

Editorial: Thoughts on Climate Change and Sex Ratio of Sea Turtles*

N. Mrosovsky¹ & Matthew H. Godfrey²

¹Department of Ecology & Evolutionary Biology, University of Toronto, 25 Harbord St., Toronto, Ontario, M5S 3G5 Canada (E-mail: nicholas.mrosovsky@utoronto.ca);

²North Carolina Wildlife Resources Commission, 1507 Ann St. Beaufort, NC 28516 USA (E-mail: matt.godfrey@ncwildlife.org)

More than two and a half decades ago an editorial in this newsletter warned that global warming might lead to “a massive feminizing bias” in sea turtle populations (Mrosovsky 1984). This concern arose from a combination of C.L. Yntema having established a method of sexing hatchling sea turtles – thought by some at the time to be impossible – with arduous field work by Peter Dutton & Claire Whitmore in Suriname – alas this was before the days of suitable dataloggers. Nevertheless, the data were sufficient to suggest that even a 2 °C increase from current levels could push beach sand temperature in Suriname up to levels at which the overwhelming majority of hatchlings would be females. These early collaborations are described in Yntema & Mrosovsky (1980), Mrosovsky et al. (1984) and Mrosovsky (1984).

Today, 26 years later, it has become almost obligatory for papers on conservation and biology of marine turtles to mention the risk of sex ratio distortion from climate change. But many of these statements are little more than ritual bows of recognition. They seldom recommend specific measures. There is no coherent strategy in the turtle community.

A decision-tree diagram with choice points (Figure 1) may be helpful in appreciating where the gaps lie and their context in an overall plan for boosting the survival prospects of turtles in a warmer world. For example, if jurisdictions currently responsible for turtles would not provide export permits for relocating eggs from warm to cool places, then there is little point in designating and preparing new beaches for renewed experiments on transplanting populations (Godfrey & Pedrono 2002; Lopez-Jurado & Liria Lopez 2007). Considering the many and multifaceted difficulties in research on this topic, it is not surprising that more of Figure 1 cannot be replaced by specific empirical data and agreements. Among the challenges are:

1. Regional: High resolution scales are needed because turtles often nest on small beaches on small islands that may not show up on low resolution maps used in modeling climate, but “people need to know how their local conditions will change, not how the average global temperature will climb” (Schiermeier 2010). Attempts are being made to develop databases on the scale of a few km, with measurements several times a day (Stott & Thorne 2010).

2. Sensitivity to thermal changes: Even 0.1 °C can make a considerable difference to sex ratio when ambient temperatures are close to the pivotal level (Figure 2). Extreme thermal sensitivity demands that extra attention be taken with seemingly minor experimental variables, especially when different nesting populations are compared. Depth of nests in the sand (Kaska et al. 1998), choice of sites for monitoring temperature on a single beach

* Freshwater and terrestrial turtles/tortoises are outside the scope of this article. For related considerations on these species, we highly recommend Mitchell & Janzen (2010).

(Godfrey & Mrosovsky 1999), and the exact way dataloggers are positioned within nests have the potential to influence results.

In laboratory work at constant temperatures, power outages can be devastating. Variables such as substrate type, moisture, and position of eggs within the incubators should also be considered. If the aim is to compare pivotal temperatures from different populations, it is recommended that clutches from each area be incubated *simultaneously* in alternating positions within the incubators. Easier said than done - especially if the two areas are far apart geographically, with different transport requirements. Above all, extreme thermal sensitivity demands that, before and after use, thermometers be calibrated against a high quality standard.

Extreme thermal sensitivity makes one wonder about suggestions (Baker-Gallegos et al. 2009) that temperatures and other physical characteristics of nesting beaches be monitored over a wide region (e.g., the Caribbean). The hope is that this could help determine which sites should be the focus of global warming mitigation – a thermal triage for sites likely to be producing more males. Of course, a large scale project of this kind might uncover useful, even surprising information, but it is not clear how detailed thermal maps of many beaches would be translated into data on sex of hatchlings or insight about the potential for the evolution of sex ratio. Moreover, inter-seasonal differences in beach temperature and sex ratio in hatchlings are not uncommon. To avoid sampling errors monitoring should last for several years; Baker-Gallegos et al. (2009) recommend two or three decades. Who will analyze the masses of data from a region-wide project? And if differences among numerous beaches were small, could one be confident they did not arise from procedural differences? Standardization is not a trivial issue.

