CSIRO Publishing

Wildlife Research

Volume 28, 2001

All enquiries and manuscripts should be directed to:

Wildlife Research
CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia

Telephone: +61 3 9662 7622
Fax: +61 3 9662 7611
Email: publishing.wr@csiro.au

CSIRO PUBLISHING

Published by CSIRO Publishing
for CSIRO and the Australian Academy of Science

www.publish.csiro.au/journals/wr

Wildlife Research, 2001, **28**, 547–554

Monitoring *Crocodylus porosus* populations in the Northern Territory of Australia: a retrospective power analysis

S. C. Stirrat[A], *D. Lawson*[A], *W. J. Freeland*[A] *and R. Morton*[B]

[A]Parks and Wildlife Commission of the Northern Territory, PO Box 496, Palmerston, NT 0831, Australia.
[B]CSIRO Mathematical and Information Services, GPO Box 664, Canberra, ACT 2601, Australia.

Abstract. In the Northern Territory of Australia, populations of the estuarine crocodile (*Crocodylus porosus*) have been subject to an annual egg harvest since the early 1980s. Since 1997, adult and juvenile crocodiles have also been harvested in some catchments. Annual surveys of crocodile populations are conducted in order to ensure that the harvest is sustainable. Boat surveys commenced in 1975 and helicopter surveys commenced in 1989. Retrospective power analysis was used to determine whether the sampling program meets the objectives of the Crocodile Management Program for the Northern Territory. Data collected during boat surveys vary in quality between river systems. The analysis of pooled data from 7 river systems with a residual standard deviation of 0.11 indicates that the power of the current spotlight survey method to detect a decline of 10% per annum in around 4 years is about 0.9. In this time the population would decline by around 33% and would fully recover in 8 years following the removal of the factor causing the decline. This allows detection of a decline within one-third, and recovery within two-thirds, of the estimated generation time of the saltwater crocodile and will allow management actions to be implemented before the impacts on populations are serious. The data from helicopter and boat surveys from a 10-year period were compared. Helicopter surveys did not provide useful management information.

Introduction

The saltwater crocodile (*Crocodylus porosus*) was protected in the Northern Territory of Australia in 1971 after decades of uncontrolled exploitation. In the 30 years since, several mechanisms to achieve conservation of crocodiles have been put in place, one of which is the commercial, sustainable use of the species. The Crocodile Management Program for the Northern Territory was the first formal program for the sustainable use of wildlife in the Northern Territory (Anon. 1986). Its development followed CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) endorsement of the Australian proposal for the listing of the Australian population of *Crocodylus porosus* on Appendix II for ranching purposes (Webb *et al.* 1984). This endorsement allowed annual egg harvests to go ahead as the basis for a crocodile industry that continues to provide financial incentives to landholders to protect crocodile habitats (Webb *et al.* 1987). Hatchlings from these harvests are grown in captivity to produce skins and meat for sale on national and international markets. In 1994, in recognition of the successful management of the species, the listing of *C. porosus* was changed to Appendix II unqualified, which allowed trial harvests of adult crocodiles to proceed.

A primary aim of the Crocodile Management Program for the Northern Territory is to ensure that commercial harvests are not detrimental to the survival of the species. This is also a requirement for international trade under CITES (Wijnstekers 1995). Consequently, crocodiles are counted in many river systems across the Northern Territory each year. The purpose of monitoring is to provide objective information on which to base timely management actions should declines in numbers be detected. A standard spotlight monitoring technique started in 1975 in some systems as part of early research programs to track the recovery of populations after protection (Webb *et al.* 1987). It was extended to important harvest areas in the late 1970s and early 1980s. Helicopter monitoring, covering 70 rivers and creeks across the northern part of the Northern Territory, started in 1989 in order to efficiently gather broad-scale information. The monitoring program showed that commercial egg harvests had no impact on the direction of change of crocodile populations (Webb *et al.* 2000). The population grew rapidly in the 1980s and the Northern

 10.1071/WR00079 1035-3712/01/060547

Territory now has a large crocodile population that is no longer growing rapidly, and may, in fact, be close to carrying capacity (Webb *et al.* 2000).

Because the population is relatively stable, future changes, whether increases or decreases, may be gradual, even under harvest regimes. In this paper, retrospective power analysis was used to determine whether the current crocodile-monitoring program is capable of detecting changes of management significance in time to allow effective remedial action to be taken. In addition, in rivers where spotlight and helicopter monitoring were carried out, the two methods were compared to assess whether the data collected by helicopter monitoring reflected trends detected by spotlight monitoring.

