Review of Hawaiian green turtle research

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1. Executive Summary

George Balazs deserves rich applause for maintaining the flag-ship times-series of nesting data for French Frigate Shoals (FFS) as well as long-running mark-recapture and stranding programmes. The value of this work continues to grow as these time-series lengthen. I would urge funding agencies to appreciate the importance of this work and the vital need for funding to be maintained for the core activities and expanded for emerging research avenues. Core activities that need to be maintained include assessment of nesting numbers in mid-season visits to East Island FFS, annual capture-mark-recapture on the foraging grounds at five sites in the Hawaiian Islands and maintaining a comprehensive stranding network. More resources should be made available to the programme to allow occasional detailed monitoring of nesting numbers throughout the nesting season both at East Island and at other potential nesting sites within FFS; monitoring of hatchling success at FFS; new focussed studies on the foraging ecology of turtles to take advantage of recent methodological advances such as advanced behavioural loggers; expansion of mark-recapture programme and supplementary counting of turtles on foraging grounds through dedicated surveys (e.g. aerial) so that estimates of total population size and size class structure can be improved.

2. Overview

The key objectives of this review are to complete a detailed examination of the data collection methods and data analysis techniques being employed for Hawaiian green turtle research, specifically within the context of assessing the recovery status of this population. As components of this review a number of scientific papers from this research were circulated and in addition a two day workshop was run in Honolulu, Hawaii, on May 9-10, 2006, during which a series of presentations were made by some of the scientists involved in the programme. The statement of work specified that the review would provide:

1. *An evaluation of the appropriateness of the quantitative methods being used for nesting beach research.*
2. *An evaluation of the experimental design and data collection methods for the marine habitat research. Are the data being collected in such a way*

that vital population parameters/rates such as: survival, recruitment, and relative abundance can be estimated?

3. *An evaluation of the analytical techniques used for trend analyses, somatic growth rates, and stock assessments with emphasis on Bayesian state-space modeling. Where necessary, the reviewers should recommend new or alternative analytical techniques.*

I have covered these three issues in the sections below.

3. Monitoring nesting numbers at French Frigate Shoals

Statement of work: "An evaluation of the appropriateness of the quantitative methods being used for nesting beach research."

3a. Overview of monitoring and recommendation for future survey work

The Hawaiian green turtle research programme is internationally famous as one of the few long-term sea turtle monitoring programmes in the world. The size of the nesting population at French Frigate Shoals (FFS) has been monitored every year by George Balazs and his team since 1973, with the time-series now in its fourth decade. As this time-series has lengthened, so its importance has grown. Most importantly the time-series has been used to show how the adult nesting population as FFS has staged a remarkable recovery, increasing by approximately 5.7% each year. This is a key result that was published in the journal *Biological Conservation* and has already received attention in high profile review articles[1]. The recovery of the Hawaiian green turtle nesting numbers parallels recoveries seen in some other populations, such as green turtles nesting on the Caribbean coast of Costa Rica. Importantly the Hawaiian recovery has been from very low numbers in the 1960s when there were <100 nesters (Fig. 1). Consequently these data suggest that recovery is not impeded for small turtle populations, i.e. Allee effects do not impede conservation efforts. This conclusion sends a key message to conservation groups working around the world where nesting numbers are often very small.

