A new method to detect illegal oil use and estimate mortality rates of endangered Ganges river dolphins based on *Clupisoma* fish catches

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ABSTRACT

Gillnet entanglement is a major threat to endangered small cetacean species around the world, including Ganges river dolphins (*Platanista gangetica*). While conservation efforts have helped to reduce the prevalence of targeted hunts, bycatch still occurs. A serious concern is the illegal opportunistic exploitation of bycaught river dolphins to evade detection and potential penalties, where oil is extracted from the blubber and illegally traded as bait for catfish (*Clupisoma garua*). While this threat is well known, enforcement is weak and evidence difficult to collect as the molecular analyses required to confirm the use of dolphin oil are expensive and time-intensive. Simpler detection methods are therefore needed to help improve enforcement. We developed a new visual test and decision-making process to help identify the use of dolphin oil while fishing for catfish, which draws on a common understanding among local fishers that oil-baited fish appear paler/whiter than net-caught fish. We conducted colour analyses and visual-perception tests, combining these results with other variables, such as catch weight, sale price and season, to identify a set of rules which can be used to determine the use of dolphin oil in a sampled catch. Based on our predicted oil-use prevalence, we estimated that five to seven dolphins (~4% of the population in our study area) may be exploited each year to support catches landed at one of two sites in our study area. This system therefore provides a simple and efficient tool to identify instances of illegal exploitation of Ganges river dolphins.

KEYWORDS: BYCATCH; GILLNETS; FISHERIES; *PLATANISTA GANGETICA*; GANGES RIVER; INDIA

INTRODUCTION

The threat of entanglement and use of Ganges river dolphin products

Bycatch, or mortality due to entanglement in fishing nets, is a primary threat facing endangered small cetacean species around the world (Brownell *et al*., 2019; Temple *et al*., 2021), including both South Asian and Amazon river dolphins (Mintzer *et al*., 2018). Ganges river dolphins (*Platanista gangetica*) are listed as 'Endangered' on the IUCN Red List of Threatened Species (Kelkar *et al*., 2022a), with bycatch in small-scale riverine capture fisheries a major threat to the species' survival (Choudhury *et al*., 2019; Kelkar & Dey, 2020; Dewhurst-Richman *et al*., 2020). This species is subject to the highest levels of legal protection in its range countries (India, Bangladesh and Nepal) and has been further designated as the 'National Aquatic Animal' in India. Bycatch mortality of Ganges dolphins is often accidental, but Sinha (2002) also suggests a strong possibility of 'assisted bycatch', where gillnets may be deployed in ways which lead to dolphin entanglement and therefore enable their 'opportunistic' exploitation. Dolphin blubber oil and flesh are used for a range of purposes, including bait for the catfish species *Clupisoma garua*, pain relief for rheumatism and common joint injuries, and human consumption. These

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applications have been well-documented over many years (e.g., Anderson, 1879; Faruqui & Sahai, 1943; Motwani & Srivastava, 1961; Lal Mohan & Kunhi, 1996; Bairagi, 1999; Sinha, 2002; Ahmed *et al*., 2018; Das *et al*., 2019). Anderson (1879) describes the historic existence of a factory used to process dolphin oil near Agra in Uttar Pradesh before the 1870s. Other possible applications have also been documented, including as an aphrodisiac, pain relief for cattle, and even to deter wild ungulates from crop fields (Kelkar *et al*., 2022a). Since the 1970s, legislation in all range countries prohibit hunting, poaching or any other intentional killing of Ganges river dolphins (Kelkar & Dey, 2020), but even though most fishers are aware this practice is illegal, river dolphins, once entangled in gillnets, are still often 'salvaged' or 'opportunistically exploited' (Branch *et al*., 2013), especially in eastern India and Bangladesh where there is a lucrative illegal market for river dolphin products (Dewhurst-Richman *et al*., 2019; Kolipakam *et al*., 2020).

Reasons for the illegal use of dolphin oil

For most fishers, the benefits of using dolphin oil outweigh the consequences of reporting bycatch. The fear of reporting bycatch is not unjustified, given that existing legislation in range countries does not distinguish between targeted hunting and accidental bycatch, regardless of any actual intention to use the associated products. As a result, many fishers choose not to report these cases. If these fishers are unable to use the oil, they tend to abandon or hide the carcasses, which suppresses the true number of dolphins lost to interactions with fisheries. Furthermore, most fishers in the region are socioeconomically impoverished, which exacerbates their fear of legal sanctions, as it can be difficult to prove that bycatch was 'accidental'. The absence of a separate legislative framework to address, manage and mitigate bycatch is therefore a crucial issue (Kelkar & Dey, 2020).

In addition to the traditional practices of some fishing communities to use dolphin oil, these factors can encourage fishers to salvage dolphin products as commodities to trade. Black market prices for dolphin oil are often high. Enforcement agencies tend to lack the resources and capacity to collect evidence or conduct raids, while routine enforcement by state departments may not be effective due to limitations in monitoring and enforcement measures, such as the seizure of nets, which are often opposed by local fishing groups as the nets of innocent fishers are also seized in the process.

Despite the growing realisation that strong law enforcement and tough sanctions in response to the illegal activities of a small number of members can deprive entire communities of income, there is also doubt about 'softer' approaches, such as financial incentives to report cases. This is due to a number of factors. For example, the uptake of alternative oils promoted for fishing has been limited (Sinha, 2002; 2004). Kolipakam *et al*. (2020) found that alternative oils were hardly used by fishers in either Assam or West Bengal because catches tended to be much lower as a result. Furthermore, the risk of potential conflict with fishers who choose to undertake illegal practices also prevents fishers from reporting cases. Therefore, irrespective of the approach taken, illegal use of oil remains largely unaddressed, despite reductions of targeted killing and poaching in some areas (Kelkar *et al*., 2022a).

