2003), who also indicated that Australia had the lowest proportion of threatened species of any of the main global regions of cycad diversity. *Macrozamia johnsonii* is a locally endemic cycad restricted to the Dalmorton area, west of Grafton, in northern New South Wales (approximately 152° 30' E; 29° 50' S), first collected by Boorman in 1907 (Johnson 1961, as *Macrozamia moorei*). In 1992 it was described (Jones & Hill 1992) as a species separate from the most similar congener, *Macrozamia moorei*, which occurs 800 km away in central Queensland. *Macrozamia johnsonii* is a large species; mature individuals have up to 120 fronds, each frond being up to 3 m long, and older plants develope a trunk to at least 2 m tall (Johnson 1961; Jones & Hill 1992).

Individuals of *Macrozamia johnsonii* (under *Macrozamia moorei*) were noted by Johnson (1961) to be "locally numerous" in NSW and regeneration was described as "copious". Jones and Hill (1992) described it as "locally common in the Dalmorton area", growing in "large colonies that are regenerating freely" and growing on "sheltered ridges and steep southerly and easterly slopes in wet and dry sclerophyll forest.". They assessed its conservation status as 2R (geographic range less than 100 km and rare) and noted that "Although not specifically protected, large populations occur in areas unlikely to be under immediate threat, and the species is not considered to be threatened in the short term".

Hill (2003) estimated the population size as > 10 000 mature plants and assessed its status as Least Concern, but provided no statement of how the estimates or conservation assessment were made. *Macrozamia johnsonii* is currently listed as

Endangered in Schedule 1 of the NSW *Threatened Species Conservation Act (1995*), having been listed on Schedule 1 in 1995 with the commencement of the Act. This listing is not consistent with Hill's assessment, though the extent to which Hill included timber harvesting as a potential threat is uncertain, nor with with general observations suggesting a species which has remained locally abundant and freely regenerating for at least the last fifty years within forests that have had a long history of timber harvesting and frequent burning for grazing.

This paper quantitatively documents the distribution, population size and structure and habitat of the *Macrozamia johnsonii* population based on recent field surveys, and makes a detailed assessment of its conservation status using current IUCN guidelines and criteria, particularly in the context of timber harvesting,.

Methods

Plant data

Data on distribution and abundance were compiled from several sources (Table 1). Only the two systematic surveys, described further below, consistently included counts of plants in plots of known area, although some other data included approximate estimates of local population size and extent. Data from the Forests NSW Flora and Fauna data base and the NSW NPWS Atlas were screened to exclude records of low locational accuracy. Where accuracy was not stated, records were regarded as unreliable, and excluded, if location descriptions were too vague to determine the location to within 500 m, or if there was a > 500 m discrepancy between the location description and the associated grid reference. Excluding such records, all sources combined provided 287 separate locations at which the species was recorded. Known distribution extent of *Macrozamia johnsonii* was derived by generating a minimum convex polygon which included the 287 records. All records at the vertices of the polygon were accurate to within 100 m.

Two surveys were conducted to obtain quantitative data on *Macrozamia johnsonii* density and distribution. Firstly, within an area of approximately 15 000 ha, defined by Crown Lands within the minimum convex polygon containing the known limits of distributional extent based on previous records, plots were sampled using simple random selection. Secondly, within an area occupying approximately 340 ha of Chaelundi National Park, considered to support consistently relatively dense stands of *Macrozamia johnsonii*, a square grid of 250 m resolution was superimposed on the area and each grid square sampled by a single randomly placed plot. The second survey area was entirely contained within the perimeter of the first area, but the two sample areas did not overlap. In both areas, at each sample point the numbers of *Macrozamia johnsonii* plants were counted in each of three size categories: mature, immature and seedling, within either a 10m or 20m radius. Plants with an evident above-ground caudex were counted as mature plants, on the basis that plants without a caudex were very rarely observed to have produced cones. Seedlings were the smallest size class, arbitrarily defined as plants with fewer than 10 leaves. All plants intermediate in size between the seedling class and the mature class were counted as immature. The choice of 10 or 20 m sample radius was determined in the field for individual plots, based on the stand density and homogeneity.