Power analysis is a valuable and, until recently, underutilised technique in conservation biology (Taylor and Gerrodette 1993; Gibbs *et al.* 1998). The power of a sampling program for monitoring population trends is its ability to detect change in population size, or an index of population size, when it occurs (i.e. a rejection of the null hypothesis of no change when it is indeed false). Prospective power analysis should be used to design new monitoring programs but power analysis can also be used to refine existing programs to meet the needs of wildlife managers (Gerrodette 1987; Thomas 1997; Gibbs *et al.* 1998; Lougheed *et al.* 1999).

Statistical power depends on sampling effort (number and precision of samples) and on the magnitude of the effect measured, in this case the trend in populations (the effect size) (Gerrodette 1987; Thomas 1997). A population trend is the systematic change in population size over time (Lougheed *et al.* 1999). To calculate power we must specify the sample size, the Type I error rate (α), the sampling variance and the effect size. In retrospective power analysis, the sampling variance is known from monitoring data. The preferred application of information is to use observed variance and a pre-specified effect size rather than observed effect size (Thomas 1997). Recent studies have analysed power of monitoring programs to detect trends (rates of decline) varying from 20% to 50% (Kendall *et al.* 1992; Beier and Cunningham 1996; Zielinski and Stauffer 1996).

The specified effect size should be relevant to management objectives because detection of small effect sizes can require considerable sampling effort, and hence expense. It should also be one that has historically been shown to allow the population to rapidly recover should the cause of the decline be recognised and appropriate management actions instituted. The Northern Territory's crocodile population exhibited an annual growth of approximately 10% between 1980 and 1990, after which the rate of growth decreased considerably (Webb *et al.* 2000). In this paper, an effect size of 10% per annum rate of decline was specified. A 10% per annum change in monitored numbers was regarded as being relatively small, potentially detectable, and not so large as to require a long period for recovery should management action be required. It also corresponds to the current maximum level of harvest permitted for the removal of non-hatchling crocodiles, and therefore the level of prescribed anthropogenic impact on breeding populations. Other unknown impacts may be occurring but the purpose of monitoring is not to determine causation, but to identify negative trends and act accordingly (McNally 1997).

It is neither practical nor physically possible to detect a relatively small change (e.g. 10% per annum in the monitored size of a wild population) the instant it occurs, irrespective of whether the change is abrupt or gradual. The time period to be allowed for detection should have some relationship to the biology of the species being monitored. The time required to detect a small change in a population of a species of mouse should obviously be less than that used to detect a similar proportional change in a population of elephants. The time allowed to detect a small change should be related to the life history of the animal concerned, rather than designed to meet some industry, or bureaucratic imperative.

The relevant life-history parameter is the animal's generation time, defined as the mean time between birth of parents and the birth of their offspring. Unfortunately, there are no reliable life or fertility tables for *C. porosus*. An approximation is the average age of sexual maturity of wild female *C. porosus*, estimated to be 12 years by Webb *et al.* (1987).

The *a priori* value of maximum time to detect a 10% per annum change in the monitored number was chosen as half a generation time i.e. approximately 6 years. This detection time would allow managers to implement an adjusted management regimen well before sexual maturity of crocodiles born at the beginning of the period. An equivalent time for an endangered species of rat would be something on the order of 4.5 months (Bonner 1965).

Methods

In the past, crocodile monitoring in the Northern Territory was based on two procedures: annual counts by boat surveys in the navigable parts of rivers and creeks, and by helicopter surveys over 10-km-long sample units of rivers and estuaries. Boat surveys are carried out at night when crocodiles can be approached closely using a spotlight. The boat survey technique was first developed by Messel *et al.* (1981) and it has been maintained ever since. Surveys have been carried out in the Liverpool, Tomkinson, Blyth and Cadell Rivers since 1975 and in the Mary, Adelaide, Daly, Finniss and Reynolds Rivers since at least 1984. These rivers were selected for monitoring because they are subject to annual egg harvests. For most rivers annual counts are available. The helicopter survey method was developed by Bayliss *et al.* (1986) and was implemented in 1989.

These enumeration methods produce indices of crocodile abundance in the form of the ratio of the number of crocodiles per kilometre of river surveyed. Data analysed were counts of non-hatchling crocodiles. Crocodiles less than 60 cm (2 feet) long are classed as hatchlings in the year of survey. Data for non-hatchlings (longer than 60 cm) are used because the number of hatchlings varies enormously depending on the success of breeding in the previous wet season. The assumptions behind linear regression, that data are normally distributed and not serially correlated and that variances for each sequence are approximately equivalent, were not noticeably violated.

