Summer distribution and abundance of the giant devil ray (*Mobula mobular*) in the Adriatic Sea: Baseline data for an iterative management framework

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**Summary:** The giant devil ray (*Mobula mobular*) is a poorly understood protected endemic species of the eastern Atlantic-Mediterranean region. However, to date there are no range-wide management actions in place. This paper provides the first overview of the summer distribution and abundance of this species and other Myliobatiformes within the Adriatic Sea based on an aerial survey. Although the survey’s primary targets were cetaceans and sea turtles, the study showed that it was possible to use the survey to monitor other species. Abundance estimates are derived using conventional distance sampling analysis. Giant devil rays were observed mainly in the central-southern Adriatic (88% of total sightings). A total of 1595 giant devil rays were estimated in the central-southern Adriatic Sea (coefficient of variation(CV)=25%, uncorrected estimate for perception and availability bias). When corrected for availability bias the number of specimens was estimated at 3255 (CV=56%). Population growth rate was estimated using life history traits and a sensitivity analysis was conducted to evaluate the benefit of improving biological knowledge on this data-poor species. A power analysis showed that a long-term commitment to an aerial survey would be necessary to monitor population trends. Conservation implications and future work, including how the study could be used to conduct an ecological risk assessment are discussed.

**Keywords:** aerial survey; conservation; conventional distance sampling; ecological risk assessment; management; Myliobatiformes; sensitivity; power analysis.

**Distribución estival y abundancia de la gran manta raya (*Mobula mobular*) en el mar Adriático: datos de base para un marco de gestión iterativo**

**Resumen:** La manta raya gigante (*Mobula mobular*) es una especie endémica protegida poco conocida de la región del Atlántico oriental-Mediterráneo. Sin embargo hasta la fecha no hay acciones de gestión que cubran todo su rango. Este artículo proporciona la primera visión de conjunto de la distribución y abundancia estival de esta especie y otras Myliobatiformes en el mar Adriático basada en un censo aéreo. Aunque los objetivos principales del censo eran cetáceos y tortugas marinas, el estudio mostró que era posible usar el censo para monitorear otras especies. Las estimas de abundancia se derivaron utilizando análisis convencional de muestreos de distancias. Las manta rayas gigantes se observaron principalmente en el Adriático central y sur (88% de los avistamientos totales). Se estimaron un total de 1595 mantas rayas gigantes en el mar Adriático central-sur (CV=25%, estima no corregida para los sesgos de percepción y de disponibilidad). Cuando se corrigió para el sesgo de disponibilidad el número de especímenes se estimó en 3255 (CV=56%). La tasa de crecimiento de la población se estimó usando aspectos de la historia natural y se realizó un análisis de sensibilidad para evaluar el beneficio de mejorar el conocimiento biológico de esta especie de la que hay tan pocos datos. Un análisis de potencia mostró que sería necesario un compromiso a largo plazo para realizar censos aéreos para monitorear las tendencias de la población. Se discuten las implicaciones para la conservación y trabajo futuro, incluyendo cómo se podría utilizar este estudio para llevar a cabo una evaluación ecológica de riesgo.

**Palabras clave:** censo aéreo; conservación; muestreo convencional de distancias; evaluación ecológica de riesgo; gestión; Myliobatiformes; sensibilidad; análisis de potencia.


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INTRODUCTION

The conservation status of a species or population can be defined in several ways. For example, the IUCN Red List of Threatened Species classifies species into categories (ranging from “Data Deficient” to “Critically Endangered”; see http://www.iucnredlist.org/) using criteria such as rate of decline, population size and distribution. These categories require knowledge of the abundance, population structure, ecology and life history parameters, as well as anthropogenic or other factors that may threaten the population. Acquiring this knowledge for elasmobranchs is particularly difficult, resulting in a near absence of the data that would be required to undertake full population assessments (Dulvy et al. 2008). Although there are some regional, temporal and geographical restrictions for directed elasmobranch fisheries (e.g. the European Council Regulation (EU) no. 57/2011, the UN ban on large pelagic driftnets in 1992, and the ban on finning by several regional fishery management organizations such as GFCM and ICCAT), many populations are still subject to unsustainable levels of exploitation (e.g. Dulvy et al. 2008, Ferretti et al. 2010).