Table 1. Characteristics of data sources for records of *Macrozamia johnsonii*.

Number of records is the number of separate locations at which *Macrozamia johnsonii* was recorded. Number of plots is the number of sample plots, including those at which *Macrozamia johnsonii* was not recorded.

Data source	Description	Record dates	Number of records	Number of plots
NSW Wildlife Atlas	Compilation of records from various sources, obtained from former NSW National Parks and Wildlife Service and not otherwise listed in this table	1952–1998	12	-
FNSW Flora and Fauna Data Base	Records of *Macrozamia johnsonii* from threatened species target survey for pre-harvest assessment, plus locations recorded incidentally during other surveys	Dec 1998–Jul 2005	173	-
FNSW systematic flora survey	Randomly located 0.1 ha plots occurring within area subsequently defined as extent of *Macrozamia johnsonii* occurrence	Jan 1991–Oct 1993	4	12
Macrozamia johnsonii systematic survey, sample area 1	Plots randomly located on Crown Land, within known distributional extent of *Macrozamia johnsonii*	Oct 2004–Jul 2005	38	53
Macrozamia johnsonii systematic survey, sample area 2	Plots randomly located within area of apparent high population density within Chaelundi National Park	May–June 2005	60	108

Stands of high density, which were judged to be of relatively homogeneous density regardless of the choice of distance, were sampled with a 10 m radius, to save time in counting large numbers of plants. All other stands were sampled using 20 m radius.

Environmental data

The environmental variables were obtained from a 25m Digital Elevation Model or from other GIS models developed during a NSW Regional Comprehensive Regional Assessment process. The variables used (Table 2) are described more fully in NSW NPWS (1994).

Analysis of habitat

To reduce potential bias, only data from surveys that used randomly located sample plots were used for analyses of environmental relationships and for estimates of population size. All randomly located plots within the minimum convex polygon defined as described above, including all those in which *Macrozamia johnsonii* was not recorded, were used for these purposes. These data were derived from the last three sources listed in Table 1. The occurrence of *Macrozamia johnsonii* in relation to environmental factors was investigated using generalised linear models (GLM, McCullagh and Nelder 1989) and tree models (Crawley 2003). For the former, the response variable used was binary (presence or absence of mature *Macrozamia johnsonii*), and a binomial link function was used. A full model was initially fitted using all environmental variables and then each variable deleted in turn. The effect of deletions was judged on the basis of the Akaike information criterion (AIC, Burnham & Anderson 2002). Variables for which deletion caused a stepwise reduction in AIC were progressively removed to give a final model. Two response variables were used in separate analyses for the tree models: 1. raw count data of mature plants only, with plots in which only immature or seedling plants were recorded being included as counts of zero; and 2. a binary (presence/absence of mature plants) response as for the GLM models. Analyses were performed using the 'glm', 'tree' and associated functions in S-Plus 4.5.

Table 2. Environmental variables used in analysis

Factor	Units	Comments
aspect to north	degrees	calculated as azimuth if ≤180° or (360–azimuth) if >180°
moisture index	index between 0 and 100	index derived from rainfall, evaporation, radiation and soil depth
slope	degrees	calculated from 25m, filled DEM
mean daily solar radiation during January	MJ m^{-2} d^{-1}	
mean daily solar radiation during July	MJ m^{-2} d^{-1}	
topographic position	index between 0 and 100	relative position, 0=gully to 100=ridge crest

Estimates of population size

A frequency histogram of the count data showed that the counts do not conform to any of the commonly used parametric probability distributions (normal, lognormal, poisson, exponential or negative binomial). In particular, the data had substantially higher tail frequencies than expected for contagious distributions such as negative binomial (Douglas 1979). As a result, mean densities (mean number of plants per 20 m radius plot) were obtained using a bootstrap mean (with 100 000 runs) and confidence limits were estimated using the BCa percentiles (Crawley 2003). Analyses were conducted using the bootstrap function in S-Plus 4.5. Four types of population estimates (mean and lower 95% confidence limit 2.5% percentile) were compared:

1. Mean density was estimated using all plots, including zero counts. The density estimates were multiplied by the total area of the sampled distribution extent to obtain estimates of total population size. Estimates for the high density area (systematic survey number 2), which was sampled at higher intensity, were obtained separately from the remaining area within the minimum convex polygon, and the two subtotals combined.