The objective of current management is to maintain populations above a nominated level so the management issue is similar to quality control. To evaluate the performance of the statistical method, it is assumed that the expected count (on the log scale) at time 0 was exactly at that level and a decline of 10% per annum occurs thereafter. Although this form of the decline is considered for the purpose of evaluation, the aim is to detect a departure from the nominated population size rather than a trend. Analyses were performed to answer the following questions: how long would it take to detect that a drop below the nominated level had occurred using

(1) annual spotlight counts for single rivers?
(2) annual spotlight counts pooled across all mainstream systems?
(3) spotlight counts conducted every two years?
(4) spotlight counts conducted every three years?
(5) annual helicopter counts?

Data analysed were the natural logarithms of the number of non-hatchling crocodiles per kilometre. The log-transformation has the benefit of tending to stabilise the variance and make the distributions more nearly normal. It is also convenient that the exponential trend in the ratio becomes a line after this transformation.

The test statistic chosen for detecting change is the mean log-ratio of non-hatchling crocodiles (as observed by standard spotlighting protocol). This statistic is based on the mean of n data taken since the start of the hypothetical trend. The mean of the n data is used rather than a linear trend with a fixed starting point because the mean gives equal weight to all data and is therefore more sensitive to other forms of change. The n data are, in reality, at the end of a much longer sequence of observations, and the fact that the starting time for the decline would not be known in practice is not taken into account. However, comparisons can be made with the power analyses for trend detection, as in Gerrodette (1987), for which the same would be true. The power of the test in this paper is greater than that for trend detection because the method refers to a fixed level, the nominated mean log-count.

Let d be the log-decline rate (for 10% per annum $d = 0.1054$) and k the interval between successive observations (in years). z_α denotes the upper 100α% point for the Normal distribution; for $\alpha = 0.05$, $z_\alpha = 1.645$. Assuming that at the first observation the population is at its nominated level, the sample mean (minus the log-nominated level) has expectation $-(n-1)kd/2$ and variance s^2/n. We standardise the expectation by dividing by the square-root of the variance. The standardised expectation is subtracted from z_α to get the power function:

$$1 - \beta = \Phi\,[z_\alpha + (kd/s)n^{0.5}((n-1)/2)],$$

where Φ is the standard Normal distribution function. The value of z_α has been derived from the supposition that a one-sided test is to be performed; this is appropriate because the intention is to detect a one-sided change, a decrease.

The method requires knowledge of the true standard deviation of the sampling error. This is taken as 'known' from the previous data from which an estimate, the residual standard deviation s, is obtained. This parameter is the root mean-square error after fitting a linear trend to the whole data sequence. There is clearly the assumption that the standard deviation for the current data is the same as estimated in the past. If this was not correct, a solution would be to insert the upper percentage point of the t-distribution in place of z_α, and then s could be estimated from the current data.

Desired probabilities of two types of error were specified: Type 1 (α) is the probability of identifying a change when there is none, and Type 2 ($1-\beta$) is the probability of not identifying a change when there is one. The value chosen for α was 0.05. The Type II error rate was set at 0.1, giving a power of at least 90%.

The ability of helicopter observations to predict the spotlight observations was assessed by regression of the spotlight log-ratio on the helicopter log-ratio. The statistical significance is the same as for analysing their correlation. We compared the significance of the trends in log-ratio obtained from the two monitoring techniques.

Where mainstream data were combined, the years used were those for which there were data for all rivers. Otherwise the pooled mean log-ratio would be distorted according to the typical abundance in the rivers that happened to be included. This resulted in a relatively small sample for analysis.

Results

Table 1 shows the probability of detection (power) of a decline of 10% per annum for annual surveys, surveys every two years and every three years. This table can be used to estimate the number of observations (years) required to detect the change with specified power. For example, if a sequence of observations has a residual standard deviation $s = 0.20$, and the concern is a decline in the nominated mean log-ratio, then $n = 5$ annual observations would have a probability of 0.762 of producing a significant result from a 5% significance test. If a power of $\beta > 0.90$ were required, then $n = 6$ with a power of 0.943 would suffice. Similarly, for a power of at least 90% when surveys are carried out every 2 years, $n = 4$ observations (i.e. years 1, 3, 5, 7) would be required. For surveys every 3 years, $n = 4$ (years 1, 4, 7, 10) would be needed.