While the strengths and weaknesses of generic conservation systems, such as that of the IUCN, are open to debate, many status classifications lack sufficient quantitative data to inform actual management and conservation actions. For example, assessments are often at the species rather than the population level, which is inappropriate for developing mitigating actions and evaluating the success of management. Moreover, for poorly understood species, classifications often rely on inferred and qualitative evaluations (see Camhi et al. 2009), which can lead to inconsistencies among and within taxa. Such inconsistencies make it difficult to compare population status within species, for instance using fisheries management reference points with the IUCN criteria (Rice and Legace 2007).

One approach to move towards quantitative assessments with limited data is the use of ecological risk assessments (ERAs) (see Cortés et al. 2010, Arrizabalaga et al. 2011, Hobday et al. 2011) to identify populations at risk and fisheries of concern. ERAs combine biological productivity analysis with susceptibility analysis to assess the likelihood of a population being impacted by threats such as direct or incidental capture.

The giant devil ray (Mobula mobular) is included in Appendix II of the Bern Convention (1982) and in Annex II of the “Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean” (1996) of the Barcelona Convention (1976). These listings provide a framework for the development of national protection measures and for the creation of ad hoc international management schemes. While many States have fulfilled their formal legal commitments in respect of the protection of the giant devil ray (Notarbartolo di Sciara et al. 2006), to date there are no national or international management measures or monitoring programmes in place. For example, there are no fishing prohibitions on Mobula mobular and the species is not included in the Data Collection Framework (Council Regulation (EC) 199/2008); this is in direct contrast to the situation for the closely-related Manta birostris (see Council Regulation (EC) 692/2012 and Council Regulation (EC) 39/2013).

Information on the biology of the giant devil ray is scarce (Couturier et al. 2012). The limited data have largely been obtained from opportunistic measurements of a few specimens caught at various locations in the last century (e.g. Couturier et al. 2012, Holcer et al. 2013). By analogy, the giant devil ray is assumed to be a typical K-selected species with a long reproductive cycle and low fecundity.

The sparse information on its distribution is again based largely on opportunistic observations of varying reliability (Notarbartolo di Sciara et al. 2006, Couturier et al. 2012, Holcer et al. 2013). It is considered to be endemic to the eastern Atlantic and Mediterranean and its extension into Atlantic waters has never been confirmed (Notarbartolo di Sciara et al. 2006). Most sighting reports are for deep pelagic waters, but there are also occasional records from the shallow waters of the northern Adriatic Sea, the Gulf of Gabes and the southwestern coastal part of Sardinia (Bradaï and Cappe 2001, Storai et al. 2011, Holcer et al. 2013).

While the giant devil ray is not considered to have been subjected to a directed fishery, ‘incidental’ catches in the otherwise highly selective Sicilian swordfish harpoon fishery were reported until the late 1990s (Bauchot 1987, Celona 2004); despite the absence of abundance data, the level of exploitation was considered ‘low’ by Bauchot (1987). It should be noted that a recent mass-stranding of about 500 specimens along the coast of the Gaza Strip (Palestine) appeared to be the result of a recently developed unregulated fishery taking advantage of winter aggregations (Couturier et al. 2013).

With respect to incidental catches, there have been numerous reports for purse-seines, long-lines, trawl nets, mid-water/pelagic trawls and traditional tuna traps in addition to IUU (illegal, unregulated and unreported) driftnet fisheries (e.g. Marano et al. 1983, Akyol et al. 2005, Holcer et al. 2013). Bycatch from large pelagic driftnet fisheries was reported until two decades ago (Di Natale et al. 1995, Di Natale 1998).

The IUCN Red list classification for the giant devil ray is ‘Endangered’. This was based mainly on ‘expert judgement’ due to the scarcity of data; it took into account a combination of factors including limited range, inferred low densities and presumed unsustainable interactions with IUU fisheries (Notarbartolo di Sciara et al. 2006).

Expert judgement evaluations should only be a warning sign and a prelude to obtaining the necessary data to undertake a quantitative assessment of the effect of anthropogenic mortality and the need for management measures. As a minimum, this requires estimates...
of abundance (and/or series of relative abundance values), productivity and the level of human-induced mortality.