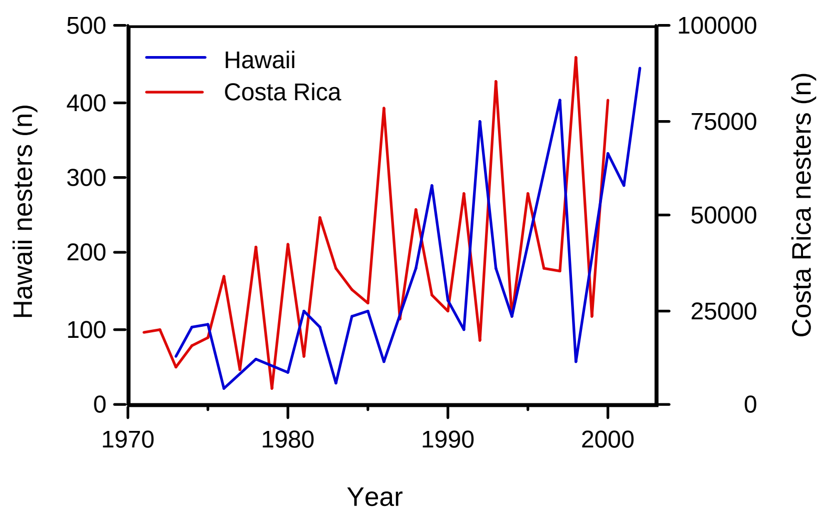

Figure 1. The numbers of green turtles nesting at French Frigate Shoals, Hawaii (blue line) and Tortuguero on the Caribbean coast of Costa Rica (red line) (from ref 1).

Central to the monitoring work conducted at FFS is the annual assessment of nesting numbers. This is an apparently simple task involving tagging of turtles on nightly patrols of the nesting beach and then subsequent re-identification of turtles as they return to nest during the season. However this apparent simplicity of monitoring hides the practical difficulties of this work. First there are logistical difficulties in conducting this work in remote locations such as FFS. FFS is relatively inaccessible and hence there are constraints in conducting detailed season-wide monitoring of all nesting sites in the FFS archipelago every year. Second, the FFS archipelago is also an important area for the endangered Hawaiian monk seal. Hence there needs to be a balance between turtle monitoring versus seal disturbance. In light of these constraints, George Balazs and his team have come up with an annual survey protocol involving several weeks of intensive beach monitoring during the height of the nesting season on a key index beach in FFS called East Island where initial surveys estimated that 55% of the nesting activity occurred. From this intense mid-season sampling at East Island, estimates of total nesting numbers are generated. The development of this annual monitoring strategy followed intensive recording of the nesting activity throughout the season over 5 years between 1988 and 1992.

The monitoring system employed at FFS has led to robust estimates of nesting numbers and hence the time-series of population recovery. The work conducted at FFS should be applauded. Through the efforts of George Balazs and his team a vitally important time-series of nesting numbers has been built up. It is crucial that the time-series is maintained and in addition I would advocate that additional resources are made available to the Hawaiian team to augment the ongoing work at FFS. While it may be impractical to conduct detailed monitoring throughout the season at all sites in FFS for the reasons outline above, it important that in occasional years detailed surveys are conducted to check how the focussed mid-season work at East Island reflects nesting patterns across the FFS archipelago. It is therefore timely now for the team to be given extra resources to conduct a couple of seasons of very detailed monitoring where they assess nesting numbers (a) throughout the season and (b) on different islands throughout FFS so that the relative importance of East island can be re-assessed. Following a couple of years of detailed monitoring, the scaled down monitoring of only the index beach, East Island, can then be resumed with added confidence. Probably a balance of 2-years extensive season-wide and FFS archipelago-wide sampling every 10 years would be a good balance to ensure the continued confidence in the developing time-series.

3b. Lessons learnt from other turtle rookeries

As nesting beaches are dynamic and as the climate changes, we might predict some processes that could theoretically lead to key changes in the nature of sea turtle nesting and hence the ability of monitoring programmes to detail population trends.

First turtles might switch their intensity of nesting on different beaches within the same general area. Such switches have been described elsewhere in the world. For example, long term monitoring of loggerhead turtle nesting at Little Cumberland Island on the Atlantic coast of the USA has revealed as decline in nesting numbers linked, not to population decline per se, but to the gradual erosion of this beach and the movement of nesters to other nearby sites. On Ascension Island (Atlantic) my team re-initiated population monitoring of nesting green turtles in 1998 following assessment of nesting numbers in the mid-1970s by Jeanne Mortimer. We have surveyed over 30 nesting beaches on the island each year and found that the intensity of nesting across these beaches has changed since similar surveys were conducted in the 1970s[2]. Importantly one beach that was relatively little used in the 1970s has now become the major nesting site on the island, corresponding with a change to low level lighting in a nearby settlement making the beach a more attractive site for the turtles. In short, at Ascension Island using the same index beach that was used 1970s and extrapolating up to total nesting numbers, would have led to large errors in our estimate of the status of the population. These examples reiterate that it is important that resources are made available to George Balazs and his team so that a couple of years of detailed surveys can be made throughout FFS above and beyond the annual mid-season surveys on East Island.

