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ORIGINAL PAPER

Cetacean stranding rate correlates with fish stock dynamics: research of harbour porpoises in the Sea of Azov

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Abstract The dynamics of the endangered population of the harbour porpoise (*Phocoena phocoena*) in the Azov Sea is currently unknown. It can be, however, estimated by stranding analysis. In 1999–2014, the porpoise stranding rates were regularly monitored at the southern coast of the Azov Sea, particularly at the uninhabited abraded coast of the Tarkhan Cape. Specifically, the general trends and annual fluctuations in strandings were compared to the catch reports of the Azov anchovy (*Engraulis encrasicolus*), an important prey for porpoises. It was observed that the fluctuations in stranding rates closely correlated with the population dynamics of the anchovy stock. A cosine function, based on the data from 1999–2012, correctly predicted maximum strandings in 2013 and their substantial decline in 2014. The function worked particularly well, when possible biases affecting carcass preservation, such as discovery rate and drift conditions, were reduced. In certain environments and over established time periods, the cetacean stranding rate can be an indicator of population trends. The use of stranding rates as such indicator may be verified by external factors, including the dynamics of prey stocks.

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Introduction

Cetaceans are large and long-living top predators in marine ecosystems. Their populations, many of which are vulnerable or endangered, have low density and inhabit vast water areas. Therefore, their assessment and monitoring are costly and technically difficult and take a long time comparable with their life span. In some cases, indirect methods of stock assessment, such as monitoring of strandings on the coastline, can be applied; however, the effectiveness of such an approach depends on understanding the factors affecting cetacean strandings and populations in general. Environmental predictors for cetacean mortality and population dynamics have been identified in various regions (Peltier et al. 2013; Truchon et al. 2013; Meager and Limpus 2014), but finding direct biotic correlations can be important as well.

The harbour porpoise *Phocoena phocoena* (Linnaeus, 1758) in the Sea of Azov, as well as the Black, Marmara and Aegean Seas, is a geographically isolated subspecies, *Phocoena phocoena relicta* Abel, 1905 (Zalkin 1938; Tomilin 1957; Viaud-Martínez et al. 2007), the smallest living cetacean (Gol'din 2004), which is now listed as endangered by the IUCN (Birkun and Frantzis 2008). A few stocks (populations or sub-populations) are tentatively identified within its distribution range (Mikhalev 2005), and one of them, the most remote from the ocean, is in the Sea of Azov (Gol'din 2004). The Sea of Azov, the small enclosed sea (37,000 km^2) joining the Black Sea with the narrow Kerch Strait, is a good area for research and modelling of factors affecting cetacean populations and their dynamics. The Sea of Azov is covered by ice in winter, so porpoises leave it in autumn and come back in spring (Zalkin 1940). In the early twentieth century, the Azov stock was very abundant (Zalkin 1940; Kleinenberg 1956),

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giving the Russian name *azovka* to all the Black Sea porpoises (Tomilin 1957), but later it was severely depleted by extensive hunting annually taking up to tens of thousands animals (Zemsky and Medvedev 1977). Its abundance had catastrophically declined by 1960s (Yakushev 1964), and it has not attained a sustainable level after the ban on hunting claimed by the USSR in 1966 (Sirotenko et al. 1979). The Azov stock was also affected by mass mortality of Black Sea cetaceans in 1989–1990 (Birkun et al. 1992) which was likely due to invasion of jellyfish *Mnemiopsis leidyi* Agassiz, 1860 (Vinogradov et al. 1989; Bushuev 2000), and now its status and dynamics are uncertain, although some preliminary hypotheses were made (Gol'din 2008). The seasonal patterns of strandings and bycatch of the Azov porpoises and the possible factors underlying them were recently described by Vishnyakova and Gol'din (2014).

The Sea of Azov contains the separate migrating population of the European anchovy *Engraulis encrasicolus* (Linnaeus, 1758). It is genetically and morphologically different from the Black Sea stocks. Similar to porpoises, the Azov anchovy migrates between the Sea of Azov and the Black Sea. Anchovy fisheries are an important traditional fishing industry in the Sea of Azov. At present, the most of landings are taken by purse seine fisheries during the autumn and winter when the Azov anchovy aggregates in large stocks, passes through the Kerch Strait and concentrates on winter feeding grounds in the Black Sea coastal waters of Crimea and Caucasus (see the review by Chashchin 1996). There are also minor catches by artisanal fisheries using weirs and other small nets.