There are no well-developed methods to estimate the abundance of *Mobula*. Aerial surveys using distance sampling techniques have been used for some time to estimate the abundance of a variety of air-breathing marine species, including marine mammals, sea birds and sea turtles (e.g. see review in Buckland et al. 2004). More recently, they have been applied to certain fish species that spend time close to the sea surface, including tuna and elasmobranchs (e.g. Cliff et al. 2007, Rowat et al. 2009, Bonhommeau et al. 2010). The giant devil ray spends up to half of its time near the surface (Canese et al. 2011) and was thus considered a suitable candidate for aerial surveys, especially in waters with high clarity, such as the Adriatic Sea.

The Adriatic Sea is a semi-enclosed basin of 133000 km² in area characterized by three biogeographic regions (Bianchi 2007):
- the shallow northern continental waters (less than 100 m in depth), strongly influenced by the Po river plumes, with lower salinity, lower water temperature and high productivity;
- the central Adriatic characterized by bathymetries ranging between 100 and 270 m in depth, and influenced by the inflow of Levantine Intermediate Water (LIW); and
- the deep pelagic southern Adriatic, with steep slopes and water depths up to 1200 m, with warmer waters and higher salinity.

The three sub-regions also have noticeable differences in sea current gyres (Cushman-Rosin et al. 2001, Bianchi 2007). While the northern and central sub-regions represent about half of the sea surface of the entire Adriatic Sea, they encompass only 20% of its volume (Cushman-Rosin et al. 2001). These sub-region characteristics affect the distribution of megafauna and their prey. Holcer et al. (2013) suggested that seasonal observations in the central-south Adriatic coincided with the distribution of potential prey (small pelagic fish and macrozooplankton). Giant devil ray distribution within the Adriatic was thought to be similar to that of other pelagic species, including cetaceans [e.g. the Cuvier’s beaked (Holcer et al. 2007) and sperm whales (Bearzi et al. 2011)], cheloniids [e.g. the leatherback turtle (Lazar et al. 2008)] and other species with an obligate epipelagic phase in oceanic ecosystems, such as green turtles (Lazar et al. 2004, 2010) and loggerhead turtles (Casale et al. 2007).

This paper provides the first overview of the summer distribution and abundance of the giant devil ray and other Myliobatiformes in the Adriatic Sea. Based on systematic aerial survey data, it proposes an iterative framework for the development of a reliable assessment of the conservation status of the giant devil ray, the determination of appropriate monitoring options and the development and evaluation of any necessary management measures. It is intended to stimulate future targeted work to assess the status of the species and any conservation and management needs.

**MATERIALS AND METHODS**

**Distribution and abundance**

Data were collected during a survey for which the primary target species were cetaceans and sea turtles. Given the ecological characteristics of the giant devil ray, two strata were chosen: (1) the entire Adriatic Sea (133000 km²); and (2) the “central and southern Adriatic”, i.e. the pelagic portion of the Adriatic Sea (about 88400 km²). Both strata were covered by 20 km-spaced parallel transects with a random start point (Fig. 1) providing equal coverage probability using the Distance 6.0 software (Buckland et al.
The survey took place between 31 July and 16 August 2010 when weather conditions were expected to most likely allow coverage of the predetermined tracklines under acceptable conditions for the target species (i.e. sea states ≤3 and good visibility). A twin engine high-wing aircraft (Partenavia P-68) equipped with two bubble windows was used as the research platform. The observer team consisted of three researchers: two searching for animals through opposite lateral bubble windows and a third recording data onto a semi-automated logging system. Based on experience from surveys elsewhere, the plane flew at an altitude of approximately 200 m (650 ft) with a ground speed of about 185 km/h (100 knots)—precise height and speed was obtained from the GPS records. Only ‘on-effort’ encounters (searching along the predetermined track-lines under acceptable conditions) were used for the final abundance estimation. The distance between transects (20 km), survey speed and the average distance covered daily by giant devil rays (2.5-3.7 km/day, Canese et al. 2011) minimize the risk of double counting animals/groups.

Data recorded, in addition to the GPS data, were (1) time of sighting when abeam; (2) species identification (discussed below); (3) school size; (4) declination angles measured using Suunto PM-5/360PC inclinometers on the observed animals when abeam (to allow calculation of perpendicular distance of the sighting from the track-line); (5) environmental information (including sea state, turbidity, cloud cover, etc.); (5) effort (e.g. whether plane is ‘on-effort’, i.e. circling to confirm data, or ‘off-effort’, i.e. transiting or in unacceptable conditions) and positional/time data; and (6) approximate estimated disc width (DW) category (“<0.5 m”, “0.5-1 m”, “2-3 m” and “>3 m”) using average lengths of sea turtles, striped dolphins and bottlenose dolphins as a reference.

