

# Pacific leatherback turtles face extinction

Fisheries can help avert the alarming decline in population of these ancient reptiles.

The dwindling numbers of leatherback turtles are signalling a threat to biodiversity in the oceans. A mathematical model based on our assessment of a once-large leatherback population predicts that unsustainable adult mortality, apparently due to human fishing activity, will soon drive this population to extinction.

In 1982 there were 115,000 adult female leatherbacks in the world, but in 1996 there were only 34,500 (ref. 1). However, many accounts of decline were based on anecdotal information and indirect measurement. Individuals could not be reliably identified over a period of many years, and the reproductive effort of individual turtles was seldom determined during a given year. Therefore, although leatherbacks had disappeared from India before 1930<sup>2</sup>, declined to near zero in Sri Lanka by 1994<sup>1,3</sup>, and fallen from thousands to two in Malaysia by 1994<sup>4</sup>, we did not have enough data to predict the fate of other colonies.

Since 1988 we have studied leatherbacks (Fig. 1) at Playa Grande, Costa Rica, the fourth largest nesting colony in the world<sup>1</sup>. Since 1993 we have permanently identified female turtles by injecting them with passive integrated transponder tags. We encountered more than 95% of nesting turtles each night<sup>5</sup>. This enabled us to determine how many nests a turtle laid, how many individual turtles nested in a given year, and how many turtles returned to nest in later years.

In 1988–89 (July–June), 1,367 leatherbacks nested on Playa Grande. By 1994–95, 506 turtles nested there<sup>5</sup>; in 1998–99, there were only 117 (Fig. 2a). In 1996–97, 1997–98 and 1998–99, only 26.7, 27.1 and 20.6%, respectively, of turtles were remigrants. Only 11.9% of turtles tagged in 1993–94 and 19.0% tagged in 1994–95 returned to nest in the next 5 years, with the peak return being in the third year. This population was in the midst of a collapse. In contrast, at St Croix in the Caribbean, remigrants averaged 48.5% from 1989 through to 1995 and the population grew<sup>6</sup>.

How could the Playa Grande turtles have vanished? They could have died; they could still be in the ocean and nesting less frequently; or they could have nested elsewhere. The second explanation is possible but unlikely, as we have determined the mean re-nesting interval to be 3.7 years. Of the 15.4% of leatherbacks that returned to nest in subsequent seasons, 0.5% returned after 1 year, 20.3% returned after 2 years, 46.5% returned after 3 years, 15.5% returned after 4 years, and 17.2% returned



**Figure 1** Leatherback turtle (*Dermochelys coriacea*): once abundant in the Pacific, populations have plummeted as a result of capture by fisheries.

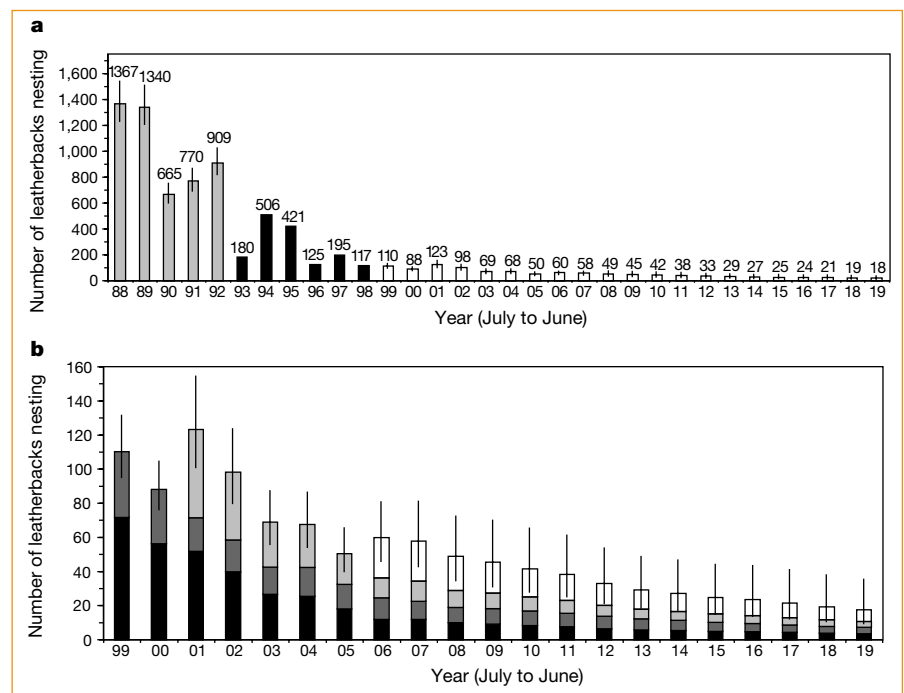
after 5 years. Other studies indicate that over 91% of leatherbacks have remigration intervals of 5 years or less<sup>7,8</sup>. The third explanation is also unlikely because aerial surveys from Mexico to South America have not revealed any other major nesting beaches (R.D.R. and J.R.S., and P. Dutton, unpublished results) and no new major nesting beaches have been reported since 1982<sup>1</sup>.