In this paper, we analyse the annual dynamics of porpoise strandings on the southern coast of the Sea of Azov in 1999–2014, identify the factors related to it, discuss its correlation with anchovy landings and substantiate its use as a tool for further studies of population biology. Such studies, combined with the data on demography, mortality factors (including bycatch) and immigration, would be necessary for the further population assessments, predictions of the population dynamics and elaboration of conservation and management strategies.

Materials and methods

Data sampling

The data for this study were obtained in the course of routine regular monitoring surveys of the 35-km-long coastal area on the southern side of the Sea of Azov and the Kerch Strait west to the Fonar Cape during 15 years, in 1999–2014 (except 2004) (Fig. 1). All skeletal remains and incomplete carcasses, as well as carcasses at various stages of decomposition, were recorded. Age, sex and status of sexual maturity were identified. The age was determined as the number of growth layer groups in the dentine of thin haematoxylin-stained longitudinal sections of teeth. Neonates were considered as animals with healing umbilicus, non-erupted teeth, and no neonatal line in the dentine. The sexual maturity of females was identified from the presence of *corpora lutea* or *corpora albicantia* on the ovaries, evidences for recent delivery, pregnancy or lactation; in addition, all females of 4 years and older were classified as sexually mature (see also Vishnyakova and Gol'din 2014).

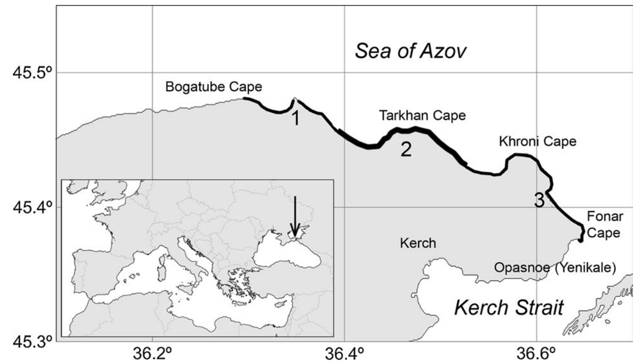

Fig. 1 The area of study on the southern coast of the Sea of Azov: 1–3, geographical sub-areas

Data correction and selection

As suggested by Moore and Read (2008), records of neonate strandings can be significantly underestimated, so their number sometimes can be better estimated from the strandings of lactating females, suggesting that the death of a lactating mother inevitably leads to the death of the offspring (Woodley and Read 1991). It is often hard to identify the state of lactation in stranded carcasses, so the number of sexually mature females adjusted to the annual birth rate can be used. We presumed the annual birth rate as 1 (the maximum possible), like in the neighbouring northern Black Sea population (BLASDOL 1999). Therefore, we calculated the number of missed neonates as the difference between the numbers of sexually mature females and neonates, if the former one was greater.

In order to exclude the sources of possible biases in the discovery rate (see below), we selected the sub-sample "Tarkhan", which included only summer strandings on the unpopulated 16 km coast of the Tarkhan Cape (with abrasion as the primary type of the beach), excluding neonates.

Data on anchovy stock

Various procedures of the stock assessment have been applied, bringing quite different estimates (Chashchin 1996, 1997). In this paper, the indicator of abundance of the anchovy stock was identified as the total annual catch by Ukraine and Russia as estimated following the procedure by Chashchin et al. (2012); this estimate was chosen as more consistent than other methods of abundance assessment, which varied across years.

General statistics and time series analysis

The annual stranding rates were calculated as the number of *recorded* strandings on the coast per year. In addition, the densities of strandings (number of strandings per km per year) were calculated as the general characteristics of the region for the comparison with other geographical areas. The density of strandings in the Tarkhan sub-sample was calculated per summer (instead of year).

The time series analysis was applied to the data on porpoise annual stranding rates in two variants (overall dataset and Tarkhan sub-sample) and anchovy landings in 1999–2012. 2013 and 2014 were not included in the models because of the extreme values observed in these years. Values for 2004 (missing year of observations) were calculated as average between 2003 and 2005. Linear trends describing midterm general tendency of growth or decline of populations or available resources were separately calculated for porpoises and anchovy as linear regression functions of time (years) and values (annual stranding rates or landings in thousand tons). Expected strandings were predicted under the hypothesis of following the uniform linear trend in the time frames of the study.