Conventional distance sampling (CDS) analysis was applied and data were analysed using the Distance 6.0 software. In summary, density was estimated from:

$$
\hat{D} = \frac{\hat{n}s}{2\hat{d}L}
$$

where \( n \) is the number encounters on-effort; \( s \), the school size; \( L \), the length of transect; and \( w \), the effective strip half width.

The effective strip width was estimated by fitting a detection function to the distribution of perpendicular distances of sightings from the track-line. Since the reliability of the detection function analysis is dependent upon sample size, we chose to use all available sighting data for Myliobatiformes. Myliobatiformes other than \( M. \) mobular are somewhat smaller and more difficult to detect and their inclusion will not introduce any major bias into the detection function and hence \( w \). The best model fit was chosen using Akaikké’s Information Criterion (AIC), as proposed in Buckland et al. (2004). Total uncorrected abundance (\( \hat{N} \)) was then calculated from the density estimate and the surface of surveyed area.

Total abundance corrected (\( \hat{N} \)) for availability bias (\( \hat{a} \)) and its coefficient of variation

$$
CV(\hat{N}) = \frac{\hat{N}}{\hat{a}}
$$

were calculated as follows: \( \hat{N} = \frac{\hat{N}}{\hat{a}} \) and

$$
CV(\hat{N}) = \sqrt{CV(\hat{N})^2 + CV(\hat{a})^2}.
$$

Species identification

Whenever possible, Myliobatiformes were identified to species. In the Adriatic, adult giant devil rays (DW=2-4 m) are easily identifiable from the air at 200 m in sea state ≤3 (Fig. 2). In addition to the dark stripe on the head and the two obvious cephalic fins extending beyond its head, this species is characterized by a white lateral ventral colouration apparent when it is filter feeding. When observed dorsally, it appears to be a bluish black to brown colour, with a distinctive darker and lighter pattern between the eyes.

Smaller animals (DW≤2 m) may include young giant devil rays, bull rays (\( Pteromyotylaevus bovinus \)), common eagle rays (\( Myliobatis aquila \)) or the dasyatid pelagic sting ray (\( Pteroplatytygon violacea \)), which are also present in the Adriatic Sea (Fortuna et al. 2010). The bull and common eagle rays, although generally similar in shape to the giant devil ray, are smaller and lack cephalic fins (adult DW 100-170 cm and 40-80 cm, respectively; Jardas et al. 2004, Dulčić et al. 2008). The sting ray is also smaller (80 cm maximum) and has a more discoid shape (Bauchot 1987, Mollet 2002).

Abundance estimates are presented for (1) adult giant devil rays in central-southern Adriatic; and (2) all Myliobatiformes combined, in the entire Adriatic Sea.

Bias correction

The CDS assumes that all animals on the track-line are seen (commonly stated as \( g(0)=1 \)). This is rarely the case in any survey and certainly not the case for animals that do not spend all their time at the surface. There are two primary categories of bias affecting \( g(0) \):

$$
\hat{D} = \frac{\hat{n}s}{2\hat{d}L}
$$
(1) availability bias, where the diving behaviour of the animal renders it unavailable to be seen by the observers; and (2) perception bias caused by observers missing animals that in principle are available to be seen (i.e. they are at the surface as the plane passes over). However, if appropriate data are available these biases can be accounted for and thus an unbiased estimate of absolute abundance can be obtained. It should be noted that if a time series of relative abundance estimates is required (e.g. to estimate trends), then the g(0) issue can be ignored if it can be assumed that it does not change over time.

Availability bias was corrected using time depth recorder data from Canese et al. (2011), who tagged three animals within the Tyrrenian Sea and Sicily Channel between June and October 2007. These animals spent approximately 49% (SD = 0.25) of their time between 0 and 10 m depth. In the Adriatic Sea in summer, the limpidity of the northern offshore Italian waters normally ranges between 2 and 10 m (Casellato et al. 2005, Anonymous 2006). On the Croatian side it increases to 21 m during the summer, the limpidity of the northern offshore Italian waters normally ranges between 2 and 10 m (Casellato et al. 2005, Anonymous 2006). On the Croatian side it normally ranges from 11.7 to 17.5 m in summer 2010 (IOR 2011). These water characteristics allow for the potential sighting of animals below but near the surface. As an initial correction for the availability bias, 0.49 (SD = 0.25) was applied. While the availability bias correction appreciably increases the point estimate, it also substantially increases the CV.