Knowledge gaps

Due to these limitations, there are major knowledge gaps as to the overall extent of removal rates and bycatch-driven mortality, which means the illegal use of dolphin oil remains little understood. In general, its impacts on population dynamics are difficult to infer from largely opportunistic reports of mortality events (e.g., Authier *et al*., 2014; Meager & Sumpton, 2016). The ability to detect the use of dolphin oil in fishing practices is therefore a significant problem which restricts the efforts of conservation agencies. In addition, the lack of effective methods used to gather evidence in the field further restricts the scope for effective management and enforcement. For example, molecular methods to confirm the presence of dolphin oil in fish samples is expensive and requires technical expertise (Singh *et al*., 2021; Kolipakam *et al*., 2020). Forest and environment departments tend not to have access to these resources, which means there is an urgent need to develop and implement low-cost methods to solve this problem.

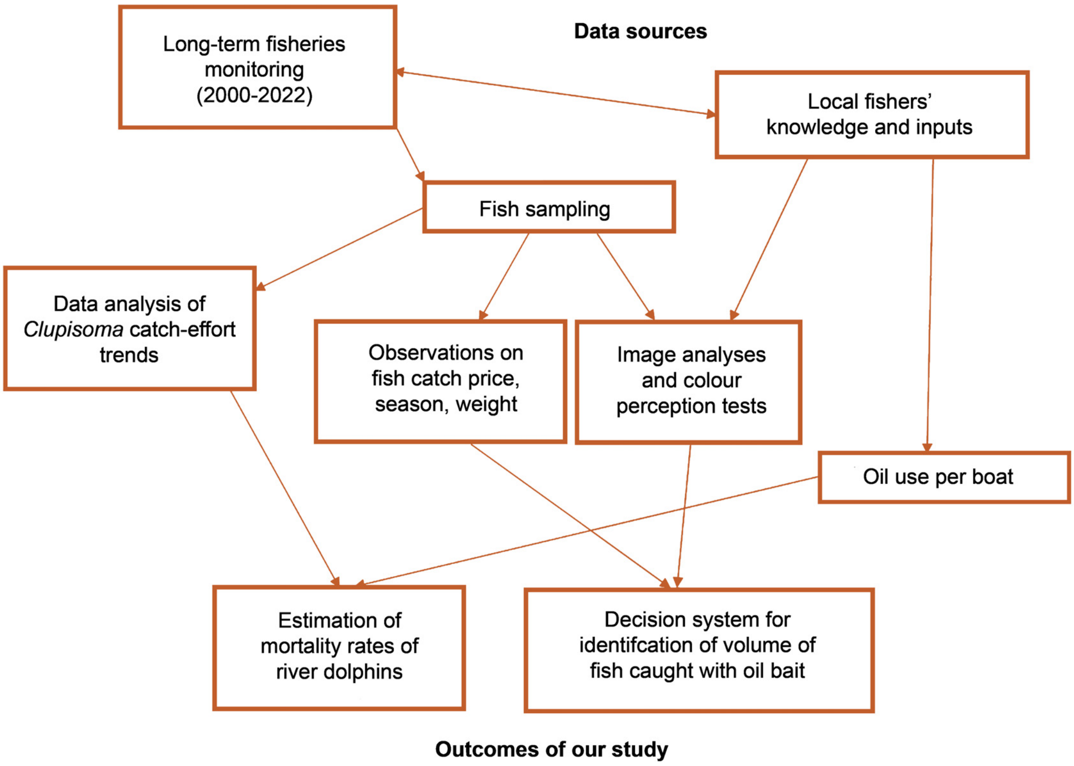


Figure 1. Study workflow from inputs to outcomes.

Our approach

We describe the development of visual tests and a standardised decision-making process to detect the potential use of dolphin oil by observing catches of *Clupisoma garua* in fish markets (Fig. 1). This system draws on the widespread understanding among local fishers that oil-baited fish appear paler/whiter than net-caught fish and often putrefy faster (in three to four hours). We therefore predicted that *Clupisoma* samples caught with dolphin oil would be paler and whiter in appearance than those caught without oil-bait. We tested for differences between each sample through colour analysis and visual tests. We also included sale price, catch weight and season as variables to predict whether a specific catch came from oil-baited lines. Using this system, we were able to estimate the total amount of fish caught with dolphin oil and in turn, the potential number of dolphins used. Our system therefore provides a simple but powerful tool to target fishers carrying out illegal activities and estimate the extent of bycatch.

METHODS & MATERIALS

Ethical considerations

We do not disclose the exact location of our study for ethical reasons. Fishers voluntarily shared their knowledge about these colour variations as part of informal discussions about a wide range of issues affecting fish stocks and bycatch. In the course of these discussions, we gave assurances that their identity would not be disclosed. Furthermore, as *Clupisoma garua* is not a protected species, we did not need permission to sample catches. Based on the analyses presented in this paper, we reported the extent of illegal dolphin exploitation to appropriate enforcement agencies in order to emphasise the need for stronger monitoring. We did not disclose the names of our sources in order to protect innocent fishers.

Study area

We studied two settlements along the Ganga River in India. The area in question has a fishing community of approximately 100–200 (max. 300) active fishers, but this number varies between seasons. The mid- and post-monsoon (Aug–Nov) and summer (March–May) periods are the most popular seasons, with catches peaking post-monsoon. There were only a few active fishers in Settlement A, most of whom had stopped the practice of fishing with dolphin oil in recent years. Settlement B had more active fishers who appeared to still continue the practice. A description of the method can be found in Annex 1.

The main fishing practices include the use of drifting and fixed, nylon or high-density polyethylene fibre, mono- and multi-filament gillnets (mesh size 18–300 mm), large river seines (mesh sizes 10–20 mm), smaller shore seines (mesh sizes 1–25 mm), barricading mosquito-nets (1 mm), fishing traps and boxes, lift-nets and brush-pile traps. Gillnets, trap nets and hook-lines are used to catch several species of catfish: *Clupisoma garua*, *Eutropichthys vacha*, *Sperata spp*., *Wallago attu* and *Mystus spp*. Sinha (2002) reports that *Clupisoma garua* and *Eutropichtys vacha* are captured with the use of dolphin oil. In our study area, the dominant catches (over 95%) with oil-bated lines were *Clupisoma garua*.