Second, climate change might conceivably lead to changes in the timing of the nesting season. Such phenological changes have been widely reported in various marine and terrestrial systems. For example, many species of birds now lay their eggs earlier in the year in the UK as a consequence of increasing temperatures. How climate might impact nesting turtles is little known, but at loggerhead turtle nesting sites in Florida it has been shown that turtles have shifted their nesting to earlier in the season, possibly as a result of increasing water temperatures[3]. While the causality of changes in the timing of turtle nesting seasons are still very speculative, it is important that the possibility of changes in the timing of nesting at FFS is assessed as monitoring continues into future decades. Again detailed surveys of FFS in some years of the type outlined above are important to tackle this issue.

Recommendations: ***Maintain monitoring of nesting activity at FFS with occasional years of more detailed monitoring across the season and across all available sites within FFS.***

3c. The importance of long biological time-series

It is often difficult for scientists to maintain long term support from funders for monitoring, but the crucial message is that the importance of long time-series, such as the green turtle monitoring at FFS, increases as the time-series lengthens. I can draw parallels with long-term monitoring of plankton populations in the Atlantic conducted by the Continuous Plankton Recorder survey (see also box 3 in ref 4) a programme of broadly the same order of magnitude. After a few decades of support from NERC (the UK research funding council for environmental research), support was withdrawn in the 1980s. This was a potentially catastrophic decision, made in ignorance of the value of long-times series. Luckily the survey was able to survive as an independent charity until NERC realised the error of its decision and resumed funding. The value of this time-series has continued to grow as it has lengthened and has led to a series of hugely influential findings, including seven *Nature* and *Science* papers published between 2002-2005:

Beaugrand,G, Reid PC, Ibanez F, Lindley JA, Edwards M (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296**: 1692-1694.

Beaugrand G, Brander KM, Lindley JA, Souissi S, Reid PC (2003). Plankton effect on cod recruitment in the North Sea. *Nature* **426**: 661-664.

DeYoung B, Heath MR, Werner F, Chai F, Megrey B, Monfay P (2004). Challenges of modeling of ocean basin ecosystems. *Science* **304**: 1463-1466.

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004). Lost at sea: where is all the plastic? *Science* **304**: 838.

Richardson AJ, Schoeman DS (2004). Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* **305**: 1609-1612.

Edwards M, Richardson AJ (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* **430**: 881-884.

Frank KT, et al. (2005). Trophic cascades in a formerly cod-dominated ecosystem. *Science* **308**: 1621-1623.

I list these outputs from the long-term plankton monitoring programme as this serves as a useful model for the importance of maintaining long-term support for Hawaiian green turtle monitoring and providing resources for continued and expanding collaborations. For example of the seven papers detailed above, four were led by post-docs at the plankton lab brought in specifically to bring new eyes to the data analysis and three by external collaborators. As the Hawaiian green turtle time-series lengthens, I fully expect that a continuing stream of important discoveries will be made with important conservation and management implications and I see no reason why this strong data set will not lead to publications and coverage in the top tier of ecological journals as well as *Nature* and *Science*.

Recommendations: ***Maintain existing collaborations and continue to develop new collaborations. They provide excellent value for money !***

3d. Temperature dependent sex determination / hatchling success

As well as the monitoring of nesting numbers at FFS, I was happy to see that studies on the implications of temperature dependent sex determination (TSD) are well underway. The occurrence of TSD in sea turtles has very clear conservation implications. The worst-case scenario is that climate change and/or physical changes to nesting beaches might lead to a rise in incubation temperatures and hence the production single sex hatchling cohorts (in sea turtles, females are produced at warmer temperatures). The ultimate end point of single sex hatchling production is population extinction, although in the shorter term there might be an increase in female nesting numbers due to skewed sex ratios. It is therefore important to record incubation temperatures on nesting beaches and describe the pivotal temperature (where a 50:50 sex ratio is produced) for different populations. These types of work are well underway for the Hawaiian green turtles through collaboration between George Balazs and Thane Wibbels (University of Alabama). Continued monitoring of incubation conditions at FFS should be encouraged, so that trends in incubation conditions can be identified and hence possible management implications can be considered with quantitative data. Ultimately, we might find ourselves in a position (possibly only many decades away) where intervention is required to manipulate incubation conditions so that single sex populations are avoided.