Perception bias can be corrected by using independent observer approaches (e.g. Buckland et al. 2004). However, the limitations of the sighting platform prevented collection of independent observer data. Not correcting for this bias will result in an underestimate of true abundance, to an unknown degree.

### Population growth rate analysis

The sparse information on the biology of the giant devil ray is summarized in Table 1. Disc width maximum size and average DW length at birth were 520 cm and 152 cm, respectively. Length at maturity is unknown as is frequency of reproduction (a single pup is believed to be the norm). As for many fish species, natural mortality (M) is unknown.

As an initial step towards developing a more quantitative assessment approach, growth was assumed to follow the von Bertalanffy (1938) growth curve:

\[
L_t = L_\infty \left(1 - \exp\left(-\frac{t}{t_0}\right)\right)
\]

where \(k\) is the growth rate, \(L_\infty\) is the asymptotic length and \(t_0\) is a parameter of the von Bertalanffy growth formula, which represents the time at which the size is equal to 0. We therefore used \(L_0\), which can be derived from \(t_0\), i.e.

\[
t_0 = \log\left(\frac{1 - \frac{L_0}{L_\infty}}{k}\right)
\]

In the following analyses all lengths and length-based parameters (e.g. \(L_a\)) were based on disc width (DW). Empirical studies have shown that life history parameters, such as \(L_\infty, k, M\) and natural mortality, are correlated and can be used to obtain estimates for data-poor stocks (e.g. Roff, 1984, Jensen 1996, Reynolds et al. 2001). Therefore, due to the lack of data on life history parameters for \(M.\) mobular, length-based parameters were derived by fitting linear regressions to data from related species and families. \(L_a\) was derived from maximum size (Fig. 3A) and \(k\) from \(L_a\) (Fig. 3C) using data on the families Myliobatidae and Rajidae in FishBase (Froese and Pauly 2012) and the genus from Couturier et al. (2012). These relationships (see linear regressions fitted in Figures 3a, b and c) provide estimates for \(L_a\), length at maturity and \(k\) of 880 cm, 320 cm and k = 0.09 per year, respectively. Owing to the large size of \(M.\) mobula, in some cases this required extrapolation, but the extrapolations did not result in excessively large confidence limits and so were not rejected (Gislason 2010). Life history param-