Table 2 gives river names and the corresponding residual standard deviation (s), the linear trend in the log-ratio on time, its p value (two-sided probability) and the auto-regression coefficient. There were clear increases in the number of crocodiles in the Daly, Liverpool and Mary rivers. Autocorrelation was never significant and not of consistent sign, and can therefore be ignored.

Table 2 also shows the regression slope of spotlight log-ratio on helicopter log-ratio and its one sided (upper tail) p-value for each river. The helicopter counts showed no significant association with the spotlight counts, except for the Cadell River and the pooled data, where the relationship was not very strong. Some of the non-significant estimates actually had a negative value. The conclusion is that helicopter counts generally bear no useful relationship to the spotlight data.

Except for the pooled counts, Table 3 indicates that the values of s from helicopter counts are beyond the range of s for the spotlight data given above, and that an expected decline of 10% per annum would take a long time to detect. The helicopter counts failed to detect the highly significant upward trends in the Daly River, the Liverpool River and the downstream section of the Mary River that were apparent in the long-term spotlight data (Table 2). Of these three, the

Table 1. Probability (β) of detection of a 10% per annum change from a nominated mean log-ratio of a population in relation to the residual standard deviation (*s*) and number of samples (*n*) using annual, biennial and triennial spotlighting counts

s	Annual counts							Biennial counts						Triennial counts					
	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
0.10	0.571	0.935	0.999	1.000	1.000	1.000	1.000	0.439	0.978	1.000	1.000	1.000	1.000	0.723	1.000	1.000	1.000	1.000	1.000
0.11	0.506	0.890	0.996	1.000	1.000	1.000	1.000	0.386	0.953	1.000	1.000	1.000	1.000	0.651	1.000	1.000	1.000	1.000	1.000
0.12	0.451	0.839	0.989	1.000	1.000	1.000	1.000	0.343	0.919	1.000	1.000	1.000	1.000	0.586	0.998	1.000	1.000	1.000	1.000
0.13	0.405	0.784	0.976	1.000	1.000	1.000	1.000	0.309	0.878	0.999	1.000	1.000	1.000	0.530	0.995	1.000	1.000	1.000	1.000
0.14	0.366	0.730	0.957	0.999	1.000	1.000	1.000	0.281	0.832	0.998	1.000	1.000	1.000	0.481	0.988	1.000	1.000	1.000	1.000
0.15	0.334	0.678	0.933	0.996	1.000	1.000	1.000	0.257	0.785	0.995	1.000	1.000	1.000	0.439	0.978	1.000	1.000	1.000	1.000
0.16	0.307	0.630	0.903	0.992	1.000	1.000	1.000	0.238	0.738	0.989	1.000	1.000	1.000	0.402	0.962	1.000	1.000	1.000	1.000
0.17	0.284	0.585	0.870	0.984	1.000	1.000	1.000	0.221	0.692	0.981	1.000	1.000	1.000	0.371	0.942	1.000	1.000	1.000	1.000
0.18	0.264	0.544	0.835	0.974	0.999	1.000	1.000	0.207	0.649	0.969	1.000	1.000	1.000	0.343	0.919	1.000	1.000	1.000	1.000
0.19	0.247	0.508	0.798	0.960	0.997	1.000	1.000	0.195	0.609	0.954	1.000	1.000	1.000	0.320	0.892	1.000	1.000	1.000	1.000
0.20	0.232	0.474	0.762	0.943	0.994	1.000	1.000	0.184	0.571	0.935	0.999	1.000	1.000	0.299	0.863	0.999	1.000	1.000	1.000
0.21	0.219	0.444	0.725	0.923	0.990	1.000	1.000	0.175	0.537	0.914	0.998	1.000	1.000	0.281	0.832	0.998	1.000	1.000	1.000
0.22	0.207	0.418	0.690	0.901	0.985	1.000	1.000	0.167	0.506	0.890	0.996	1.000	1.000	0.265	0.801	0.996	1.000	1.000	1.000
0.23	0.197	0.393	0.659	0.877	0.977	1.000	1.000	0.159	0.477	0.865	0.993	1.000	1.000	0.250	0.769	0.993	1.000	1.000	1.000
0.24	0.188	0.372	0.625	0.852	0.967	1.000	1.000	0.153	0.451	0.839	0.989	1.000	1.000	0.238	0.738	0.989	1.000	1.000	1.000
0.25	0.180	0.352	0.595	0.825	0.956	1.000	1.000	0.147	0.427	0.812	0.983	1.000	1.000	0.226	0.707	0.984	1.000	1.000	1.000

Table 2. Trends and autocorrelation in long-term spotlight count data and the regression slopes of spotlight log-ratio on helicopter log-ratio
s = residual standard deviation