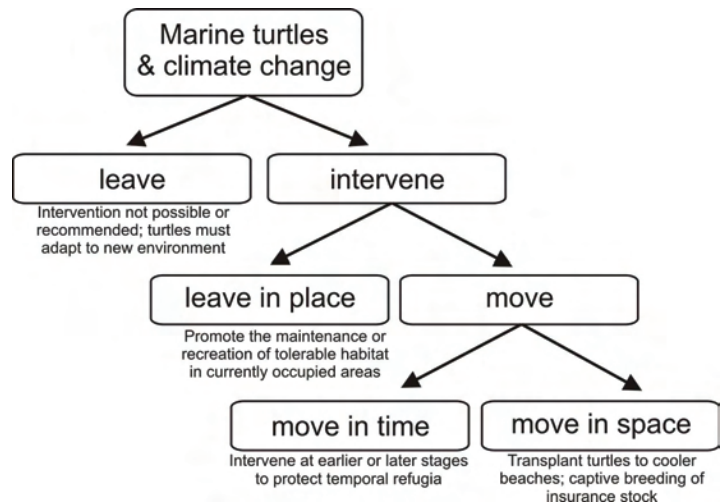


Figure 1. Decision-tree diagram for management of marine turtles and climate change

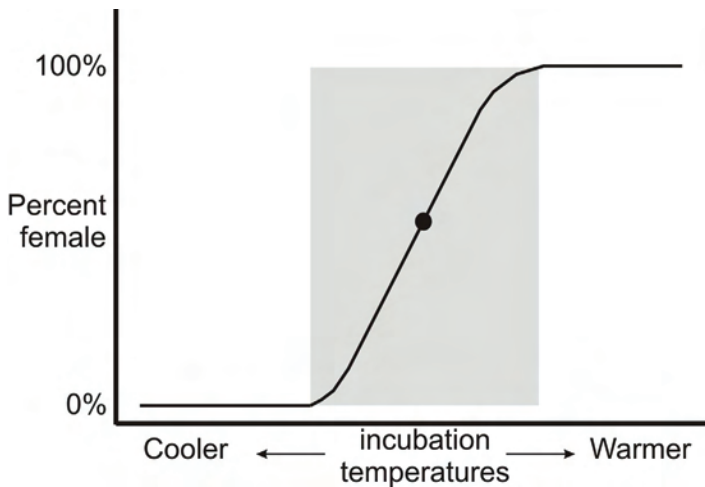


Figure 2. The pivotal temperature (solid point) is the constant temperature that produces 50% of each sex. In this article, the term pivotal temperature is used to include the relationship between temperature and sex ratio from which the 50% of each sex is derived. The difference between temperatures producing 100% males and those producing 100% females is the transitional range of temperatures (TRT), shown by the shaded area, and is often only a few °C. In theory, the TRT can vary without altering the pivotal temperature. In practice, in work so far on marine turtles, the TRT often appears narrow and symmetrical on each side of the pivotal.

3. Sexing: Classifying sex of hatchling sea turtles is troublesome and contentious because at present the most reliable method is histology of the gonads, and that entails sacrificing the animal. Even if one compensates for this by saving an equal or even greater number of other hatchlings, some will wish to maintain their preservationist purity. For a discussion of whether conservationists should be guided more by possible benefits to populations or to individuals, see Loftin (1985).

Gross et al. (1995) have reported that neonate sea turtles can be sexed by hormonal assays of the chorio-allantoic fluid left in the egg after hatching, but others have not confirmed this method (Merchant Larios 1999). Wyneken et al. (2007) have advocated laparoscopy as an alternative to histology for sexing hatchlings. However, this alternative is expensive. Hatchlings must be maintained in captivity for several months, until they are large enough to survive laparoscopy; impacts on fitness are unknown. Sex is derived from a combination of ratings of a number of different features. This probably involves more subjectivity than does histology.