Clupisoma garua

Clupisoma garua (Hamilton, 1822) is a medium-sized carnivorous species that is widespread across large rivers in the Indian subcontinent. Adults are known to grow to about 30 cm standard length and 300 g max. body weight. The breeding season occurs during the early monsoon period (peak: June, range: May–August), producing 14–16,000 eggs. Length at sexual maturity is approx. 18 cm (Hasan *et al*., 2020; Bhakta & Sonia, 2020). While the species' status is 'Least Concern' as per the IUCN Red List of Threatened Species, it is still likely to be overfished in the Ganga River (Mishra *et al*., 2009; Akter *et al*., 2019), as indicated by a lower nucleotide diversity than in tributaries with lower fishing activity (Saraswat *et al*., 2014).

Data collection and analyses

We monitored catch-effort data for over 80 riverine fish species from landing sites and markets in Settlement A (since 2000) and Settlement B (since 2010). As part of this work, we collected data on fishers' space-use patterns, fishing behaviour and practices, seasonality and effort-investment decisions. We also documented fishers' knowledge and perceptions of trends in the yields of fish species and the reasons behind declining catches. Details of this work are published in Choudhary *et al*. (2006), Kelkar *et al*. (2010; 2022b), Montana *et al*. (2011), Dey *et al*. (2020) and Kelkar (2018; 2021).

We obtained information from three main sources: (1) data collected at landing and market sites (2000–23; Settlement A); (2) data collected from logbooks maintained by traders purchasing fish either from fishers or through retail vendors (2010–23, Settlement B); and (3) data collected from interviews with fishers. We recorded the seasonality, price variations in Indian Rupees (INR per kg), and average catch sizes from all available *Clupisoma* catch data (n = 5,480 catches) and from all catch sources. We also assessed trends in seasonal yields, effort, selling price per kg and CPUE. We investigated the relationship between CPUE and log-scaled total yields to test for proportionality, hyperstability or hyperdepletion in catches. As the *Clupisoma* fishery is dominated by hook-line fishing restricted to specific areas along the river, hyperstability would indicate stable catches despite overall depletion, and hyperdepletion would indicate catch declines despite no reduction in yields. Linear or non-linear relationships between CPUE and total yield can result from spatial behaviours of fishing and fish-habitat use, often resulting from aggregation or dispersion of fish densities in a fishing area relative to the spread of fishing effort (Alós *et al*., 2019). In our regression model, a slope coefficient of less than 0.5 was taken to indicate hyperstability while a coefficient greater than 2 was taken to indicate hyperdepletion. Coefficients close to 1 were taken to indicate CPUEs proportionate to total estimated yields of *Clupisoma*. This analysis helped to assess whether fishing with dolphin oil could negatively affect *Clupisoma* abundance and availability.

Sampling

Since 2021, we focused our sampling effort on *Clupisoma* catches. During visits to Settlements A and B, we recorded catches which fishers confirmed had been caught both with dolphin oil and gillnets. To test our predictions, we collected 20 samples of fish caught with both methods and randomly selected five samples from each for image analyses. We used this minimal sample size for two reasons: (1) only a limited number of fishers confirmed catch sources; and (2) we wanted to test the effectiveness of our method on small samples, as rapid market-based assessments would typically involve quick sampling of a few fish – so the consistency of differences in appearance with small samples was important.

Analysing colour levels

We placed these samples side-by-side against a white background, and then photographed both samples at one-hour intervals with a Sony DSC camera, between 08:00–15:00 IST, until significant putrefaction had occurred.

In order to compare the colour levels between samples, we extracted Red-Green-Blue (RGB) values using 'jpeg' (Urbanek, 2022) and 'colordistance' (Weller, 2021) packages in R 4.2.0. (R Core Team, 2021). Images of all fish samples were cropped, and the backgrounds removed to nullify any minor shadow effects. No further processing was carried out. We then statistically compared RGB values of all photographed samples in relation to time and treatment (oil vs. net), using a two-way repeated measures ANOVA (Bakeman, 2005) in the 'rstatix' package (Kassambara, 2022).

Conducting visual tests

We conducted a visual test on 51 human participants who did not have any prior knowledge of fish, fisheries, fish-image analyses, etc. The aim of this test was to check whether participants without any relevant expertise could detect differences between the samples. Participants were chosen deliberately to explore whether the system could be used by frontline staff who receive no formal training in fisheries monitoring. The objective of our test was only shared after the test was completed to avoid any priming effects. The identities of all participants were kept anonymous. Two sets of questions were posed in random order. In Set 1, participants were asked to describe the three main colours in the relevant image. In Set 2, the participants were shown pairs of fish in a random order. Two pairs were 'controls', i.e., fish with the same provenance were shown in both images (e.g., two fish caught in gillnets or two fish caught with dolphin oil), and two pairs were 'tests', i.e., fish from both samples. For this set of questions, participants were asked to choose the most suitable statement from a number of multiple-choice answers about the similarities or differences between the brightness and colour(s) of the two images. The multiple-choice answers were shuffled randomly for each question in Set 2. Responses to Set 1 and Set 2 were compared using exact binomial tests and McNemar tests (Agresti, 1990). Qualitative comparisons were also conducted to compare the colour and hue from the descriptions provided. Exact binomial test results assessed statistical significance of whether participants accurately identified similarities or differences between the samples with treatments and controls. McNemar test results assessed whether participants who gave correct answers for sample comparisons for treatments/controls also gave correct answers for corresponding controls/treatments, which would indicate consistent (non-random) association in identification of similarities and differences.

A new decision-making process

In order to develop our new rule-based, decision-making process, we used random forest models (RFs) to predict the probability of dolphin-oil use based on the sale price, season and catch weight of *Clupisoma* catches. These models were evaluated based on the Out-Of-Bag misclassification errors and also the consistency and homogeneity of node selection using multiple diagnostics (Annex 2). The rules identified from the random forest models were included in a Bayesian network model for use as a decision-support tool to estimate the probability that an observed *Clupisoma* catch may have been caught with dolphin oil, conditional on appearance, catch weight and season. The Bayesian network model was constructed using conditional probability tables in the software package MSBNx (Annex 3) (Kadie *et al*., 2001). Based on these rules, we estimated the proportion of total catches that could have been caught with the use of dolphin oil at Settlement B.

Oil yield data from individual dolphins

In order to estimate the number of dolphins used for oil, we assumed the volume of oil yield from an individual Ganges river dolphin at 20 litres for an animal of 60–70 kg body mass. This assumption was based on Kasuya (1972) who estimated blubber to be approx. 30% of total bodyweight based on Ganges river dolphin carcasses.