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**Table 1.** – Life history parameters and ecological aspects of the giant devil ray (*Mobula mobular*). * These are actual measurements: not estimates or rough measures/estimates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size</th>
<th>Sex</th>
<th>n</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embryo disc width, cm*</td>
<td>61</td>
<td>-</td>
<td>1</td>
<td>Capapat and Zaouali 1976 as cited in Notarbartolo di Sciara 1987</td>
</tr>
<tr>
<td>Juvenile disc width, cm*</td>
<td>165</td>
<td>-</td>
<td>1</td>
<td>Bruni 2006</td>
</tr>
<tr>
<td></td>
<td>147</td>
<td>M</td>
<td>1</td>
<td>Notarbartolo di Sciara 1987</td>
</tr>
<tr>
<td></td>
<td>166</td>
<td>M</td>
<td>1</td>
<td>Notarbartolo di Sciara and Serena 1988</td>
</tr>
<tr>
<td></td>
<td>131</td>
<td>M</td>
<td>1</td>
<td>Zaccaroni et al. 2007</td>
</tr>
<tr>
<td>Adult disc width, cm*</td>
<td>230</td>
<td>-</td>
<td>1</td>
<td>Zaccaroni et al. 2007</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>F</td>
<td>1</td>
<td>Capapat and Zaouali 1976 as cited in Bradai and Capapat 2001</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>M</td>
<td>1</td>
<td>Capapat et al. 1990 as cited in Bradai and Capapat 2001</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>M</td>
<td>1</td>
<td>Bradai and Capapat 2001</td>
</tr>
<tr>
<td></td>
<td>209</td>
<td>F</td>
<td>1</td>
<td>Bradai and Capapat 2001</td>
</tr>
<tr>
<td></td>
<td>340</td>
<td>F</td>
<td>1</td>
<td>Notarbartolo di Sciara and Serena 1988</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>-</td>
<td>1</td>
<td>Pellegrin 1901 as cited in Notarbartolo di Sciara 1987</td>
</tr>
<tr>
<td>Mean adult disc width, cm</td>
<td>320.5</td>
<td>Both</td>
<td>8</td>
<td>Mean of the previous 8 historical records.</td>
</tr>
<tr>
<td></td>
<td>264.8</td>
<td>Both</td>
<td>6</td>
<td>Mean of the previous 8 historical records, except 1901 and 1928 accounts.</td>
</tr>
<tr>
<td>Length at birth, cm</td>
<td>152.3</td>
<td>Both</td>
<td>4</td>
<td>Mean of 4 records on juvenile DW (see above)</td>
</tr>
<tr>
<td>Weight at birth, kg*</td>
<td>35</td>
<td>M</td>
<td>1</td>
<td>Notarbartolo di Sciara and Serena 1988</td>
</tr>
<tr>
<td>Maximum length (L∞), cm*</td>
<td>520</td>
<td>-</td>
<td>1</td>
<td>Pellegrin 1901 as cited in Notarbartolo di Sciara 1987</td>
</tr>
<tr>
<td>Reproductive strategy (mobulids)</td>
<td>Aplacental viviparous</td>
<td></td>
<td></td>
<td>Notarbartolo di Sciara et al. 2006</td>
</tr>
<tr>
<td>Average litter size</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>Notarbartolo di Sciara et al. 2006</td>
</tr>
<tr>
<td>Pregnancy duration</td>
<td>Unknown</td>
<td>Notarbartolo di Sciara et al. 2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fecundity rate</td>
<td>Unknown</td>
<td>Notarbartolo di Sciara et al. 2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length at maturity (L∞), cm</td>
<td>290</td>
<td>1</td>
<td>Notarbartolo di Sciara et al. 2006</td>
<td></td>
</tr>
</tbody>
</table>

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eters also allow an approximate rate of natural mortality to be derived from life history ‘invariants’ (e.g. Beverton and Holt 1959, Jensen 1996), i.e.

\[ M = 1.5k \]

where \( k \) is the growth coefficient from the von Bertalanffy growth equation. Methods for estimating approximate size-dependent natural mortality vectors are also available (e.g. Peterson and Wroblewski 1984, Lorenzen 2000). However, an increase in \( M_0 \) and a reduction in fecundity have the same effect, i.e. they reduce recruitment, so to simplify this already exploratory analysis we considered recruitment, rather than \( M_0 \) and fecundity separately.

The population growth rate \( (r) \) was estimated in the standard manner from the Leslie Matrix \( (A) \), a transition matrix with columns representing age classes (Caswell 1989), i.e. \( N_{t+1} = AN_t \), where \( N_t \) is a vector describing the

\[
A = \begin{pmatrix}
    s_0 f_1 & s_0 f_2 & \cdots & s_0 f_{n-1} & s_0 f_n \\
    s_1 & 0 & \cdots & 0 & 0 \\
    0 & s_2 & \cdots & 0 & 0 \\
    \vdots & \ddots & \ddots & \ddots & \ddots \\
    0 & 0 & \cdots & s_{n-1} & 0
\end{pmatrix}
\]

\( r \) can be derived from \( \lambda \), the dominant eigenvalue of \( A \):

\[ r = \log (\lambda) \]

For a given value of \( r \) the population doubling time is:

\[ T_d = \frac{\log(2)}{\log (1+r)} \]

Since nothing is known about the breeding frequency of \( M. \) mobular, 1.5 years, the mean value provided for the closely-related \( Manta birostris \) (Dulvy et al. 2008) was used in this exploratory approach.

Assuming the relationships described above, we conducted a sensitivity analysis in which parameters were varied in turn, to examine the importance of the levels of uncertainty for the various parameters.

**Power analysis**

When designing monitoring programmes, it is important to determine what magnitude of population changes, should they occur, is detectable by proposed survey approaches over given time scales. Power analyses can be undertaken to evaluate the survey CV and frequency required to be reasonably certain to detect a given change in population size (Gerrardte 1987). Here we chose to examine a significance level of 5% and a detection power of 60% based on conventional practice. Survey CVs considered were 20% and 30%.
RESULTS

Sightings and distribution

Figure 1 shows the transect lines covered on-effort (Beaufort ≤3).