Anomalies were defined here as annual fluctuations around the expected values, as predicted by the linear trends (see also Peltier et al. 2013). These fluctuations were considered as indicators of short-term effects along the general tendency: given the short life history cycles of both anchovy and porpoises, the null hypothesis was the association of the short-term fluctuations with the cyclic events in population dynamics.

Anomalies were analysed on detrended data, using cosine regressions. For anchovy catches, a single cosine function was applied:

$$\text{Anomaly} = A_1 \cos(b_1 t + c_1)$$

where Anomaly = Observed value − predicted value (linear trend); t is the year; A, b and c are constants.

For porpoise strandings, a function with multiple periods was applied in the following form:

$$\text{Anomaly} = A_1 \cos(b_1 t + c_1) + A_2 \cos(b_2 t + c_2) + d$$

where Anomaly = Observed value − predicted value (linear trend); t is the year; A, b, c and d are constants; $b_2 = 2b_1$

The longest period (expressed as $b_1 = 2\pi/T_1$) was taken as equal to that calculated in the equation for anchovy catches ($T_1 = 11.81$ years, see below).

Results

In total, 652 porpoises were recorded to strand on the examined coastline in 1999–2014. After the correction on the missed neonates (38 cases), the corrected estimate was 690 (Fig. 2a). This gives the density of 1.24 specimens per km per year for the uncorrected estimate and 1.31 specimens/(km year) for the corrected estimate.

Geographical distribution of strandings

The area of study includes three sub-areas: (1) western coast: accumulative and abrasion beaches, populated or frequently visited by people; (2) Tarkhan Cape: abrasion

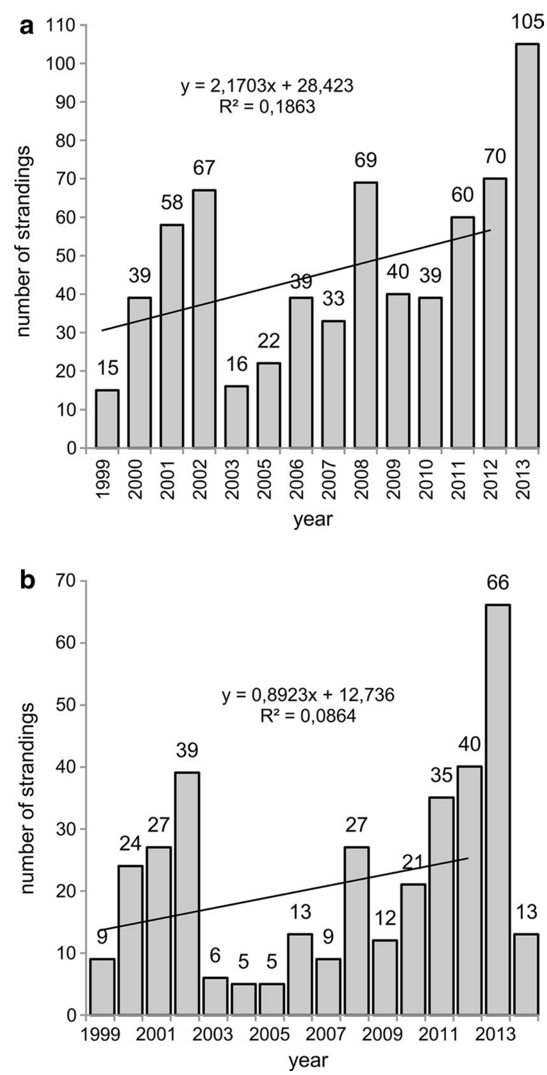

Fig. 2 Annual dynamics of strandings of harbour porpoises on the southern coast of the Sea of Azov: **a** total data corrected on neonate strandings, **b** summer Tarkhan sample, excluding neonates, with the estimated data on 2004. Linear trends on 1999–2012 intervals are provided

beaches, unpopulated and unvisited; and (3) eastern coast: abrasion and accumulative beaches, moderately populated and frequently visited. These areas differ in the character of taphonomy, preservation of carcasses and carcass recovery rate (Gol'din et al. 2013). Tarkhan Cape, the unpopulated area with abrasion beaches, is characterized by notably high occurrence of strandings and preservation of carcasses: two-thirds of all findings (416) fell on this sub-area and were recorded in summer. Thus, the summer density of records for the latter estimate is 1.73 specimens/(km year), a third more than the overall density and 1.7 times more than on the rest of the area. Excluding the neonates, 346 animals [1.44 specimens/(km year)] were recorded in the Tarkhan sub-sample in 1999–2014.