Fishers also informed us that, on average, 15–20 litres of oil could be easily extracted from a near-adult or adult dolphin.

Estimating annual use of dolphin oil

We obtained information from fishers that fishers may use 100–250 ml of Ganges river dolphin oil as bait in a single trip. We were not given exact amounts. However, as catches were likely to vary based on weather conditions, location, effort and skill, we used the whole range for our estimates. To be conservative, we assumed that a minimum of 50 ml and maximum of 250 ml was used in a single day's trip. From these estimates, we estimated the use of oil per trip and the total requirement of oil for all trips in the entire *Clupisoma* season. From the estimated dolphin-oil catches in each year, we estimated the total oil used and divided it by the average oil yield from an individual dolphin to calculate the number of dolphins likely to have been used in the region, either directly obtained from carcasses or supplied from elsewhere. We obtained average estimates and confidence intervals with calculation inputs varying for: (1) oil use per fishing trip (between 50–250 ml); (2) average catch from oil use per fishing trip (between 7–14 kg); and (3) oil yield per dolphin (15–20 l) for annual corrected catch data for *Clupisoma* between 2013–21. These were conservative estimates based on the catches reported by a single trader.

RESULTS

Trends and patterns in Clupisoma catch-effort data

Two clear seasons of *Clupisoma* fishing activity emerged from analyses of market and field data: (1) August–November; (2) March–May, when *Clupisoma* were captured with dolphin oil and gillnets. Occasional catches also occurred in other months, but these were mostly by gillnets. Since 2017, *Clupisoma garua* has been the top-ranking species of the multi-species fishery at Settlement B and the sixth-ranking species at Settlement A. At Settlement B, catches of *Clupisoma* increased in their relative rank from 14^{th} (2000–01) to 8^{th} (2012–13), 3^{rd} (2013–15), 2^{nd} (2016) and 1^{st} (2017–20), accounting now for an average of 20% (± 24% SD) of seasonal catches of all fish species. At Settlement A, trends in *Clupisoma* catches fluctuated but were generally stable as compared with the similar catfish species *Eutropichthys vacha* (Fig. 2).

At Settlement B, *Clupisoma* annual catches ranged between 1,400–23,000 kg between 2013–21, with the magnitude of catches higher during high-flooding years in 2016, 2018 and 2019, when annual catches were > 13,000 kg. Seasonal and annual trends in *Clupisoma* total catches, effort and CPUE showed consistent increases in the peak fishing seasons from August–November and March–May (Fig. 3, Table 1). There were stable *Clupisoma* trends despite a significant declining trend in overall fishing effort in the area (Pearson's $r = -0.35$, $P = 0.005$).

Clupisoma CPUEs indicated proportionality (i.e., catches per individual fisher per day were proportionate to total yields of all catches recorded in the market). The slope coefficient of the regression model was estimated at 1.61 (SE 0.19), suggesting that the catch trend did not seem to indicate that the stock was not stable (log-linear model: intercept = –5.49 (SE 1.34), slope 1.61 (SE 0.19), $R^2 = 0.70$, $P < 0.0001$, $F = 67.35$, df = 1, 28).

Typically, dolphin-oil catch-weights and numbers of individuals captured were greater than unbaited hooks or hooks baited with alternative oil (not distinguishable). Gillnet catch-weights were the lowest. Prices (mean ± SD) of August–November catches (peak season of oil use) were the lowest: 126 ± 50 INR per kg, followed by December–February catches (176 ± 36), March–May catches (192 ± 43.5) and June–July (231 ± 44 INR per kg). Catches predicted with high certainty to involve dolphin oil fetched the lowest prices (103 ± 73 INR per kg), perhaps due to faster putrefaction or higher catches at lower effort. Prices of gillnet-captured *Clupisoma* were the highest (186 ± 74 INR per kg). Prices showed minor variations within a month (CV < 10%), depending on time of sale (proximity to festivities, observance days or holidays) and source of purchase (local buyers or remote markets). Between 2010–20, *Clupisoma* catch prices in the August–November season remained stable or increased at annual rates of 1–6%, well below the inflation rate for fish at 9% in India (Fig. 4). In all other seasons, price increases were at or above the inflation rate. The ready availability of dolphin oil and its use in the monsoon season would have facilitated consistent and abundant catches to be sold in bulk at low and stable prices, rather than higher prices.