2. Mean density was estimated only from plots where *Macrozamia johnsonii* was recorded, and the proportion of non-zero records used to estimate the proportion of the sample area on which *Macrozamia johnsonii* is expected to occur, assuming that the probability of occurrence follows a binomial distribution and is equal throughout each of the sample areas. As for the previous estimates, the two sample areas were treated separately.

3. A refined version of method two, where the proportion of each sampled area occupied by *Macrozamia johnsonii* was estimated using probabilities of occurrence in each 25 m square grid cell. The probabilities were obtained using parameter estimates from the final GLM habitat model and the values of the relevant environmental variables in each grid cell.

4. Based on mean counts in environmental classes obtained from the regression tree models based on count data. Mean counts were estimated for each 25 m grid cell based on the environmental thresholds provided by the model. No attempt was made to estimate confidence limits in this case.

Assessment of conservation status

Assessment is made in relation to the criteria described in IUCN (2001), interpreted using the associated guidelines (Standards and Partitions Working Group 2006). For criteria where we do not have quantitative data from which to estimate parameter values, we have considered what we believe to be a plausible range of values based on available circumstantial evidence. This corresponds to the categories of lowest quality information in the IUCN guidelines, used to 'infer' or 'suspect' taxon characteristics relative to threshold values. In these cases, we have attempted to use a precautionary but realistic attitude to risk, as suggested in the guidelines.

Results

Habitat

The area in which *Macrozamia johnsonii* occurs comprises an intergrading mosaic of grassy open eucalypt forest and shrubby wet sclerophyll forest, with patches of rainforest in the most sheltered sites. Common canopy dominants include *Corymbia variegata*, *Eucalyptus microcorys*, *Eucalyptus biturbinata*, *Eucalyptus carnea*, *Eucalyptus siderophloia* and *Lophostemon confertus*. Based on the GLM model, the factors that most strongly influenced the occurrence of *Macrozamia johnsonii* were moisture index and slope. *Macrozamia johnsonii* is much more likely to be found on sites with high moisture index ($p<<0.001$) and steep slopes ($p=0.007$). The addition of any of the other variables was found to not significantly affect the model which included these two variables, although some were significant on their own due to correlations among some variables. This result was consistent with the tree model derived from binary data, for which the major split was moisture index > 81.5 and other major splits were on slope. However, for the wettest sites, topographic position was also important in the tree model, with *Macrozamia johnsonii* being most likely to occur on lower slopes. For the count data, the major split was on solar radiation, with the stands of highest density found on the more sheltered sites, but subsidiary splits were based on moisture index and slope as for binary data.

Population size and extent

The minimum convex polygon enclosing all records (extent of occurrence) covers 22 200 ha. IUCN guidelines suggest that area of occupancy should be estimated at a scale appropriate to the relevant biological aspects of the taxon being considered. In the case of *Macrozamia johnsonii*, the scale of sample plots (20 m radius) could be considered appropriate as it is well within the range of short-term genetic exchange and short-term seed dispersal. On this basis and using the proportion of plots occupied by mature individuals, the extent of occurrence of 22 200 ha is equivalent to an area of occupancy of 10 100 ha. This represents an extreme minimum estimate relative to IUCN guidelines, which indicate that a scale of 1–4 km^2 is appropriate for many species. The population estimate from each of the four methods (Table 3) is approximately 3.5 million mature plants, equivalent to a density of about 158 plants per ha. The highest density recorded was 228 mature plants in a 20 m radius plot.

Population structure

There is a strong correlation between the density of mature plants and that of immature plants and seedlings (Spearman Rank correlation $p<<0.01$ in each case). The density of immature plants in each plot (bootstrap mean = 48.2, 95% BCa limits = 36.8 to 62.9) is not significantly different to that of mature plants, but seedling density is significantly greater than either (mean = 122.8, 95% BCa = 79.8 to 207). There

Table 3. Estimates of population size, of total number of mature plants

Methods are numbered as described in the text. Sample areas 1 and 2 refer to the general and high density areas respectively. Plots are 20 m radius (0.126 ha).