4. Permits: As it is now, one of the biggest obstacles to research and learning about life cycles of turtles and indeed about many species listed - whether justifiably or not - as threatened on IUCN's Red List, is the paperwork required and the time it takes (Bowen & Avise 1994); a permit may be granted only to expire while permission from some other agency is still being processed.

5. Adaptive value of TSD: Despite all the obstacles, we know much more about sex ratio of turtles than we did two decades ago (reviews in Wibbels 2003; Hulin et al. 2008). Two tentative generalizations are emerging. Tentative because there are possible exceptions and some of the investigations, our own included, are deficient, inadequate. Nevertheless, it does seem that the natural

production of hatchlings on most beaches investigated so far, although highly variable, is overall female-biased, sometimes extremely so. The other tentative generalization is that the pivotal temperature appears to be remarkably consistent among different geographical and climatic regions. This leads to the thought that there may not be one natural sex ratio in sea turtle hatchlings. Yet, despite the beginning of an empirical data base, a prized ingredient is missing: understanding. Why make sexual differentiation depend on temperature of the embryo? What is the advantage of this system for marine turtles? We have information without understanding, knowledge without wisdom.

6. Multiple threats to turtles: This article considers only one threat of global warming: sex ratio distortion. In reality there are several climate-related concerns: sea level rise, hurricanes, rainfall, flooding, effects on sources of food, and others (Hamann et al. 2007; Hawkes et al. 2009). Figure 1 needs elaborating to include interactions between thermal and other requirements (Hawkes et al. 2009).

With so much uncertainty, where should one start? Indeed, should one start at all? Is intervention called for at all? The key questions about sex ratio and climate change remain essentially the same as those raised nearly 3 decades ago (Mrosovsky 1984).

Is there enough genetic variation in nest-site selection of beach and of thermal zone within a beach to allow for the evolution, albeit gradual, of preferences for new nesting places? Nest-site infidelity is what is needed! Or instead, is there enough genetic variance in pivotal temperatures and the associated curves of sex ratio as a function of incubation temperature, to support staying put but still allow for the production of enough males on the now warmer beaches? Species with wider transitional ranges of temperature are more likely to adapt to climate change (Hulin et al. 2009).

Questions about variance inherently demand a sizeable number of data points to build up a distribution. Since it might not be known in advance to what new sites a wandering female turtle might stray, a systematic search for nest site infidelity based on nightly beach patrols would have to cover multiple potential nesting sites. A failure to find a tendency in any individuals to nest elsewhere than the natal beach would not rule out its existence because only a small fraction of the population might have this characteristic. Absence of evidence is not evidence of absence.

More satellite tracking could help in revealing where females come ashore for nesting (Tucker 2009, 2010). However, deployment of satellite tags in sufficient numbers could be expensive; ideally one would want to learn if nest-site preferences were maintained from season to season.

There is, however, another approach to assessing whether, from a thermal and sex ratio point of view, a turtle population has a good chance of surviving global warming. This is based on including the timing of laying as part of nest site selection. Perhaps a change of nesting to cooler times of year would be enough.

Numerous animals and plants have advanced the timing of reproduction along with the warming in recent years (Visser & Both 2005). A genetic contribution to various aspects of migration in some avian species is implicated (Pulido & Berthold 2010). These findings encourage studies of phenology in turtles. For loggerhead turtles nesting in Florida, Weishampel et al. (2004) reported that the median date of nesting was significantly earlier in years when nearby sea surface temperatures in May were warmer. Also, the

nesting season shifted 10 days earlier from 1989 to 2003, although a trend for warming of near shore waters over these years was not significant. Similar studies with both loggerhead and green turtles have produced a variety of results (Pike et al. 2006; Pike 2009; Hawkes et al. 2007; Weishampel et al. 2010). It is suspected that longer data sets may be needed to understand the complexities of seasonality in turtles (B. Witherington pers. comm. 16 Mar 2010). At least methods for such studies are available already. Studying the timing of the first nest of a season is straight forward. It can be done at one location. To catch the first nest, patrols must be started well before any nesting actually occurs - not exciting work but simpler than trying to reveal the extent of movements away from natal beaches to any or several unspecified places.