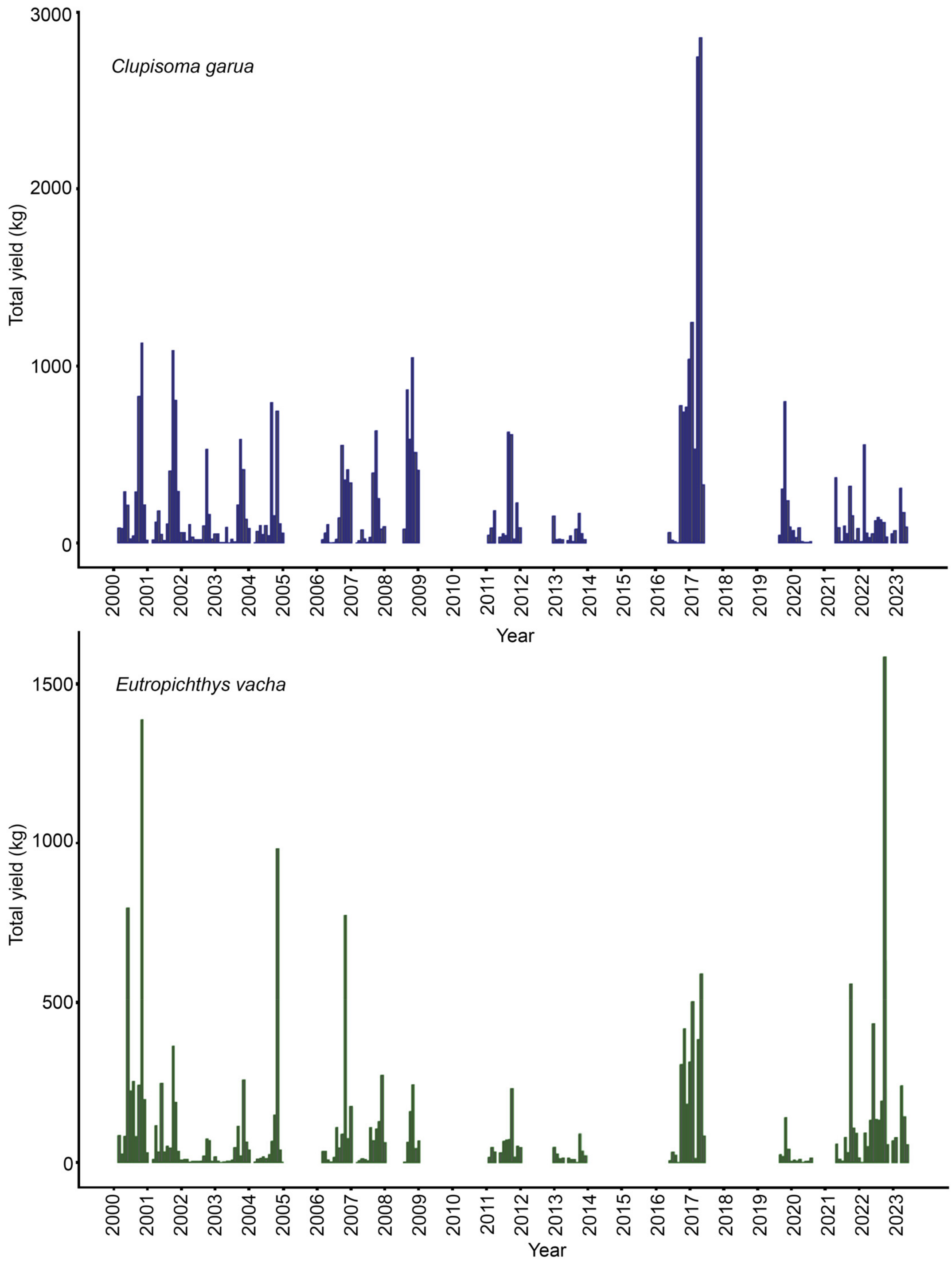


Figure 2. Trends in the yield of *Clupisoma garua* and *Eutropichthys vacha* at Settlement A between 2000 and 2023.

Appearance and odour of *Clupisoma* fish samples

The appearance of *Clupisoma* captured with dolphin oil was discoloured, pale-faded or white, in contrast with *Clupisoma* captured on unbaited lines or in gillnets which retained their colours (Fig. 5). We also found that dolphin-oil samples degraded, with their odour becoming worse at a faster rate than net samples.

Estimating colour levels of photographs

RGB levels of fish samples caught with dolphin oil were generally higher than those caught without dolphin oil. Pair-wise differences between R, G and B levels were statistically significant (Table 2). Effect sizes of treatment

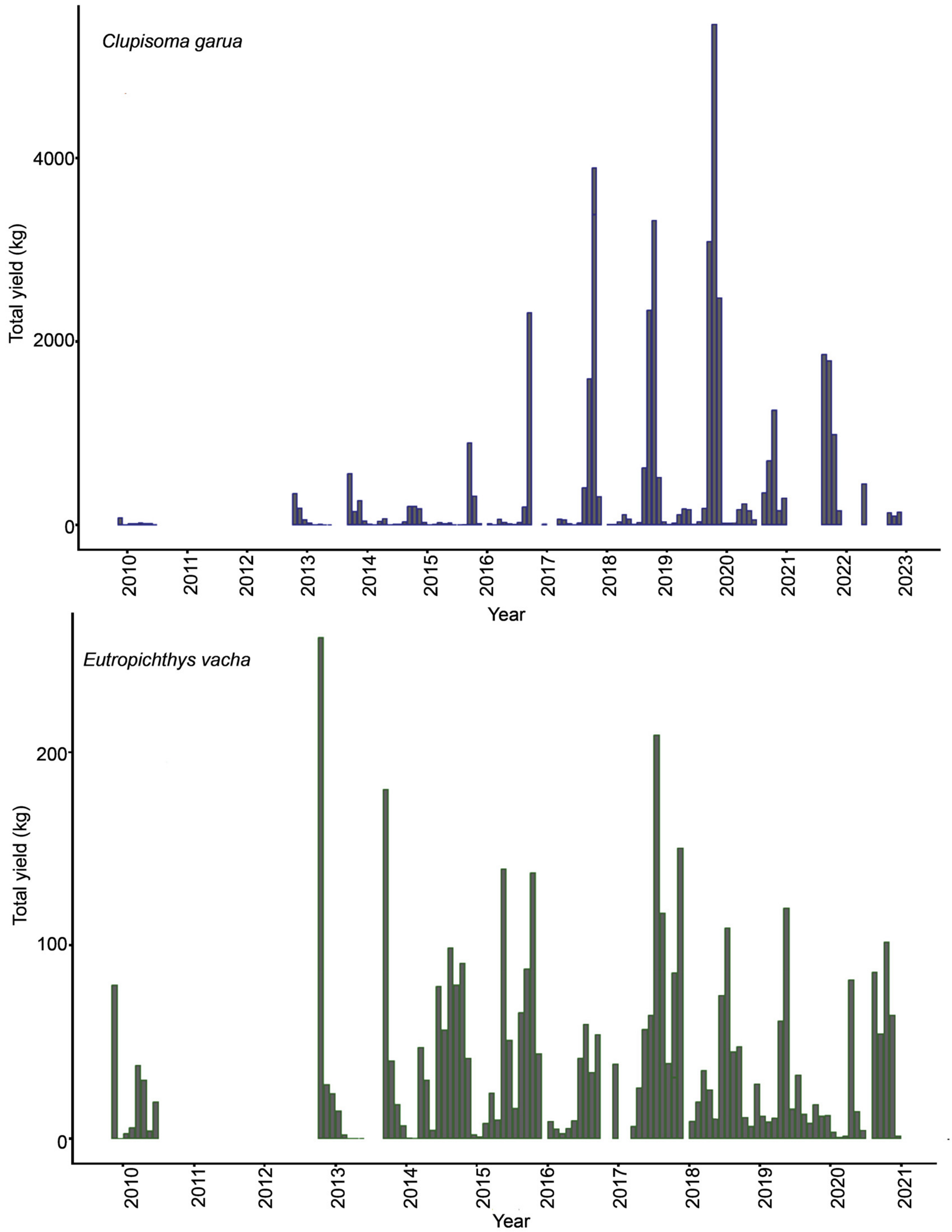


Figure 3. Trends in the yield of *Clupisoma garua* and *Eutropichthys vacha* at Settlement B between 2010 and 2023.

and time on R, G and B levels indicated that colour differences remained consistent and any changes over time may not have affected the accuracy of detecting paler fish (oil catches) from colour-retaining fish (net catches) (Table 2).