Method	Sample area	Effective area (ha)		Density (plants per plot)		Population estimate	
		Mean	Lower 2.5 percentile	Mean	Lower 2.5 percentile	Mean	Lower 2.5 percentile
1. Overall mean, all plots	1	21860	-	19.5	13.6	3.39×10^6	2.36×10^6
	2	340	-	30.1	16.0	81400	43300
	Total					3.47×10^6	2.40×10^6
2. Non-zero mean x proportion	1	9520	7650	44.7	32.9	3.39×10^6	2.00×10^6
	2	170	120	61.3	38.6	814 00	37600
	Total					3.47×10^6	2.04×10^6
3. GLM	Total	9038	6099	50.6	38.6	3.64×10^6	1.87×10^6
4. Tree model on counts	Total	-	-	-	-	3.63×10^6	-

were three plots with only mature plants present, with a single plant in each case. There were 24 plots with immature or seedling plants but no mature plants. If it is assumed, as seems reasonable, that mature plants represent at least as long a time interval as non-mature plants, then the proportion of plots with only non-mature plants is significantly higher than expected by chance. The mean density of plants in plots which contained only non-mature individuals was 8.2 plants per plot (95% CI = 5.3–15.9). This is substantially and significantly lower than the mean for non-mature individuals for all plots combined (mean = 150, CI = 104–223).

Distribution by land tenure

The distribution extent includes National Park reserve, State forest used for timber harvest and private land. Since all systematic sampling has been in the former two tenures, relatively little is known of the occurrence of *Macrozamia johnsonii* on private land. However, based on estimates of effective habitat area (i.e. summed probabilities of occurrence) from the GLM model, and assuming mean plant density is the same for all tenures, approximately 59% of the total population occurs in State forest, 30% in National Park and 11% on private land. Using mean plant density by tenure, the proportion of the population in National Park is 31%. The private land includes some cleared areas, especially on flatter areas in the main river valley, but these are also areas of very low predicted probability of occurrence of *Macrozamia johnsonii* so are assumed to not substantially affect the estimates.

General field observations

Although no systematic data were collected, most of the stands sampled during recent surveys were observed to have been recently burnt (within the previous 3–5 years) and some casual observations were made, both within sample plots and of plants observed while traversing other stands. As a conservative estimate, several tens of thousands of live plants were seen during surveys. Almost all mature plants in recently burnt areas had charred leaf bases but had well-developed crowns of live fronds which in many cases appeared to have regrown following fire. Approximately 15 dead individuals, or remains, were seen. Time since death is unknown, but most appeared to have died within the previous 2–3 years. For three plants, death could be confidently attributed to direct effects of fire. In all three cases, individuals had relatively tall trunks (at least 1 m long) and fire had burnt completely through the vascular cortex at the base of the trunk. A few other plants had fallen trunks, but it was not certain that these were killed by the fire or had been subsequently burnt. Other plants were crushed under fallen trees and were probably indirect casualties of fire, although in a few cases crushed plants had survived. In any case, it seems that the natural mortality rate for mature plants from all causes is very low. Plants with cones were observed to be scattered through the population in various stages of cone development. Although no quantitative data were collected, there was no evident synchrony of cone development with the occurrence of the recent fire.