A total of 68 sightings (56 on-effort) of all Myliobatiformes were obtained. The mean group size of Myliobatiformes was 1.1 animals (SD=0.49; range=1-4). Within this, 42 (39 on-effort) were confirmed as adult giant devil rays. The mean group size was 1.2 animals (SD=0.6; range=1-4).

Adult giant devil rays were mostly (88%) observed in the central and southern Adriatic Sea, whereas sightings of other “Myliobatiformes” were more frequent (65%) in the northern portion of the basin (Fig. 1). The distribution of sightings was more clumped offshore in the central stratum than in the southern stratum.

Of the 23 (17 on-effort) ‘other’ Myliobatiformes encounters, only 7 could be identified to the level of family (6 myliobatids and 1 dasyatids).

Abundance

Figure 4 shows the distribution of perpendicular distances for all Myliobatiform sightings combined. There were fewer sightings close to the track-line than would be expected but the maximum sighting distance was relatively small, with a severe drop in sightings after about 236 m (at 40° declination angle). The best fit was to a uniform model with a truncation distance of 225 m; this effectively equates to a strip census. The variance in density was affected more by group encounter rate (90%) than by group size (10%), as apparent from the clustered distribution of sightings (Fig. 1). The uncorrected CDS abundance estimates for confirmed adult giant devil rays for the central and southern Adriatic are shown in Table 2, along with the uncorrected estimate for all rays for the whole Adriatic Sea. When we applied the availability correction factor (0.49; SD=0.25) to the uncorrected estimate (N=1595; CV=0.23) for confirmed adult giant devil rays, the estimated abundance increased to 3255 with a substantially larger CV(CV=0.56).

Population growth rate analysis

Table 3 summarizes the results of the sensitivity analysis for the exploratory population modelling exercise. The ‘base case’ gave a population growth rate of 0.036 and a population doubling time of 19.5 years. Increasing M or k has a similar effect since M is a function of k, i.e. population doubling time increases to 135 years. The analysis shows that the population growth rate and doubling time are very sensitive to the assumed parameters, i.e. a 25% increase in recruitment leads to a 7 fold increase in r.

Power analysis

Figure 5 shows the results of the power analysis for two levels of survey CV (20% and 30%) and two survey frequencies (1, 2 and 3 years). CVs of this level Table 2. – Results of CDS uncorrected abundance estimates for adult giant devil rays and Myliobatiformes in general; DS, group density; D, animal density. CV and 95% CI are given in parenthesis; * strip-transect with right truncation at 225 m.

<table>
<thead>
<tr>
<th>Species</th>
<th>Effort (km)</th>
<th>DS (groups/km²)</th>
<th>D (animals/km²)</th>
<th>Uncorrected abundance estimate</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult giant devil ray</td>
<td>3700</td>
<td>0.016 (21.4%; 0.010-0.024)</td>
<td>0.018 (22.6%; 0.011-0.028)</td>
<td>1595 (22.6%; 1010-2,519)</td>
<td>Uniform*</td>
</tr>
<tr>
<td></td>
<td>Central and southern Adriatic only (88400 km²) – giant devil ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dasyatids</td>
<td>5600</td>
<td>0.016 (20.5%; 0.010-0.023)</td>
<td>0.019 (21.2%; 0.011-0.026)</td>
<td>2,301 (21.2%; 1509-3509)</td>
<td>Uniform*</td>
</tr>
<tr>
<td></td>
<td>Adriatic Sea (133000 km²) – all rays</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
are plausible if uncorrected estimates are considered as relative abundance estimates, and if it can be assumed that availability and perception bias remains constant over the survey periods investigated. The curved lines represent a power of 0.6 to detect a trend constant over the survey periods investigated. The intercept of the corresponding horizontal line with the power curves. For example, for a CV of 20% and an r of 0.1 with surveys every 1, 2 or 3 years it would take 6, 7 and 10 years, respectively, to detect a change in the population. In contrast, detection of a growth rate of −0.1 would take longer, i.e. 7, 10 and 14 years, respectively. With growth rates of between 0.05 and −0.05 it appears difficult to detect a significant change in the population can be found from the intercept of the corresponding horizontal line with the power curves. For example, for a CV of 20% and an r of 0.1 with surveys every 1, 2 or 3 years it would take 6, 7 and 10 years, respectively, to detect a change in the population. In contrast, detection of a growth rate of −0.1 would take longer, i.e. 7, 10 and 14 years, respectively. With growth rates of between 0.05 and −0.05 it appears difficult to detect any change in the population within a reasonable timeframe.