Visual tests

Colour-perception tests carried out by a random sample of participants (n = 51) revealed that it was possible for an average of 80–85% of respondents to accurately distinguish between the two, as against similar controls (Fig. 5, Table 3).

Table 1

Seasonal & annual trends in total catches, effort & catch-per-unit-effort (CPUE) at Settlement B (2013-20). Season: ASON (Aug–Nov); DJF (Dec–Feb); MAM (Mar–May); JJ (Jun–Jul). Pearson r values represent correlation with year. Yields & effort showed increases in all seasons except Dec-Feb. CPUE showed weak significant trends across seasons, indicating stable or slightly increased catches. Statistical significance levels: ^{NS} = Not significant, ^P > = 0.05, *P > = 0.01, **P > = 0.001, ***P < 0.001.

Variable	Season	Pearson's r	t, df	P-value
Total catch (kg)	ASON	0.38	2.18, 28	0.038*
	DJF	0.32	1.219, 13	0.24^{NS}
	MAM	0.68	3.93, 18	0.0009***
	JJ	0.628	2.67, 11	0.02*
	Annual	0.23	2.098, 76	0.039*
Number of fisher-days	ASON	0.447	2.648, 28	0.013*
	DJF	0.346	1.33, 13	0.206^{NS}
	MAM	0.55	2.79, 18	0.012*
	JJ	0.67	2.98, 11	0.012*
	Annual	0.287	2.617, 76	0.01*
CPUE (kg/fisher-day)	ASON	0.32	1.808, 28	0.08^
	DJF	0.20	0.74, 13	0.47^{NS}
	MAM	0.414	1.93, 18	0.07^
	JJ	0.43	1.58, 11	0.14^{NS}
	Annual	0.219	1.95, 76	0.05^

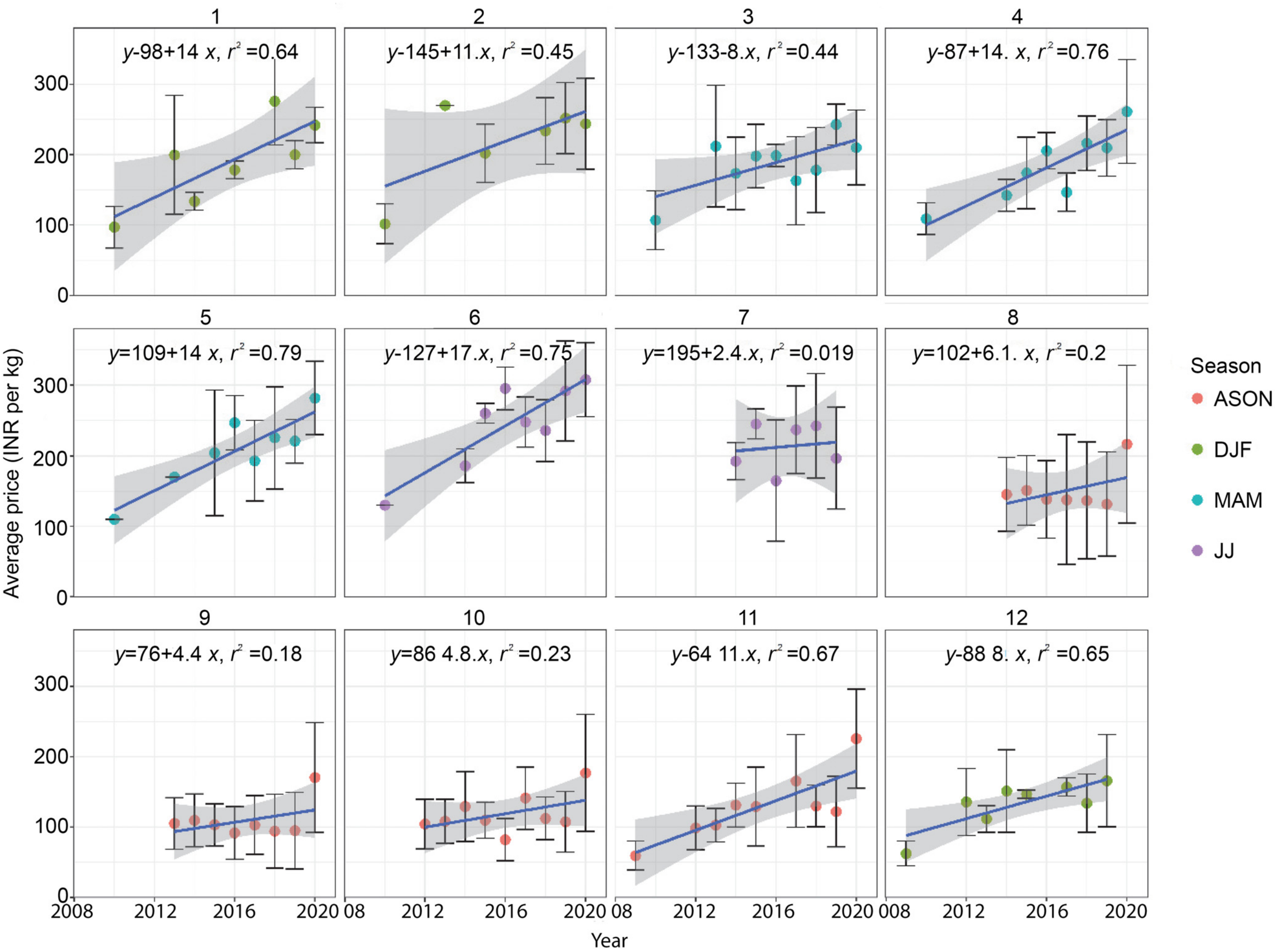


Figure 4. Trends in price of *Clupisoma* (INR per kg vs. time). During peak season (ASON), price trends did not show consistent increases.