Discussion

Population size and structure

The high proportion of non-mature plants (about 80% of the population) across both non-mature size classes suggests that the species is regenerating freely and has done so in the recent past. This provides some quantitative evidence to support previous observations of this nature. The significantly higher proportion of plots with only non-mature plants, compared to those with only mature plants, along with the lower density in the former, is indicative of local-scale recruitment into areas not previously occupied by *Macrozamia johnsonii* within the last few decades. This suggests that the population currently may be expanding. The alternative scenario is a declining adult population, on the basis that mature individuals have been lost from sites where they are currently absent and that the species relies on a juvenile plant bank for recruitment, with a high turnover of juveniles and slow recruitment into the mature population. This alternative is very unlikely. Dead mature plants leave distinct cavities in the soil surface following decomposition of the caudex. It is reasonable to expect that these would be evident for considerable time, until obliterated by soil movement. Very few such cavities were observed. Also, non-mature plants comprised a full range of sizes between class size limits. This is not consistent with a juvenile plant bank with high turnover, which would be expected to comprise mainly small plants. If the population is expanding as suspected, the most likely explanation is the change in fire regimes over the last few decades. There is strong anecdotal evidence that frequency of deliberate fires has declined during this time. As discussed further below, frequent fire may prevent or slow new recruitment. Increasing the fire interval will thus provide more opportunities for new recruitment and potentially lead to an expanding population in the longer term.

Potentially adverse disturbances and main threats

General threats to cycads have been identified as small population size, land clearing, selective eradication, harvesting of plants and seeds, loss of genetic variation, loss of pollination mutualisms, drought, fire and timber harvesting (Donaldson 2003). *Macrozamia johnsonii* has a relatively very large population for a threatened cycad, so population size is not a conceivable threat to this species. The other factors are considered below.

Clearing

Past clearing in the area where *Macrozamia johnsonii* occurs has been restricted mainly to the river valley and has been limited elsewhere due to the steepness and relative inaccessibility of most of the area. Currently, most (about 90%) of the uncleared habitat is on public land, not subject to clearing. The remaining 10%, on private land, is potentially subject to clearing, but due to the topographic and other constraints that prevented earlier clearing, it is very unlikely that any further clearing will occur in the area without very substantial changes in the economic context for pastoralism.

Eradication and harvesting

In Australia, cycads are recognised as being poisonous to domestic stock and have sometimes been the targets of specific attempts at eradication. The extent to which this has occurred for *Macrozamia johnsonii* is unknown, but it is unlikely to have been significant, because the area in which the species occurs has been used historically for extensive rough grazing, with low stocking rates, and it is unlikely that the intensive labour required for systematic eradication would be compensated by increased commercial return on anything other than a very small scale.

The extent of illegal collection is unknown. Due to the large size of mature plants, and the steepness and relative inaccessibility of most of the habitat, it is very unlikely that significant numbers of mature plants would be taken. Some seeds and small plants may be taken, but the abundance of seedlings in the population make it unlikely that this would significantly affect ongoing recruitment.

Fire

Field observations described above show that mature plants and larger seedlings are resilient to a single fire, an observation consistent with the behaviour of other Australian cycad species. Even seedlings with only 2–3 leaves were observed to re-sprout after low intensity fire. However, since cycads do not accumulate a soil-stored seed bank for more than a few years, repeated fire at short intervals (less than 1–3 years) may prevent or impede recruitment, even though it has little or no effect on larger plants. Ornduff (1990) suggests that lack of fire may suppress recruitment, due to shading and competition from mature plants, but the abundance of seedlings observed under mature canopies in unburnt stands suggests that shading and competition is unlikely to suppress recruitment for *Macrozamia johnsonii*. Over long periods, repeated higher-intensity burning may eventually breach the otherwise fire resistant trunk of mature plants and may be the most common cause of natural mortality. However, based on field observations noted above, the mortality rate is inferred to be very low. There may also be positive aspects of fire. There is some evidence that fire stimulates cone production in related species (e.g. *Macrozamia communis*, Ballardie & Whelan 1986). No data are available for *Macrozamia johnsonii*, but casual observations described above suggest that it may not be as responsive as other species.

Timber harvesting

Timber harvesting changes the structure of the forest habitat and physically damages some plants, the proportion of both depending on the intensity of the logging operation. The immediate impact of timber harvesting is thus to reduce the size of *Macrozamia johnsonii* populations. In the longer term, populations may increase or decrease, depending on the extent to which the changed vegetation structure facilitates or impedes recruitment, and the extent to which surviving plants respond to release from competition. There are no data on the longer term impact of logging, but in a qualitative sense, *Macrozamia johnsonii* is common in areas which have been subject to repeated logging over a period of at least 50 years. In NSW State forests in the area concerned, timber harvesting is currently selective and impacts are minimised by a range of legislated and other harvesting constraints. Although there are no quantitative data available on the response of *Macrozamia johnsonii* to physical damage by timber harvest, casual observations suggest that individual plants are fairly resilient and generally survive, although plants are killed if the trunk is severed, the plant is uprooted or the growing point destroyed. About 30% of the gross area of State forest in the area is available for harvesting (R. Kirwood, FNSW Resources Officer, *pers. comm. 2007*), the remainder being reserved for management exclusion zones or inaccessible due to topographic constraints.