Annual dynamics of strandings and anchovy landings

General trends

The stranding rate of harbour porpoises shows a positive annual trend ($b = 2.17$ for 1999–2012, excluding 2004). The number of strandings predicted by this trend first exceeded the average annual stranding rate in 2008. The maximum of strandings was reached in 2013. The similar pattern was observed in the Tarkhan sub-sample, with a more gradual slope of the trend ($b = 0.89$). The annual stranding rate in the overall sample highly correlates with the rate in the Tarkhan sub-sample (Spearman's correlation: $r = 0.93$, $p = 0.000$).

Biomass and catches of anchovy of the Azov stock steadily increased during the study period: in 1999, landings were among the lowest historical records of fisheries industry, and by 2012, they have reached the level of 1987–1988 (Chashchin et al. 2012) (Fig. 3).

Annual fluctuations

The annual stranding rate (Tarkhan sub-sample) shows a strong Spearman's correlation with annual anchovy catches ($r = 0.78$, $p = 0.001$); the correlation even increases between their detrended values ($r = 0.81$, $p = 0.000$). The intervals of 2000–2002 and 2011–2013 are characterized by both positive phases of anchovy catches and stranding rates, while 1999 and 2003–2010 are characterized by negative phases. In 1999–2005, the stranding anomaly tended to lag in a year following the fluctuation of anchovy landings, for example, the maximum of landings was observed in 2001 and the maximum of strandings in 2002. Since 2006, both indicators have been synchronous (excluding 2008 with the distinct positive stranding anomaly) (Fig. 4).

The detrended annual landings of anchovy (1999–2012) are well described as a single cosine function with the period of 11.81 years ($r^2 = 0.92$, $p = 0.000$). This function also predicts the observed maximum in 2013. The

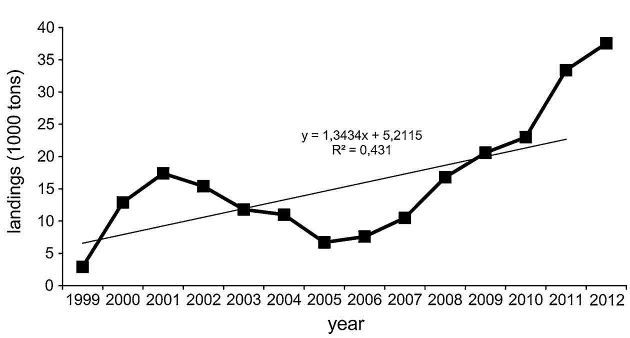

Fig. 3 Annual landings of the Azov anchovy in 1999–2012, combined catch of Ukraine and Russia