In addition monitoring of hatchling success would be very useful. At the workshop it emerged how currently healthy population (e.g. green turtles nesting at Raine Island, Australia) may have an uncertain future due to increasing mortality within clutches caused by worsening incubation conditions. Certainly there is no reason to suspect invariant conditions for developing eggs at FFS – nesting beaches are often dynamic and can change rapidly. Hence monitoring of hatchling success would be valuable.

Recommendations: ***Maintain monitoring of incubation conditions and develop monitoring of hatchling success as FFS.***

4. Work on the foraging grounds

Statement of work: "An evaluation of the experimental design and data collection methods for the marine habitat research. Are the data being collected in such a way that vital population parameters/rates such as: survival, recruitment, and relative abundance can be estimated?"

Working with sea turtles on the foraging grounds is logistically challenging as turtles are widespread and generally difficult to sample. Hence while there are established mark-recapture techniques for assessing the number of individuals in populations (techniques that are very widely employed, for example, in terrestrial systems), employing these techniques with sea turtles is extremely difficult and hence rarely attempted. However, George Balazs has developed an extensive mark-recapture programme with several selected focal sites throughout the Hawaiian Islands. As with much sea turtle research, the experimental design for this aspect of the programme is driven by logistic constraints. The team have come up with a design of having three focal capture-mark-recapture sites. This is a good system for collecting data to allow population parameters to be assessed. Data collection methods are entirely appropriate, with basic morphometric data being collected as well as marking of turtles with numbered tags. Morphometric data allows growth rates to be estimated while recapture data allows survival rates to be estimated using established statistical procedures.

This impressive field programme has provided measurements of the growth rate for individuals across a range of different sizes, sites and years. The programme has identified site specific growth rates, indicative of different foraging conditions for turtles within the Hawaiian Islands. In addition, a key result is that growth rates have declined during the time-series which suggests density dependent effects are operating and that the population might be approaching its carrying capacity. These growth rates results are therefore complimentary to the monitoring of nesting females on FFS – both sets of results indicate a population well on the way to recovery.

In theory the mark-recapture programme might be able to provide estimates of population size and size-class specific survival, albeit the confidence in these estimates will be confounded by the sampling constraints and in particular by animals moving outside focal sampling sites. However the focus of the review documents is on the growth rates from this mark-recapture programme and certainly these growth rate estimates are robust and insightful. I am impressed with the field programme that has been implemented to collect these data.

From a management perspective it is important that the sampling programme can identify rapid changes (e.g. due to catastrophic events) as well as longer term trends. If extra resources were made available it might be possible to expand the in-water sampling of turtles so the problems of turtle movements could be assessed or additional in-water assessment of turtle numbers (e.g. aerial surveys) might be instigated. However, any catastrophic events in the population would most probably be picked up by the extensive stranding network set in place by George Balazs and his team. They have done a fantastic job on public outreach and education such that stranded turtles are efficiently reported from many sites. The stranding data seems to give fairly reliable index of the population size with the trend in stranding paralleling the increase in nesting numbers. This stranding network, which takes a lot of time and effort to maintain, is clearly a very important component of the overall research programme and it should certainly continue to be supported.