Location	*s*	Spotlight trend (s.e.)	*P*	Autocorrelation (s.e.)	Regression slope (s.e.)	*P*
Adelaide R. (downstream)	0.167	0.015 (0.010)	0.148	0.001 (0.065)	0.075 (0.182)	0.346
Adelaide R. (upstream)	0.213	0.027 (0.008)	0.004	0.013 (0.049)	0.182 (0.215)	0.215
Blyth R.	0.195	0.018 (0.006)	0.004	0.008 (0.057)	–0.203 (0.136)	0.923
Cadell R.	0.225	–0.001 (0.007)	0.804	–0.001 (0.061)	0.407 (0.176)	0.025
Daly R.	0.116	0.068 (0.006)	<0.001	0.039 (0.026)	0.072 (0.154)	0.327
Liverpool R.	0.163	0.026 (0.005)	<0.001	0.019 (0.048)	–0.051 (0.106)	0.679
Mary R. (downstream)	0.202	0.103 (0.012)	<0.001	0.059 (0.076)	–0.027 (0.504)	0.520
Mary R. (upstream)	0.218	0.122 (0.013)	<0.001	0.050 (0.062)	–	–
Tomkinson R.	0.237	0.018 (0.007)	0.027	0.010 (0.053)	–0.201 (0.116)	0.939
Pooled	0.107	0.017 (0.007)	0.038	0.005 (0.035)	0.263 (0.112)	0.040

Liverpool River population was estimated by helicopter counts as declining, though not significantly so. The fact that the helicopter sequences were shorter than the spotlight sequences is partly the cause of these differences, particularly for the Liverpool River. The 1978 data point for the Daly River had an influential effect in making the spotlight trend significant but even since 1989 this river had a steady increase in crocodile numbers detected by spotlight counts.

The comparison of the methods in Table 3 restricts the analysis of the spotlight data to the years when helicopter data were collected (i.e 1989–99). While there was no increase in crocodile numbers in the Liverpool River in this period, the spotlight data still show highly significant increases in the Mary and Daly Rivers that were not detected in the helicopter data (Figs 1 and 2). As would be expected, the estimates of *s* differ from those of the longer sequence of spotlighting data.

The spotlight counts for sidestreams were generally lower than they were in mainstreams, and were sometimes zero. To avoid taking the logs of zeros, these counts were regarded as being one half. This does not seriously distort the conclusion that *s* is large (or equivalently, the counts uninformative) such that detection of any trend cannot be expected to be achieved within a reasonable time. With the exception of the Adelaide River sidestreams, there can be no confidence in detecting a decline in less than 12 years after the start of the sequence.

Discussion

The commercial value of crocodiles in the different rivers varies according to the nature of the uses to which they are put. In some rivers the tourism value vastly exceeds that of the egg harvest, and some have harvests of adult crocodiles while others do not. Achieving sustainability of these uses depends upon monitoring systems sensitive to change within those rivers, as well as sensitive to change in the meta-population distributed across river systems.

Large monitoring programs are expensive and often cannot be repeated (Thomas 1997) so it is crucial to ensure that the resources expended have the greatest chance of detecting changes when they occur. The inescapable conclusion from this analysis is that, notwithstanding its considerable cost efficiencies in undertaking counts in

Table 3. Trends in crocodile populations between 1989 and 1999 using helicopter counts and spotlight counts
s = residual standard deviation

Location	*s*	Helicopter trend (s.e.)	*P*	*s*	Spotlight trend (s.e.)	*P*
Adelaide R. (downstream)	0.282	0.0064 (0.0268)	0.817	0.151	0.0015 (0.0158)	0.929
Adelaide R. (upstream)	0.333	–0.0283 (0.0402)	0.504	0.150	–0.0306 (0.0156)	0.085
Blyth R.	0.419	0.0023 (0.0400)	0.955	0.188	0.0000 (0.0196)	1.000
Cadell R.	0.429	–0.05015 (0.0409)	0.240	0.284	–0.0214 (0.0296)	0.491
Daly R.	0.398	0.0085 (0.0380)	0.827	0.093	0.0435 (0.0120)	0.009
Liverpool R.	0.541	–0.0778 (0.0515)	0.165	0.195	–0.0007 (0.0186)	0.970
Mary R. (downstream)	0.337	0.0221 (0.0321)	0.509	0.070	0.1509 (0.0132)	<0.001
Tomkinson R.	0.437	–0.0295 (0.0417)	0.497	0.180	0.0086 (0.0188)	0.659
Pooled	0.223	–0.0245 (0.0269)	0.392	0.087	–0.0273 (0.0164)	0.157