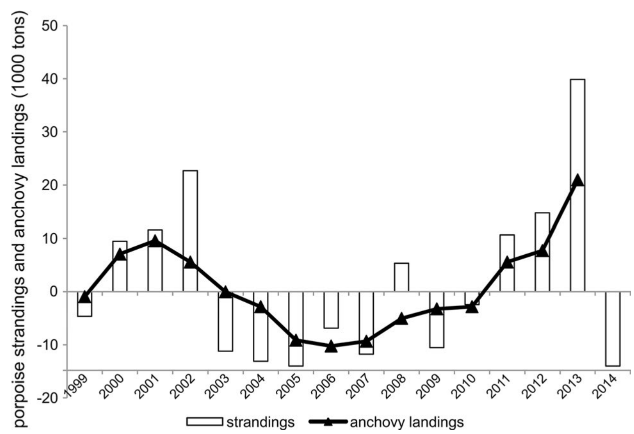

Fig. 4 Annual fluctuations of detrended porpoise strandings and anchovy landings

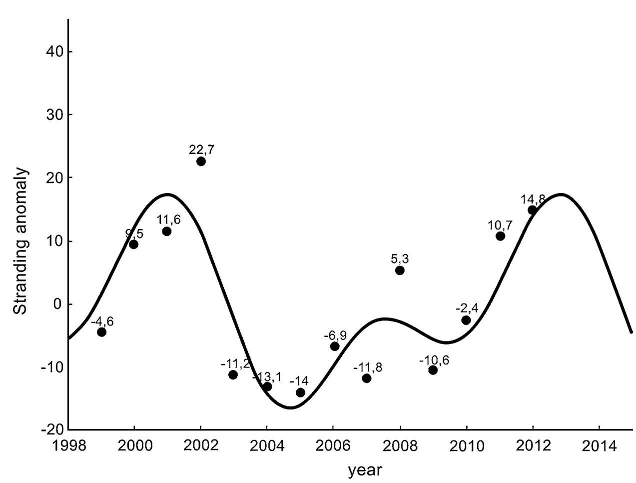

Fig. 5 The cosine function with the periods of 11.8 and 5.9 years describing the annual fluctuations of porpoise strandings (Tarkhan sub-sample) in terms of stranding anomaly

Table 1 Parameters of cosine functions describing annual fluctuations of anchovy landings and porpoise strandings

Parameter	Value	SE
Anchovy landings		
A	8.2612	1.0937
b	0.5318	0.0357
c	4.8063	0.3097
Porpoise strandings		
A_1	−11.3945	2.8356
b_1	0.5318	–
c_1	1.1909	0.2661
A_2	8.3822	2.9484
b_2	1.0637	–
c_2	1.3817	0.3435
d	1.3817	0.3435

detrended stranding rate is described by a more complex cosine function with two periods, one of which (T_1 = 11.81 years) is taken as equal to that from the anchovy function, and another one, $T_2 = ½\ T_1$ (Table 1, Fig. 5). The resulting function well fits the observed fluctuation of the stranding rate ($r^2 = 0.86$, $p = 0.02$), showing maximums in 2001–2002 and 2008 and minimums in 2004–2005 and 2009; furthermore, it precisely predicts the maximum in 2013 and substantial decline in 2014.

Discussion

Stranding rate and its general trend

The stranding rate of harbour porpoises in the Sea of Azov is among the highest in the world: on average, it exceeds the stranding rates on the North Atlantic coasts in 3–23 times (Peltier et al. 2013), and for the Tarkhan sample, this ratio is 1.5 times greater. However, in some areas of the neighbouring Black Sea, it is even higher up to 2.3 specimens/(km year) on the western Turkish coast (Tonay et al. 2013) and at least 3 specimens/(km year) on the western Crimean coast (Gol'din et al. 2014). The extremely high stranding rates in the Azov and the Black Sea region are partly explained by the wind and current regimes of the enclosed sea area (Lomakin et al. 2010; Ivanov et al. 2010; also see the "Drift conditions and buoyancy" section), high bycatch rate in the coastal and shallow waters preferred by porpoises (for the updated review see Vishnyakova and Gol'din 2014) and unknown health and mortality factors. However, a special study of these mechanisms is still required.

The rising trends for anchovy and porpoise records are associated with the positive trend in abundance of the Azov stocks of anchovy and other fishes, observed since 1999 (Chashchin et al. 2012), which, in its turn, is an aspect of general recovery of the ecosystem of the Sea of Azov after a long depression in the second half of the twentieth century. This depression was caused by a complex of factors, among which the changes in river inflow and extensive fisheries have been identified (Volovik et al. 1993; Kideys 1994). The deepest phase of the depression fell on 1989–1999, the years after the invasion of ctenophore *M. leidyi* (Vinogradov et al. 1989), which led to a catastrophic decline of zooplankton and anchovy stocks (Volovik et al. 1993; Shiganova and Bulgakova 2000; Chashchin et al. 2012) and mass mortality of harbour porpoises in the Black Sea in 1989 and 1990 (Birkun et al. 1992; Bushuev 2000). This period ended with the invasion of its predator, ctenophore *Beroe ovata*, first recorded in the Sea of Azov in 1999 (Shiganova and Bulgakova 2000) and extensively propagating since 2005 (Vinogradov et al. 2006; Chashchin et al. 2012); various fish stocks were reported to increase during recent years. In addition to the Azov anchovy, the Azov stocks of gobies [the most abundant of which is the round goby *Neogobius melanostomus* (Pallas, 1814)] have been rapidly rising since late 1990s (Shlyakhov 1997; Shlyakhov and Miryushchenko 2012): the gobies also are important prey objects for harbour porpoises (Zalkin 1940).