The stranding network provides animals for necropsy and veterinarian examination so that the causes of turtle deaths and live strandings can be quantified (boat strikes, diseases etc.). The stranding network is a very useful component of the marine habitat work. I was very impressed with the work that has been done on the tumours (fibropappilomas) that afflict green turtles in Hawaii. Through collaborations with Thierry Work (USGS, Honolulu Field Station), a series of important publications have documented the occurrence and impact of these tumours. The plight of turtles afflicted with these tumours has received worldwide attention and is heartening that monitoring on the foraging grounds is starting to show a decline in the incidence of this disease as if the population is acquiring a level of immunity.

Coupled with the mark-recapture work and the stranding network, there has been the development of some studies to look at specific aspects of the foraging ecology of green turtles such as depth selection, incidence of basking and diet selection. Again I would highlight the value of collaborations in this work and I was impressed to see how the team are developing programmes involving a range of suitable techniques. Data-loggers are being deployed onto turtles to examine their depth selection and studies on algal food types will start to tie down the energetic gain from foraging on different food stuffs. I am sure the team will be at the vanguard of studies into foraging ecology. For example, within my team feeding sensors are being developed to quantify ingestion rates of turtles, GPS loggers are being deployed to assess movements on a metre-by-metre basis within coastal sites and combined with measurements of the energy density of prey types we will soon be close to informed bioenergetic models of the annual energy budget of individual turtles. Such studies, which I expect will start to come to fruition over the next few years, are closely related to issues such as the carrying capacity of different foraging grounds, age-specific and density dependent growth rates, trajectories of growth rates for juveniles to recruitment into the adult breeding population, and body condition trajectories of adults between nesting seasons.

An additional possibility that might be worth pursuing is to consider measuring growth rates on green turtles over very short intervals. The technology is now available for measuring tiny growth rates. In the 1980s short-term growth rate experiments began to be performed with various shellfish, with growth over periods of a few days being measured with precise lasers. This approach was developed so that the impact of various factors (e.g. temperature, food type, food concentration, pollution levels etc) on growth rates could be explored in short-term experiments. Nowadays, devices for measuring small growth rates (sometimes called IMASENs or IMASUs) involve a Hall sensor measuring the distance to a small magnet (technology that is widely used in industry – e.g. counters, burglar alarms etc) with the output being stored in a robust data logger that can record data on free-living animals. For example, IMASENs have been used to record flipper movements and jaw movements of a fraction of a mm with great precision (see for example ref 5 for a description of this technology and ref 6 for deployments onto turtles). Therefore by mounting a data logger on the carapace it should be possible to record short-term growth rates as well as diving behaviour, water temperature as well as ingestion events. This sort of work might help pin down the reason underlying different growth rates in different sites. Also measuring short-term growth rates might allow "gaps" in the existing data (e.g. absence of growth rates for certain size classes) to be plugged as well as detailed measurements of the growth rate of undiseased turtles versus those with tumours. Work on short-term growth rates would undoubtedly be challenging and I suspect would require at least one dedicated post-doc and several years to accomplish, but I have no doubt that a series of high profile important publications would be produced and the understanding of the green turtle foraging ecology would be vastly improved. Given the importance of measuring growth rates, I would recommend conducting tank trials to show the utility of data-loggers for this purpose.

In short, appropriate experimental design and techniques are being used in the marine habitat work. The programme could benefit from technological developments that are allowing increasingly focussed studies on the free-living ecology of sea turtles. The team in Hawaii are well aware of the need for such studies and should receive the resources to allow their in-water foraging programme to take advantage of developments within this field.

Recommendations: ***Maintain stranding programme. Maintain and expand mark-recapture programme to improve estimates of population size for juveniles and size-structure. Exploit emerging techniques for focussed studies on the foraging ecology of turtles.***

5. Data analysis and the importance of collaboration

Statement of work: An evaluation of the analytical techniques used for trend analyses, somatic growth rates, and stock assessments with emphasis on Bayesian state-space modeling. Where necessary, the reviewers should recommend new or alternative analytical techniques.