Turning to physiological influences, to discover occasional clutches with high pivotal temperatures could also rival behavioral work in expense: incubators with power back-up, maybe a dedicated facility including a histology bench, technical help, funds for the collection and transport of the eggs. In our experience, to prevent eggs being delayed in customs, turned upside down or otherwise mistreated in transport, it is essential for someone to travel with them. So both physiological and behavioral work on variance, on a sufficient scale to be illuminating, is likely to be costly.

Conclusions and recommendations: Will sea turtles be able to survive current climate change? This question might become academic if there are other fiscal and political priorities. With respect to sex ratio distortion the question cannot be answered without a better idea of the extent and rapidity of the warming to which turtles would have to adapt. Nevertheless, there are some potentially useful immediate actions that should be debated and discussed by the sea turtle community now. Consideration must include costs, logistics, and length of commitment.

Describe male-producing nesting beaches. Effort should be directed at discovering and/or confirming the existence of any such places. However, cautions are in order. It is at best inadequate, at worst misleading, to announce a male-biased hatchling sex ratio on the basis of temperatures of a few nests only, studied over a third of the nesting season only, in one year only, especially if no validation is provided of the method of assigning sex based on temperature as a proxy, and even more so if that proxy method appears to have been elaborated for a different species (e.g., Steckenreuter et al. 2010).

There are sounder ways of learning about sex ratio in natural conditions. These include histology of sub-samples of hatchlings throughout the season combined with monitoring of nesting frequency, or if there were enough information on pivotal temperatures, by converting nest temperatures into sex ratios (see methods review, Mrosovsky et al. 2009). Work along these lines was conducted recently across different loggerhead nesting beaches in the Mediterranean (e.g. Margaritoulis 2005; Zbinden et al. 2007).

Beaches producing strongly male-biased sex ratios might cushion and delay population crashes, allowing more time for other measures to be devised and take effect, but the question of whether, ultimately, there is enough variance in the relationship (Figure 2) between temperature and sexual differentiation to enable evolution of functions appropriate for warmer climates, would remain a formidable challenge. Perhaps the matter could be made more manageable and focused by rewording the question. Rather than ask if at present there is enough variance in the relationships

between sex ratio and temperature to provide the capacity to evolve, one could ask if any present day populations have already adapted to the existing variety of weather at current nesting beaches.

Most sea turtle species have multiple nesting sites, some far apart from one another. For example, loggerheads nest from Virginia, through the Carolinas, Georgia, and Florida, into Cuba and Mexico, and then on down to Bahia, Espirito Santo, and Rio de Janeiro in Brazil (Marcovaldi & Chaloupka 2007). If cooler air temperatures at the extremes of this range are accompanied by cooler sand at turtle nest depth, and if the turtles have adapted to a cooler nest environment by lowering their pivotal temperatures, then similar hatchling sex ratios to those found elsewhere would be expected. If they have not adapted, then these beaches might be predominantly male producing. Either way it could be instructive to focus attention on TSD and sex ratios of these populations at range limits.

For loggerheads nesting along the east coast of the United States, a gradient of pivotal temperatures has not yet been detected, but small sample sizes preclude robust conclusions. An initial step would be to discover whether or not sand at nest depth at the extremes of the breeding range was indeed relatively cool during times of year when nesting occurs. If not, then the problem of explaining a combination of similar pivotal temperatures and similar sex ratios for different beaches disappears.