**Behaviour**

On 14 August 2010, a group of four giant devil rays was observed northeast of the Otranto strait. Three animals had an estimated DW of about 3 m and one appeared to be smaller (Fig. 2). Animals were observed for about 6 minutes swimming in anticlockwise circles. During this observation the small individual and one of the larger animals engaged in belly-to-belly swimming and flipping over while circling. Such behaviour in Myliobatiformes is usually connected with courtship and mating (Tricas 1980, Yano et al. 1999).

**Abundance**

As concerns the quantitative estimate of summer abundance of giant devil rays (and indeed Myliobatiformes) in the Adriatic Sea, the limitations of the study have been described and explain the high CV for the availability-corrected estimate. The estimate is only partially corrected and underestimates the actual abundance to an unknown extent for two main reasons: (1) the lack of data to correct for "perception bias" (which may be high given the need for good condition to see and identify them); and (2) the fact that possible unidentified sub-adult giant devil rays are among the 26 smaller ray sightings. The partially corrected estimate of 3255 (CV=0.56) may be considered to challenge the existing general perception of the ‘rarity’ of the giant devil ray. In absolute terms, a middle estimate of over 3000 animals would not be considered ‘rare’ as suggested in Holcer et al. (2013). Note that while the species may not be considered ‘rare’, this does not mean that the population has no conservation problems.

In addition, it should be noted that given the total surface area of the central-southern Adriatic (about 88400 km²), our estimate represents a maximum density of about 4 adults per 100 km². It is difficult to
evaluate how this density relates to the IUCN qualitative evaluation that this species is present in ‘very low densities’ throughout its range (Notarbartolo di Sciara et al. 2006). Finally, any full consideration of status would need some knowledge of ‘pristine’ densities.

Management implications and questions

The giant devil ray is ‘protected’ in most Mediterranean countries and thought to be of limited commercial value (Bauchot 1987). That being said, as discussed above, there is information suggesting a recent directed fishery (e.g. in Israeli and Palestinian waters) and, possibly considerable ongoing incidental catch with various types of fishing gear for other target species.

There is considerable uncertainty over the status and present trends of the giant devil ray population, despite its presence in the appendices of various conventions and its ‘Endangered’ IUCN Red List classification. While the present study suggest that the species may not be as rare as previously thought (the ban on pelagic driftnets since the early 1990s may have been successful in promoting population recovery), it is not known whether the population(s) is/are increasing, decreasing or static under the present conditions. As yet there is no research or management regime in place to evaluate this. If commitments to international agreements are to be kept, progress must be made, especially in the light of newly identified source of mortalities (e.g. Couturier et al. 2013). In addition, there is no information on what the original size of the population was in the 1970s before the “driftnet era” and no agreement on an appropriate conservation objective e.g. a biomass reference point corresponding to ‘good conservation status’ or an agreed desired (and reliably measured) trend in abundance.

A fuller assessment of the impact of fishery-related mortality should be carried out by conducting an ERA in which the sustainability analysis is stratified by management sub-regions and fishing métiers. To conduct the ERA and evaluate the likely and actual success of any mitigation management measures requires: (1) improved information on recruitment; (2) a time series of relatively precise indices of abundance; (3) information on stock structure (if any) and the geographic and temporal distribution of the species; (4) robust estimates of removal rates from potentially impacting fisheries; and (5) appropriate reference points.

An interesting approach to examining recruitment (i.e. taking into account ‘natural’ biological parameters and anthropogenic removals) is to monitor population indices directly through, for example, aerial surveys. The present study has shown that this is possible in principle for the Adriatic Sea. While effective monitoring of population trends in devil rays is possible, this will require a long-term commitment to a monitoring programme and aerial surveys are probably the most cost-efficient approach. Given the observed densities of the giant devil ray, an increase in the research effort (e.g. by increasing the number of transects) will decrease the CVs of the estimates and thus shorten the time needed to detect trends should they occur.

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