Mortality therefore seems to be the best explanation for the population decline.

From 1993–94 to 1998–99, the annual mortality for Playa Grande leatherbacks that nested in 1993–94 was 34.6%, and for those that nested in 1994–95 it was 34.0%. This is much higher than previously estimated<sup>1</sup> and could be responsible for the rapid decline of this population.

Our model predicts that, without protective measures, the population will fall to less than 50 nesting females by 2003–04 (see Box and Fig. 2b). If beach and hatchery protection is continued, the fall to under 50 animals could be postponed by 5 years. Recovery of this population cannot be achieved by increasing hatchling production alone — even with total protection of beaches, any population suffering these rates of adult mortality cannot survive for more than a few years.

The situation at Playa Grande is reflected at many other Pacific nesting beaches. The large Mexican nesting colony declined exponentially from 70,000 in 1982<sup>1</sup> to under 1,000 by 1994<sup>9</sup> and to fewer than 250 in 1998–99 (S. Eckert, unpublished results). The annual mortality between 1984 and 1996 was 22.7% (ref. 9).



**Figure 2** Number of leatherback turtles nesting on Playa Grande, Costa Rica, from 1988–89 to 2019–20. **a**, Stippled bars, numbers based on nest counts and estimated clutch frequency (ECF); black bars, numbers based on individual tagging of leatherbacks with passive integrated transponders. Predictions (white bars) are from the mathematical model (see Box, overleaf). For 1988–92, error bars represent an ECF of 6.0 to 7.5. For 1999–2019, error bars represent effect of maximum and minimum offspring-to-adult (*O:A*) ratio. **b**, Predictions of the number of leatherbacks likely to nest on Playa Grande are based on the mathematical model, the number of leatherbacks nesting in the past, and the effect of protecting the beach. Black portions of bars represent new turtles; dark grey, remigrants; light grey, new leatherbacks resulting from beach protection since 1993–94; and white, new leatherbacks resulting from a hatchery started in 1998–99. Error bars represent effect of maximum and minimum *O:A* ratio.

## A model of the leatherback population on Playa Grande

The model is based on data from previous years and predicts the number of immigrants using the equation

$$R = \sum_{n=1}^{n=5} (r_n \times X_{y-n})$$

where  $R$  is the number of turtles returning in year  $y$  from previous years,  $y$  is the year of prediction,  $n$  is the number of years before  $y$ ,  $r_n$  is the decimal fraction of turtles from year  $(y-n)$  that return in year  $y$ , and  $X$  is the number of turtles nesting in a previous year. The model predicts the number of new turtles by comparing the number of recruits nesting in a given year with the number of turtles that nested 6, 7, 8, 9 and 10 years previously, assuming

that new turtles were adult offspring of turtles nesting 6 to 10 years earlier<sup>11</sup>. We calculated this offspring-to-adult ( $O:A$ ) ratio across the range of years for which we had data, and determined the mean  $O:A$  by using the equation

$$O:A = \bar{X}_{m=10}^{m=6} (N_y / O_{y-n})$$

where  $\bar{X}$  is the mean ratio for year  $y$ ,  $O$  is the number of turtles nesting in the previous year,  $m$  is the age at sexual maturity,  $N$  is the number of new turtles, and  $y$  is a given year. We computed the overall mean  $O:A$  ratio for different ages of maturity in order to apply a single  $O:A$  ratio for a predicted year. Mean,

maximum and minimum  $O:A$  ratios were 0.093, 0.120 and 0.073. Model predictions for the total number of turtles in 1997–98 and 1998–99 were within 18% of the actual number of turtles counted in those years. The model includes a feedback function to incorporate predicted data in calculations of turtle numbers until the year 2020. We did not have historical data to calculate the  $O:A$  ratio for age at sexual maturity of more than 10 years. We assumed that beach protection doubles turtle recruitment and that establishing hatcheries quadruples it.