Association between stock dynamics of porpoises and anchovy

Annual fluctuations of the porpoise stranding rate, defined in terms of the stranding anomaly, show at least two short- to midterm cycles, 5 to 6 year and 11 to 12 year, with the synchronous maximums. The 5- to 6-year cycle is weakly pronounced, and it does not correlate with known fish stocks, annual productivity, ctenophore outbreaks or weather conditions. The 12-year cycle is more distinct and highly correlates with the cycle of the Azov anchovy landings.

The anchovy of the Azov stock, as well as the sand smelts (*Atherina* sp.), are a critically important prey source for the Azov porpoises during their annual seasonal migrations from the Sea of Azov to the Black Sea and back. The anchovy and sand smelts contained the majority of the Azov porpoise stomach contents in autumn and spring, unlike in other seasons (Zalkin 1940), and the seasonal migrations of Azov porpoise are linked in time (together with other factors) with the seasonal anchovy movements (Vishnyakova et al. 2013). This easily accessible, dense and abundant prey resource is necessary for successful migration and subsequent wintering and pregnancy. Harbour porpoises of the Black Sea are possibly linked in a similar way with other anchovy stocks (Bushuev 2000). Therefore, a close positive interrelation between the anchovy and porpoise stocks seems quite reasonable: more resource is available for porpoises and fishermen, and this leads to more strandings under the assumption of increasing population size and constant mortality rate. The link with the sand smelt stock is unclear due to data deficiency; however, the sand smelt is known to be an important fishing object in the Sea of Azov and the Kerch region (Shlyakhov and Miryushchenko 2012), and its fluctuations can possibly contribute to the porpoise stranding dynamics.

Notable is the nature of these indicators. Both of them, stranding records and catch reports, have been criticized for their incompleteness and possible biases. Strandings of marine turtles and mammals were reported as strongly underestimating bycatch mortality (Epperly et al. 1996) or mass mortality due to disasters (Williams et al. 2011). However, the studies in the enclosed sea areas demonstrate high carcass recovery rate of ca. 30 % of deaths (Wells et al. 2014). Fisheries statistics is also often underestimated: this was particularly stressed for the Black Sea countries, including anchovy fishing (Öztürk 2013; Shlyakhov 2013). More generally, the precaution against using population indices was summarized by Anderson (2001): there is a widespread problem in identifying a link between the observed index and abundance data. However, this obstacle can be avoided by matching two different indices, which are independently obtained by totally different methods (Fedy and Doherty 2011). Here, we present such an example when two indices verify each other by their correlation. Furthermore, the anchovy catch statistics appears to be more reliable (and possibly less biased) population indicator than other survey methods. As for the porpoise stranding rate, the best correlations and functions were obtained on the sub-sample cleared from possible sources of bias.

Porpoise stranding rate as a population indicator

The sources of biases for the estimate during the survey depend on the observer, environmental conditions and biological characteristics of the object of study (Buckland et al. 1993).

The number of *reported* cetacean strandings can be described as a function of

Total stranding rate · Discovery rate

where the *Total stranding rate* is a function of

Population size · Mortality rate · Buoyancy · Drift conditions

where the Population size is the total number of animals, Mortality rate is the percentage of dying specimens, Buoyancy is the measure determining the number and percentage of carcasses drifting on the sea surface and Drift conditions are the complex of factors driving the carcasses ashore.

The objections against use of the number of the reported strandings as an indicator of mortality rate are: (1) supposedly low stranding rate, which in its turn can be explained as a result of sinking of carcasses, adverse effect of drift conditions or too long distance from habitats at sea to a coastline and (2) supposedly low discovery rate caused by human disturbance, rapid decomposition or deficient reporting. Most of these factors are classified following Buckland et al. (1993) as environmental conditions, except rapid decomposition (the biological characteristics) and reporting (the observer-dependent factor).