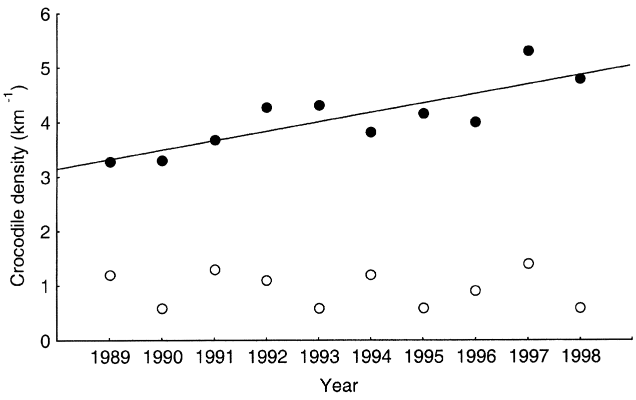

Fig. 1. Relationship between crocodile density and time for spotlight (●) and helicopter (○) counts on the Daly River.

remote areas (Bayliss *et al.* 1986), helicopter counts are not able to provide data suitable for detecting significant changes in the Northern Territory's populations of *C. porosus* within the time constraints required by management. The method is not suitable for monitoring the effects of management in individual rivers and is not as sensitive to change as spotlight count data pooled across rivers. It may prove to be a useful adjunct to spotlight surveys to determine the nature of a change in numbers detected using spotlight counts. Helicopter counts appear to detect change in the size distribution of large crocodiles better than spotlight counts because larger crocodiles tend to be more wary and therefore less approachable in a boat.

Spotlight counts in mainstreams provide the best option for detecting change in number of *C. porosus* within acceptable periods. In general, spotlight counts of side streams do not provide useful data for analysing trends, and will be pooled with mainstream data to give an index of abundance for entire river systems.

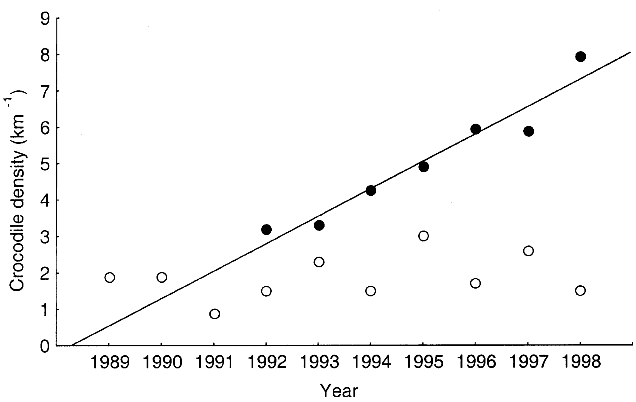

Fig. 2. Relationship between crocodile density and time for spotlight (●) and helicopter (○) counts on the Mary River.

As a result of this analysis, the Parks and Wildlife Commission will continue to use spotlighting to monitor mainstream populations of *C. porosus*. Annual counts will continue to be conducted, and some major rivers subject to harvest that were previously monitored from helicopter will be included in the survey program, including the Roper and Victoria Rivers. Table 1 clearly indicates that with the existing residual standard deviations of the log-ratios, time to detection of a significant change in the nominal level for the mean log-ratio of crocodiles would, in general, be unacceptable if counts were conducted every two or three years. These frequencies of monitoring result in detection times over, and in some cases well over, half the approximated generation time for *C. porosus*.

Table 4 combines data from Tables 1 and 2 for annual counts and a probability of detection of 0.90, with information on the extent of depletion of the population at the time of detection, and estimates of the time required for the populations to return to the pre-existing mean log-ratio. Spotlighting provides a sensitive method of detecting an overall change in the number of the *C. porosus* meta-population. A change of 10% per annum can be detected in 4 years, with a concomitant 33% reduction in the population and period of 8 years required for full recovery following removal of the factor causing decline. This is detection within one-third, and recovery within two-thirds of a generation time. The full recovery of the meta-population from its very low point at the cessation of uncontrolled shooting took approximately 19 years. This is equivalent to 1.6 generation times, which is remarkably fast.