Other factors

Individual populations of *Macrozamia johnsonii* occur in close geographic proximity, with no known disjunct outliers, and the species is regenerating freely. These factors make it unlikely that loss of genetic variation will be a significant threat to the species. Loss of pollination mutualisms is also unlikely to be a threat, in view of the abundance of seedlings and the relatively unmodified state of much of the habitat. Based on recent observations, *Macrozamia johnsonii* appears tolerant of drought.

Assessment against IUCN criteria

The following section describes the evaluation of the species against the IUCN criteria using the population estimates reported in this study together with consideration of plausible bounds for parameter values for which no quantitative data are available.

Criterion A. Reduction in population size.

Macrozamia johnsonii still occurs within the vicinity of all previous records of reliable locational accuracy. Although in most cases the accuracy of historical records is inadequate to assess whether particular stands have persisted, there is no evidence to suggest significant historical decline. The only potential threat which may reduce populations in the short to medium term is timber harvesting. Although there are no quantitative data which allow direct estimation of the impact of timber harvesting, the likely impacts may be assessed from consideration of effects on effective habitat area, as follows. As noted above, it is estimated that 30% of the State forest area is, or will be, harvested. All private land is included as net harvestable. Although this will overestimate the area affected, it at least compensates for the unknown but potentially higher harvest intensity on private land. On this basis, assuming (as described above) that 59% of the total effective habitat area is in State forest and 11% is on private land, approximately 29% (30% x 59% + 11%) of the effective area of habitat of the species is potentially subject to timber harvest. At the fine scale (metres to tens of metres), selective logging results in a mosaic of patches of different degrees of disturbance, including undisturbed patches, but there are few data on the extent of such patches following logging in the study area. Preliminary data (D. Binns, unpubl. data) from one area suggests that about 15% of the net area is affected by disturbance sufficiently severe to potentially cause mortality of *Macrozamia johnsonii*. It is very unlikely that the area so affected would exceed 30%, which represents a plausible, but extreme, upper limit for estimating annual mortality due to logging. Logging in this area is currently planned on a cutting cycle which varies from 10 to 30 years, but is conservatively assumed to average 15 years, which implies an average annual mortality of 1% (15% spread over 15 years) as a best estimate, and 2% (30% over 15 years) as an upper bound. Burgman *et al* (2001) suggest a simple formula for estimating habitat loss for stochastic events, for species which do not require periodic disturbance for recruitment. This formula is: $S = (1- p)^n$, where S is the proportion of habitat which is suitable to support mature plants, p is the annual probability of disturbance and n is the time (years) required for newly-disturbed habitat to support mature plants. To estimate n, it is necessary to estimate age at first breeding. Cultivated plants have been observed to produce cones after 15 years, but wild plants may take longer. Johnson (1961) notes that "massive plants 2 m tall have been grown from seed in less than 100 years". It is unclear whether this refers to the trunk only, or trunk and crown, but the use of the term "massive" implies substantial trunk development. Since wild plants with only a very short trunk may produce cones, we suggest a plausible range for the age at first breeding is 20–40 years. Using the formula, with annual mortality of 1% and time to maturity of 20 years, the estimate of the proportion of long-term suitable habitat is 82%. This infers a long-term population reduction of 18% within the area subject to logging and 5% (18% x 29%) over the whole population. If the annual mortality is 2% and the effective age at first breeding is 40 years (either because the age at maturity is higher than expected, or because recruitment is initially impeded in disturbed areas) then the inferred long-term population reduction is 45% within the net logging area and 13% overall. The latter represents the worst-case extreme of plausible scenarios, but is still below the Vulnerable category threshold of Criterion A3. These estimates would be higher if recruitment was impeded to a greater extent than expected in disturbed areas, or lower if disturbance facilitated recruitment or promoted growth of surviving plants through removal of competition.