Conservative estimates are that longline and gill-net fisheries killed at least 1,500 female leatherbacks per year in the Pacific during the 1990s<sup>1,10</sup>. These included Asian trawl, longline and drift-net, Central and South American longline and gill-net, and Hawaiian longline fisheries. With a population of about 6,500 adult females<sup>1</sup>, this corresponds to a 23% annual mortality, or 33% if most leatherbacks captured came from the East Pacific population of 4,600 animals<sup>1</sup>. Most of the mortality at Playa Grande was probably caused by fisheries. Leatherbacks normally live at least 30 years and reach maturity at 5–14 years<sup>11</sup>. A long-lived species like this cannot withstand such high rates of anthropogenic mortality<sup>1,12</sup>.

From our tagging data and from aerial surveys, we calculate that there are now 687 adult females and 518 subadults in the Central American population; we estimate that the Mexican population stands at 1,000 adult and 750 subadults. The East Pacific leatherback population thus contains about 1,690 adult females, down from 4,638 in 1995<sup>1</sup>. The total adult and subadult population is about 2,955 females — compared with over 91,000 adults in 1980<sup>1</sup>. We conclude that leatherbacks are on the verge of extinction in the Pacific.

If these turtles are to be saved, immediate action is needed to minimize mortality through fishing and to maximize hatchling production. Assuming leatherbacks can withstand a 1% annual mortality inflicted by humans<sup>1</sup>, the East Pacific population can tolerate the annual loss of 17 adult females and 13 subadult females per year. In 1995 there were about 1,800 females in the Western Pacific<sup>1</sup>, so anthropogenic mortality in that population from all causes should not exceed 18 adult females per year. We believe that fishing practices<sup>13</sup> in the Pacific must be changed to save marine biodiversity.

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### Palaeontology

## Fossil record of mass moth migration

The fossil record of moths and butterflies is extremely poor in comparison with other winged-insect groups, with only an estimated 600–700 specimens of fossil Lepidoptera being known<sup>1</sup>. Here I report the discovery of huge numbers of lepidopteran fossils (about 1,700 specimens) in marine, diatomous sediments of the Fur Formation from the lowermost Tertiary of Denmark (55 million years old). The abundance of the most common species indicates that mass migrations occurred over the Palaeogene North Sea, so the scant fossil record of Lepidoptera reflects poor preservation and not a paucity of lepidopteran species or individuals during the Tertiary.

The material consists of complete individuals, wingless bodies and isolated wings from at least seven species. More than 1,000 specimens belong to a species with a body length of about 14 mm. The males of this species have a bundle of wing-coupling bristles called a 'composite frenulum', revealing them to be members of the Heteroneura, the group that comprises the majority of lepidopterans.

Individuals of this species are often found embedded closely together in the sediment: one slab, with a diameter of about 150 mm, contained a group of 14 specimens. Given that these were deposited over an offshore area of the Palaeogene North Sea, the high abundance and density of individuals indicates that this species undertook mass migrations. The species'

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abundance in different horizons of the marine Fur Formation lends further weight to this idea, and shows that their flights were not a singular or local phenomenon. The great abundance of lepidopteran fossils in the Fur Formation also indicates that the rareness of fossil Lepidoptera in terrestrial deposits is mainly due to taphonomic processes<sup>2,3</sup>, and that, just as today, they were a dominant insect group in the Palaeogene terrestrial ecosystem.

Several extant species of butterflies and moths migrate across the North Sea<sup>4–6</sup>. The number of Lepidoptera, as well as other insects, caught 30 km offshore over the North Sea increases when winds are calm and temperatures over land are high<sup>5</sup>: the fossil Heteroneura specimens probably embarked on their migratory flights during similar summer conditions.

The insects found in the Fur Formation came from the former southwestern Scandinavian coast, about 50–100 km from the depositional area, where they lived in a paratropical woodland with stagnant and flowing waters<sup>7</sup>. The insect fauna from the main part of the Fur Formation remains constant through a sediment column of about 30 m. There is no evidence for major climatic or environmental changes, and I believe that the flight of the Lepidoptera and other insects was seasonal.

The otherwise common Heteroneura species is missing from the basal Ølst Formation. Instead, its laminated clay and shale deposits are dominated by poorly flying insects such as giant ants<sup>8</sup>, damselflies and crickets<sup>9</sup>. These indicate inshore conditions, whereas the Lepidoptera, and other insects capable of long-distance flight, found in the overlying sediments of the Fur