The analysis of pooled data provides a useful summary of the monitoring procedures for crocodile populations and the application of power analysis. However, monitoring regional trends is useful only where there are pervasive influences

Table 4. Time to detect a 10% per annum change, extent of the population declines at detection and the recovery period in mainstream populations, and the pooled population, using an annual spotlight survey with $\beta = 0.9$
s = residual standard deviation

River	*s*	Detection time (years)	Decline (%)	Recovery time (years)
Adelaide R. (downstream)	0.17	6	47	11
Adelaide R. (upstream)	0.21	6	47	11
Blyth R.	0.20	6	47	11
Cadell R.	0.26	7	48	12
Daly R.	0.12	5	41	9
Liverpool	0.16	5	41	9
Mary R. (downstream)	0.20	6	47	11
Mary R. (upstream)	0.29	6	47	11
Tomkinson R.	0.24	7	48	12
Pooled	0.11	4	33	8

impacting on many sites concurrently, such as anthropogenic impacts on water quality (Urquhart *et al.* 1998). In future there may be pervasive influences on saltwater crocodile populations but harvest-related impacts will vary between catchments, and management actions (e.g. cessation of harvests) are likely to be implemented within catchments on the basis of monitoring data from individual rivers. As anticipated, the sensitivity of detection of change in crocodile populations in individual mainstreams is less than that for the meta-population, and is strongly influenced by the size of the residual standard deviation. Nonetheless, only two of nine mainstreams (the Cadell and Tomkinson Rivers) have a detection time greater than half a generation time. Both these rivers had detection times of 0.58 of a generation (not markedly greater than 0.5). The populations in all mainstream rivers would recover within a single generation time after intervention.

While the lengths of time to detect change and the duration of recovery periods are biologically acceptable, any shortening in these periods would clearly be advantageous. This can only be achieved by a better understanding of the causes of variation in the spotlight counts, which would allow the residual standard deviation to be reduced. For instance, repeat surveys within survey seasons substantially increase the power of detection of trends in waterfowl populations (Lougheed *et al.* 1999). Currently, this change is not possible for crocodile monitoring because the program is already extensive and costly. However, a further advantage of reducing *s* would be a reduction in the frequency, and therefore cost, of spotlight surveys without loss of sensitivity. Testing an hypothesis with a higher Type I error rate also increases power. If crocodile populations were small or threatened, this strategy would be justified as the environmental cost of a Type II error in this situation, i.e. possible extinction, is larger than that of a Type I error, a 'false alarm' (Zielinski and Stauffer 1996). However, while crocodile populations are large and certainly not threatened, retaining α at 5% is justified.

Variation can also be reduced by modifying counting methodology. Direct counts are usually associated with low variability (Gibbs *et al.* 1998), compared with methods that involve trapping or attractants, so the spotlight method will be retained. If the methods used each survey are consistent then the component of variability due to sampling methodology can be minimised. For crocodiles, surveys are carried out at the same time of year (temperature) and under as similar tidal conditions as possible. These two factors, temperature and water level, will significantly influence the detection of crocodiles. Concurrent collection of environmental data may allow direct counts to be adjusted, using analysis of covariance, and therefore reduce variability in data sets (Nickerson and Brunell 1997).

These analyses provide an understanding of the capacity of the monitoring methods to detect change but they do not provide an effective decision-making tool. Crocodile monitoring is equivalent to quality control of an industrial process using a sampling scheme. Industry uses decision rules for action when a process is believed to have slipped or drifted out of control. There is a large array of methods available (Bowker and Lieberman 1959; Davies and Goldsmith 1972; Montgomery 1991) and development of an effective decision-making tool will be the focus of further research.

Conclusions

Harvest levels of *C. porosus* in the Northern Territory of Australia are inherently conservative. The introduction and continuation of harvests, and the use of the metapopulation for tourism, has accompanied a dramatic recovery of the population. The metapopulation is currently relatively stable although populations in some rivers continue to grow fairly rapidly. While a significant decline in either a single population or the meta-population seems very unlikely, it is critical that monitoring be designed to meet the needs of public accountability, as well as to deal with the remote probability of there being some form of decline. This means demonstrating that existing management practice is sensitive to change in populations subject to use, and sensitive to change in biological and sociological circumstances.

It is critical that monitoring, and the parameters developed for decision making be grounded in biological characteristics relevant to the species concerned, not industrial or bureaucratic dictates. There is a need for sound statistically based monitoring and decision systems. Annual spotlight counts currently meets these needs. Efforts will be made to improve the sensitivity of monitoring over the next few years, and a sound decision-making tool is being developed.

Acknowledgments

We thank the numerous people who have been involved in collection of crocodile monitoring data in the Northern Territory over many years, particularly Professor Harry Messel, who was responsible for initiating this long-running monitoring program over 25 years ago. We also thank three anonymous referees for comments that greatly improved the manuscript.