Criterion B. Geographic range (extent of occurrence or area of occupancy)

The estimated extent of occurrence of 220 km^2 and area of occupancy of approximately 100 km^2 are both below the thresholds for the Endangered and Vulnerable categories, so *Macrozamia johnsonii* meets the primary criterion for these categories. With respect to secondary criterion 'a', since the most serious potential threat (logging) creates a disturbance mosai c in logged areas and does not '..rapidly affect all individuals..' (under the definition of 'location', IUCN 2001), we do not regard it as a plausible threat in the context of this criterion. As argued above, there is also no other plausible threat which affects this species in the short term. On this basis, *Macrozamia johnsonii* cannot be assessed in relation to secondary criterion 'a'. Criterion 'b (v)' is met based on the logging impact scenario described above. With respect to criterion 'c', this is a long-lived species with very low natural mortality and long generation time. Even moderate fluctuations are very unlikely, so this criterion is not met. Thus, the species meets at most one of the required two secondary criteria, so Criterion B is not met.

Criterion C. Population size

The lower 2.5 percentile of population size is estimated in this study to be at least 1.87 million mature individuals using the most conservative estimate of the four methods. Since the species is dioecious, and if it is assumed that the sex ratio is even, the effective population size in the context of this criterion is about 0.9 million. This vastly exceeds the maximum threshold for the Vulnerable (10 000) and more threatened categories, so *Macrozamia johnsonii* clearly does not meet this primary criterion for any threatened category.

Criterion D. Very small or restricted population

The population size (> 0.9 million) and area of occupancy (> 100 km^2) exceed the threshold for this criterion under the Vulnerable and more threatened categories. The species cannot be assessed in relation to the number of locations, as noted above under Criterion B. *Macrozamia johnsonii* does not meet this criterion.

Criterion E. Probability of extinction based on quantitative analysis

A detailed population viability analysis is not possible with the existing data for this species. However, a protocol developed by Burgman *et al*. (2001) allows a relative assessment of risk of extinction using the available data. For the purpose of using this protocol, we have assumed that the species lives for 200 years and is naturally fairly resilient, both plausible characteristics for the species, which gives a value of 500 for parameter F using the table provided by Burgman *et al*. (2001). The average density (D) is estimated as 0.025 ha per plant, based on the lower 2.5 percentile mature population of 0.9 million over a total area of 22200 ha of habitat. These parameters provide a target area for protection of D*F = 12 ha. This is the area required, in the absence of threatening processes, to ensure that the risk of the species declining to less than 50 individuals ("pseudo-extinction") is no more than 0.1% over 50 years. This is intended to be used as a relative measure to rank species of concern with respect to other species, but does not indicate that this is the actual area necessary. However, since the area of *Macrozamia johnsonii* habitat (> 6000 ha) in formally reserved National Park exceeds the minimum estimate by more than two orders of magnitude, using this protocol *Macrozamia johnsonii* is rated as a species with relatively extremely low extinction risk.

Overall assessment

Macrozamia johnsonii does not meet any of the IUCN criteria for any of the threatened categories, and is most appropriately assessed in the category of Least Concern. The values of some parameters used for assessment are based on circumstantial evidence and informed opinion rather than quantitative data. We believe we have taken a realistic attitude to defining plausible bounds for these parameter values, but it is possible that some values may be found to be outside this range when quantitative data become available. In that case, the assessment would need to be reviewed. The current assessment is most sensitive in respect of the population decline criterion. If other, currently unrecognised, significant threats develop (for example, if the species was found to be highly susceptible to longer term climate change or a pathogen), it is possible that the species may meet the threshold for the Vulnerable category. However, based on present information, *Macrozamia johnsonii* fails to meet any of the criteria for listing as a threatened species. Its current listing on Schedule 1 as an Endangered species under the NSW *Threatened Species Conservation Act (1995)* is therefore not considered appropriate.

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