Table 2

Two-way repeated measures ANOVA showed statistically significant (P < 0.05) treatment effects (oil vs. net) & time effects on RGB values of fish images

Colour values compared	Effect	DFn	DFd	Test statistic, P-value	Generalised eta-squared (ges) value
Red (R)	Treatment	1	2	F = 43.15, P = 0.02	0.79
	Time	6	12	F = 65.05, P < 0.0001	0.925
	Treatment: Time	6	12	F = 2.19, P = 0.117	0.13
Mean R	Pairwise t-test	20		t = –12.6, P < 0.0001	–
Green (G)	Treatment	1	2	F = 39.99, P = 0.024	0.85
	Time	6	12	F = 44.63, P < 0.0001	0.85
	Treatment: Time	6	12	F = 1.66, P = 0.214	0.09
Mean G	Pairwise t-test	20		t = –15.1, P < 0.0001	–
Blue (B)	Treatment	1	2	F = 37.05, P = 0.026	0.84
	Time	6	12	F = 22.59, P < 0.0001	0.80
	Treatment: Time	6	12	F = 0.498, P = 0.798	0.04
Mean B	Pairwise t-test	20		t = –14.4, P < 0.0001	–

DFn & DFd denote degrees of freedom in numerator (effect) & denominator (error) of the F-statistic.

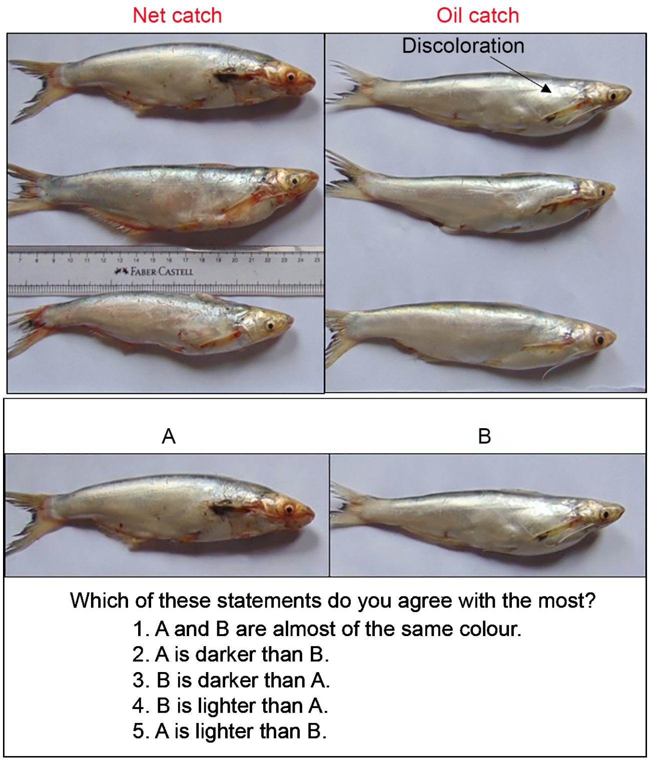


Figure 5. Top: visual comparison of *Clupisoma garua* captured in gillnets and with dolphin oil. Oil-captured fish look paler and discoloured. Bottom: an example of the visual tests conducted to differentiate between *Clupisoma garua* caught with and without dolphin oil.

Decision-making process for detection and estimation of oil use

Fish catches with dolphin oil in the August–November (ASON) season were higher in weight but had the lowest market prices (Fig. 6). Fish catches with gillnets had higher prices and lower catch weights (Fig. 6). We found that unambiguous detection of dolphin oil use in fishing was possible based on catch weight alone, provided it was during the peak fishing season (Fig. 7). Alongside season and price-weight data, the appearance of discoloured fish served as a confirmatory indicator of catches with dolphin oil (Figs. 5 and 8).

Table 3

Results of exact binomial test & McNemar's χ^2 test to check for statistical significance of differences between control & treatment images checked for appearance by respondents. All results indicated strongly significant statistical differences (for P < 0.05). Pr refers to the proportion of respondents who gave the correct answer.

Test	Colour differentiation	Hypothesis	Test statistic, P-value
Binomial test (n = 51) Exact binomial test to detect whether a significant proportion of participants gave correct answer for each test, as compared to 50/50 correct/incorrect answers.	Treatment: Difference should be detected between two fish caught with and without dolphin oil use (one each)	Null: p = 0.5 Alternative: p > 0.5	x = 42, P < 0.001, Pr = 0.823
	Treatment: Difference should be detected between two fish caught with and without dolphin oil use (one each)	Null: p = 0.5 Alternative: p > 0.5	x = 43, P < 0.001, Pr = 0.843
	Control: Difference should not be detected between two fish caught without dolphin oil use	Null: p = 0.5 Alternative: p > 0.5	x = 38, P = 0.0003, Pr = 0.745
	Control: Difference should not be detected between two fish caught with dolphin oil use	Null: p = 0.5 Alternative: p > 0.5	x = 32, P = 0.046, Pr = 0.627
Binomial test (n = 102) for misclassification rate (whether correct answer was given both for treatment & control images by participants)	Treatment 1 + Control 1	Null: p = 0.5 Alternative: p > 0.5	x = 80, P < 0.001, Pr = 0.784
	Treatment 2 + Control 2	Null: p = 0.5 Alternative: p > 0.5	x = 75, P < 0.001, Pr = 0.735
McNemar's χ^2 test (n = 51) to detect correct answers to paired control & treatment questions	Paired treatment & control questions	Probability of correct answers to control and treatment indicate significant, non-random association	McNemar's χ^2 = 4.558, P = 0.03, df = 1