The bias in the reporting rate can be avoided if the effort is conducted by experienced observers directly. Among the factors affecting the preservation rate are: age of the stranded animal (neonate carcasses rapidly decompose), type of the beach (abrasion vs accumulative) and seasonal wave activity: the best preserved are the carcasses of non-neonates on abrasion beaches during the summer. In addition, human disturbance can distort the statistics of strandings. Thus, the best discovery rate in the studied area was recorded on unpopulated and unvisited abrasion beaches in summer (Gol'din et al. 2013).

Drift conditions and buoyancy

The Sea of Azov is extremely shallow (mean depth is 7 m, maximum depth is 14 m), with summer water temperatures always exceeding 25 °C and predominating north, north-east and north-west winds in July and August (Lomakin et al. 2010). Mean speed of the surface current in the central Sea of Azov is 0.14 m/s at the north wind of 5 and 0.42 m/s at 10 m/s (Ivanov et al. 2010) that makes 12 and 36 km per day. So a carcass from the central eastern Azov, floating along the trajectory predicted by Ivanov et al. (2010), would reach the Tarkhan Cape within 3–8 days at moderate wind speeds. This interval is far shorter than the non-neonate carcass decomposition rate (Gol'din et al. 2013); thus, the drift conditions would not affect the summer stranding rate in the Sea of Azov, if the wind speed is at least 5 m/s. This suggestion is confirmed by the moderately decomposed state of the most of stranding carcasses.

Carcasses of harbour porpoises generally have positive buoyancy (Kipps et al. 2002); we often observed floating fresh porpoise carcasses even during warm season. Possible exceptions could be some adult animals in summer (Kleinenberg 1956), especially sick animals in bad body condition. However, in this case, a sinking animal starts to blow and putrefy and floats to the surface within hours (Anderson and Hobischak 2004); salt water environment could slow down this process, yet it progresses rapidly in warm water, so even such a carcass is expected to float to the surface within 1–2 days after sinking. In general, most of mammalian carcasses float in salty warm water, after drowning in shallow waters and especially with the air in lungs; and in enclosed seas, the carcasses usually reach the coast before disintegration (reviewed by Haglund and Sorg 2001). The southern Sea of Azov ideally matches these conditions (unlike the open and deep Bay of Biscay where many carcasses sink at sea: Peltier et al. 2012).

Thus, drift and buoyancy conditions would not significantly reduce the stranding rate in the southern Sea of Azov, and this rate would adequately present the mortality.

Population size and mortality rate

The mortality rate is directly related to the population size in stable or stably growing and declining populations under normal conditions, but this relationship is broken during mass mortality events, changes in reproduction or immigration processes. However, Peltier et al. (2013), based on data on porpoise strandings in the north-eastern Atlantic, substantiated the correlation between the abundance of porpoises in sea and their stranding rate. Here, we add an argument for this view: the anchovy stock correlates with the porpoise stranding rate, since the latter reflects the abundance of porpoises and their population size. There is no (or minimal) lag between the porpoise stranding rate and the anchovy dynamics, so the porpoise mortality in the Sea of Azov is not the result of a decline in the anchovy abundance: on the contrary, it increases with the rise of the anchovy stock. Therefore, as we suggest, the stranding rate is proportional to the mortality rate, which, in its turn, reflects the trend in population size.

Using of the stranding rate as a population indicator for the mortality and population dynamics Azov porpoises has some limitations. First, porpoises are stranded at the Azov coast only during the warm season; the winter aspect is inaccessible for study. Second, summer seasonal outbreaks of strandings can be driven by local or random factors, such as bycatch in coastal waters or intoxication by coastal algal blooms, which affect only a part of the population. However, the correlation with the prey stock dynamics (even if anchovy is not the single prey source for porpoises and not the single stock showing the same dynamics as porpoises) shows the robustness of this indicator.

Another constraint for use of these indicators is their time limitation. They are hard to be extrapolated into the past before 1988 because the anchovy landings were based on fishing effort rather than stock abundance and tended to overfishing (Chashchin et al. 2012). They can be possibly applied for a relatively short period of the initial recovery of the Azov ecosystem, and their development is to be verified by further research.

In conclusion, the cetacean stranding rate can be an indicator of the population trends at certain conditions neutralizing possible biases and at certain time intervals, and its usability can be verified by external factors, such as dynamics of prey stocks.

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