References

Anon. (1989). A management program for *Crocodylus porosus* and *Crocodylus johnstoni* in the Northern Territory of Australia. Conservation Commission of the Northern Territory.

Bayliss, P., Webb, G. J. W., Whitehead, P. J., Dempsey, K., and Smith, A. (1986). Estimating the abundance of saltwater crocodiles, *Crocodylus porosus* Schneider, in tidal wetlands of the Northern Territory: a mark–recapture experiment to correct spotlight counts to absolute numbers and the calibration of helicopter and spotlight counts. *Australian Wildlife Research* **13**, 309–320.

Beier, P., and Cunningham, S. C. (1996). Power of track surveys to detect changes in cougar populations. *Wildlife Society Bulletin* **24**, 540–546.

Bonner, J. T. (1965). 'Size and Cycle: an Essay on the Structure of Biology.' (Princeton University Press: Princeton, NJ.)

Bowker, A. H., and Lieberman, G. J. (1959). 'Engineering Statistics.' (Prentice-Hall.)

Davies, O. L., and Goldsmith, P. (eds.). (1972). 'Statistical Methods in Research and Production.' (Oliver & Boyd.)

Gerrodette,T. (1987). A power analysis for detecting trends. *Ecology* **68**, 1364–1372.

Gibbs, J. P., Droege, S., and Eagle, P. (1998). Monitoring populations of plants and animals. *Bioscience* **48**, 935–940.

Kendal, K. C., Metzgar, L. H., Patterson, D. A., and Steele, B. M. (1992). Power of sign surveys to monitor population trends. *Ecological Applications* **2**, 422–430.

Lougheed, L. W., Breault, A., and Lank, D. B. (1999). Estimating statistical power to evaluate ongoing waterfowl population monitoring. *Journal of Wildlife Management* **63**, 1359–1369.

MacNally, R. (1997). Monitoring forest bird communities for impact assessment: the influence of sampling intensity and spatial scale. *Biological Conservation* **82**, 355–367.

Messel, H., Vorlicek, G. C., Wells, A. G., and Green, W. J. (1981). Surveys of the tidal river systems in the Northern Territory of Australia and their crocodile populations. Monograph 1. The Blyth–Cadell River systems study and the status of *Crocodylus porosus* in tidal waterways of northern Australia. Methods of analysis and dynamics of a population of *C. porosus*. (Pergamon Press: Sydney.)

Montgomery, D. C. (1991). 'Introduction to Statistical Quality Control.' (John Wiley & Sons.)

Nickerson, D. M., and Brunell, A. (1997). Power analysis for detecting trends in the presence of concomitant variables. *Ecology* **79**, 1442–1447.

Taylor, B. L., and Gerrodette, T. (1993). The uses of statistical power in conservation biology: the vaquita and northern spotted owl. *Conservation Biology* **7**, 489–500.

Thomas, L. (1997). Retrospective power analysis. *Conservation Biology* **11**, 276–280.

Urquhart, N. S., Paulsen, S. G., and Larsen, D. P. (1998). Monitoring for policy-relevant regional trends over time. *Ecological Applications* **8**, 246–257.

Webb, G. J. W., Manolis, S. C., Whitehead, P. J., and Letts, G. A. (1984). A proposal for the transfer of the Australian population of *Crocodylus porosus* Schneider (1801), from Appendix I to Appendix II of CITES. Conservation Commission of the Northern Territory, Technical Report No. 21.

Webb, G. J. W., Whitehead, P., and Manolis, S. C. (1987). Crocodile management in the Northern Territory of Australia. In 'Wildlife Management. Crocodiles and Alligators'. (Eds G. Webb, S. Manolis and P. Whitehead.) pp. 107–124. (Surrey Beatty: Sydney.)

Webb, G. J. W., Britton, A., Stirrat, S., Manolis, C., and Ottley, B. (2000). Recovery of saltwater crocodiles (*C. porosus*) in the Northern Territory of Australia: 1971–1998. In 'Proceedings of the 15th working meeting of the Crocodile Specialist Group Species Survival Commission of the IUCN – The World Conservation Union. Varadero, Cuba January 15–20, 2000.'

Wijnstekers, W. (1995). 'The Evolution of CITES: A Reference to the Convention on International Trade in Endangered Species of Wild Fauna and Flora.' 4th Edn. (CITES Secretariat: Switzerland.)

Zielinski, W. J., and Stauffer, H. B. (1996). Monitoring *Martes* populations in California: survey design and power analysis. *Ecological Applications* **6**, 1254–1267.

Manuscript received 24 October 2000; accepted 11 April 2001