Similar considerations, but on a smaller spatial scale, arise for hawksbills. This species often nests in among littoral vegetation where it is shadier and cooler, but so far low pivotal temperatures, compared to other species, have not been detected. Values for hawksbills laying at Antigua, northern Brazil, and Mona Island (Puerto Rico) are in the 29-30 °C range, similar to those found in most studies of other marine turtles, and in line with the tentative generalization that this is a conservative characteristic. For hawksbills, thermal profiles of more places where the littoral vegetation remains intact should be obtained before deforestation destroys them all.

For olive ridley turtles from Costa Rica, a pivotal temperature of 31 °C has been reported (Wibbels et al. 1998); this is unusually high for sea turtles, and thus a hint that phylogenetic constraints on pivotal temperatures are not all-powerful. Keeping in mind the extreme sensitivity to methodological variables, confirmation of the 31 °C value is desirable; pivotal values for ridleys from different parts of the world would be welcome.

Among additional possibilities for investigating places with unusual thermal conditions are the low-lying mangrove islands off the west coast of Florida where inundation by ground water renders many eggs not viable. However, those that do survive are likely to have experienced cooler temperatures and so produce relatively more males. When sand temperatures were compared between pairs of adjacent sites that differed in the distance from the water, the sand was cooler in those closer to the water (Foley et al. 2000). The differences (about 1 °C) were modest but appeared enough to have some effect on sex ratio that was estimated from sand temperatures to be 1:1, which contrasts with the strongly female-biased ratio found elsewhere in Florida.

Another intriguing situation beckons from the Galapagos. Cold currents from upwelling of deep waters swirl around this archipelago. If the sand at turtle nest depth is also cool compared to that at other green turtle rookeries it is conceivable that the sex ratio would be different. However, preliminary work for part of the

season for some Galapagos nesting beaches does not point to the sand there being unusually cool (Zarate 2004).

Investigate the potential for manipulating temperatures. Global warming could be more of a challenge for species that are already producing relatively few males. So research should also be directed at low-tech local interventions that could, if necessary, be used to cool eggs: artificial shade, sprinkling with water (LeBlanc & Wibbels 2009), spreading whiter more reflective sand, Styrofoam boxes. Having quantitative specific recommendations available could be helpful if population crashes and crises occurred.

Consider relocation of eggs. Attempts to induce adult turtles to nest on beaches other than those on which they were laid as eggs have fallen out of favor but some success has now been documented for green turtles and Kemp's ridleys (Bell et al. 2006; Shaver 2007; review in Mrosovsky 2007). Transplanting turtles to re-establish colonies on previously used beaches, or augmenting now sparse nesting on other beaches, remains a possibility biologically. Nevertheless, it would take a long time because years must be allowed for maturation. Should more systematic attempts to do this be renewed in advance of further global warming? Most organizations are not capable of making the commitment for such long-term projects.

Study newly forming nesting aggregations. Before the 1980s it was extremely rare for a leatherback to be seen nesting on the eastern coast of the USA (Stewart & Johnson 2006). By 2009 there were >1700 nests/yr in Florida (http://research.myfwc.com/features/category_main.asp?id=1289). Any case of an apparently new nesting area coming into being is of interest in the context of climate change. To what other leatherback population is the new colony most closely related genetically?

Consider an insurance policy. If, after everything tried, turtle populations continue to decline precipitously as a result of climate change, will there be some insurance against the total loss of turtle species? It is known that marine turtle species can breed in captivity; this has been demonstrated at the Cayman Turtle Farm with green turtles (Wood & Wood 1980; Wood 1982; Fosdick & Fosdick 1994) and with Kemp's ridleys (Wood & Wood 1984; Marquez 2007). Improved success rate would be expected to come with more experience.

The moment for collaboration with the Cayman Turtle Farm has probably passed now that this organization is focusing increasingly on commercial and tourist related opportunities, as exemplified by the name change to Boatswain's Beach. In any case the Cayman Islands might not be a good location for maintaining a captive stock after climate change. But some kind of Noah's Ark policy, complemented by storage of DNA and frozen cell lines, should be on the table for serious discussion by the sea turtle community.

Climate change models are in their infancy. Global warming might be much worse than current predictions. Open discussions of possible responses to mitigate effects of climate change are needed sooner, rather than later.

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