The data collected by the programme both at the nesting beaches and on the foraging grounds are strong for assessing trends, growth rates, and stock assessments. There are always some inherent weaknesses with these types of data driven by the difficulties of working with sea turtles in their natural environments. For example, inter-annual variability in nesting numbers makes it difficult to assess nesting number trends; small growth rates make it difficult to obtain growth rate estimates over short time periods; movement of individuals on foraging grounds can compromise mark-recapture studies. I have specified earlier how the research programme might be enhanced to help mitigate some of these inherent problems with sea turtle research. However, it is clearly important that appropriate analytical techniques are use to analyse the existing data. I am impressed that among sea turtle studies around the world, work with Hawaiian green turtles uses some of the most advanced analytical techniques. I am not in qualified position to discuss the specifics of these techniques (a mathematician or statistician is needed here) but I can make the general comment that over the last few years a series of important papers from the Hawaiian green turtle research have been published in the peer-reviewed literature and the analytical techniques used in the programme have been repeated with other sea turtle programmes elsewhere in the world. To me this is testimony to the rigour of the analytical approaches and the impact the work is having. However, although I see quality in the analytical techniques that are being employed and the papers that are emerging, I would recommend that the programme continues to foster collaborations with a range of researchers that can bring different mathematical expertise to the data analysis.

A key message from biological time-series analyses around the world is that different scientists bring along different skills, and areas of interest, which allows the types of analyses to expand. Importantly George Balazs has recognised the importance of such collaborations with, for example, the emergence of a series of important papers in the last few years published with Milani Chaloupka describing, among other things, trends in population size and growth rates. I am sure such collaborations will continue to evolve and new collaborations develop. The plankton time-series example detailed above clearly illustrates how fresh eyes to the data can lead to important and novel insights. Therefore the ongoing and new collaborations George Balazs is developing should be supported and encouraged. Funds spent on such collaborations are generally very well invested and I would fully support more resources being made available to further develop collaborations with external experts.

One important new area to tackle in coming years will be the consideration of inter-annual variability in nesting numbers at FFS. While there has been a clear upward trend in nesting numbers, there is a striking inter-annual variability around this trend. Presumably this variability is driven by non-uniform foraging conditions such that turtles have temporally changing trajectories of increasing body condition between nesting seasons. The end point of these varying trajectories is that sometimes a lot of turtles are “ready” to migrate to the nesting beaches in some years, while in other years there are fewer. Once this inter-annual variability has developed there will also be a degree of autocorrelation in nesting numbers even if foraging conditions then remain stable. This topic has received some theoretical consideration[7], but the underlying factors driving body condition trajectories are unknown. This research question will be a hard nut to crack, but as the time series of nesting number at FFS continues and information on the foraging grounds increases it will become easier to disentangle the various processes that contribute to nesting variability. This question is important to gain a fundamental understanding of the determinants of the nesting number time-series. As elsewhere around the world, assessing the role of climate change in driving biological systems will continue to grow in importance if the extent of climate change increases in line with predictions. People working on the FFS nesting time-series might be able to profit from the fact that Hawaii is the location for one of the most extensive biogeochemical ocean time-series (HOTS- Hawaii Ocean Time Series) which has been one of the key sites in the international Joint Global Ocean Flux Study (JGOFS) which has set out to examine the role of the oceans in global biogeochemical cycles. Measurements made at the HOTS site for more than two decades might prove useful in trying to disentangle variability on nesting numbers, see: http://hahana.soest.hawaii.edu/hot/hot_jgofs.html

One of the things to emerge from the presentations at the workshop was the fact that Hawaii might be quite unusual amongst sea turtle populations in that the entire life-cycle of the green turtles, from juveniles to adults, might be maintained in the Hawaiian Islands rather than some life stages being strongly dependent on distant island or mainland sites. One possibility is that the oceanography of the area limits hatchling dispersal and this could potentially be investigated by oceanographic particle tracking models (e.g. ref 8 where this approach has been applied in the Atlantic). One useful line enquiry is the implementation of such models and I was impressed to see that George Balazs has developed strong collaborative programme with Jeff Polovina and Don Kobayashi along these lines.

Recommendations: ***Maintain existing collaborations and continue to develop new collaborations. They provide excellent value for money !***

6. References

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7. Appendices

Appendices 1-7. Bibliography of manuscripts provided.
Appendix 8. Statement of work