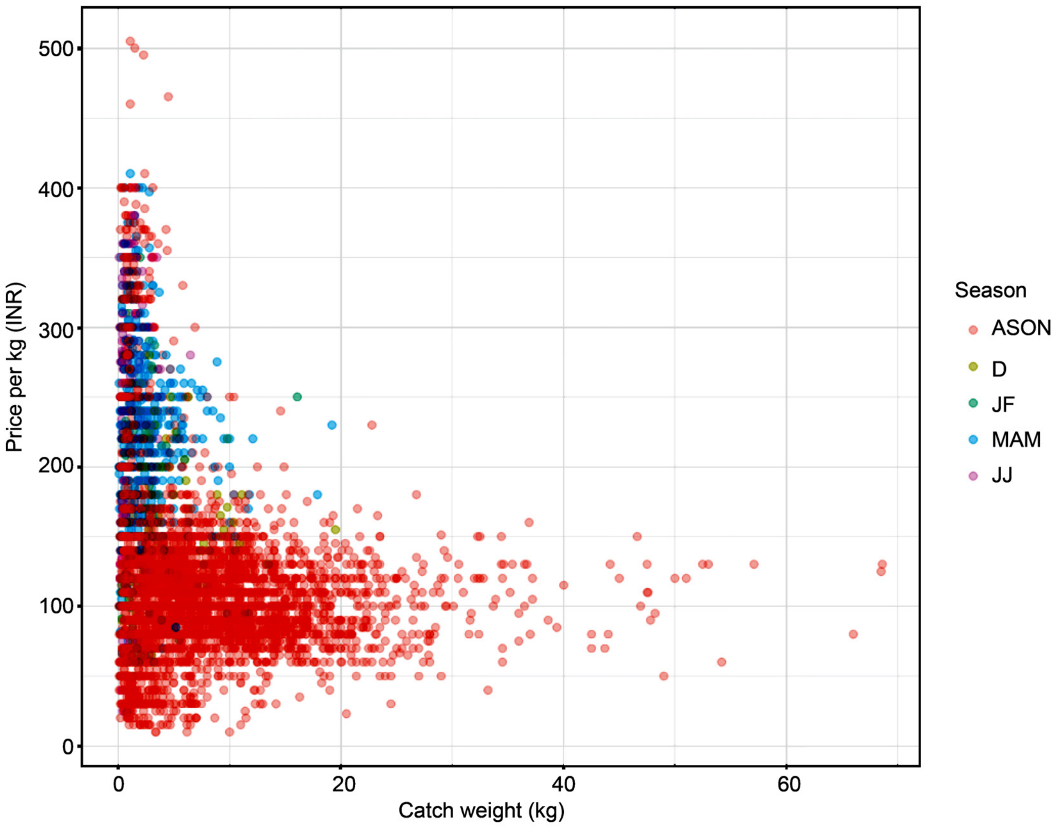
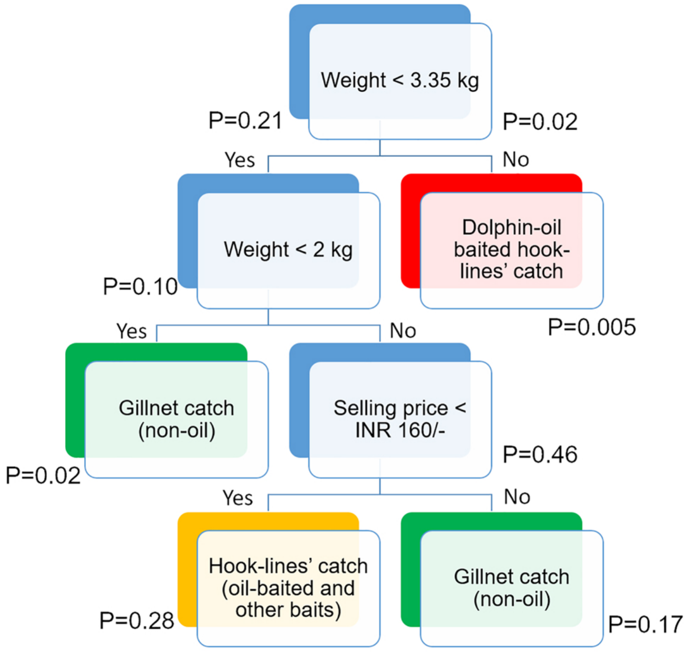


Figure 6. A scatterplot of *Clupisoma* catch weights in kg and prices per kg (INR).



Overall misclassification rate: 7.3%
Selling price as of 2020, adjusted by inflation rate.

Figure 7. A classification tree model used to predict the prevalence of dolphin oil in catches of *Clupisoma* at peak season (August–November).

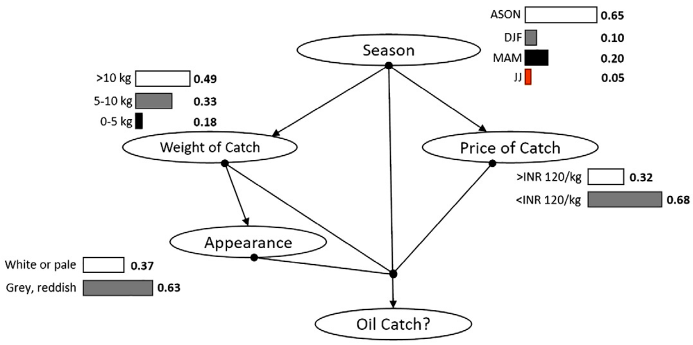


Figure 8. Bayesian network-based decision system to predict oil-bated catches, based on conditional probabilities of season, weight, colour and price.

Annual use of dolphin oil and potential removal rates from oil-based catches

Based on our data and the rules identified (Figs. 7 and 8), we found that catches at Settlement A which used dolphin oil were quite small in size and not confirmed from 2020 onwards. This was in sharp contrast to Settlement B where catches which used dolphin oil continued to dominate *Clupisoma* catches (Fig. 9). At Settlement B, we estimated that, on average, > 85% of the total annual *Clupisoma* catches resulted from the use of dolphin oil. We conclude that this fishery is currently sustained through the continued use of dolphin oil. The average number of trips involving dolphin oil in the *Clupisoma* season was estimated at 700 ± SD 650 within one year across an average of 120 fishers. Based on these simulations, we predicted that one litre of dolphin oil may last one group of fishers between five and six trips, resulting in catches between 60–70 kg (± SD 12). Based on oil yields of individual Ganges river dolphins, we estimated that five to seven (range: 1–14) dolphin carcasses would be required to maintain the estimated level of fishing at Settlement B.

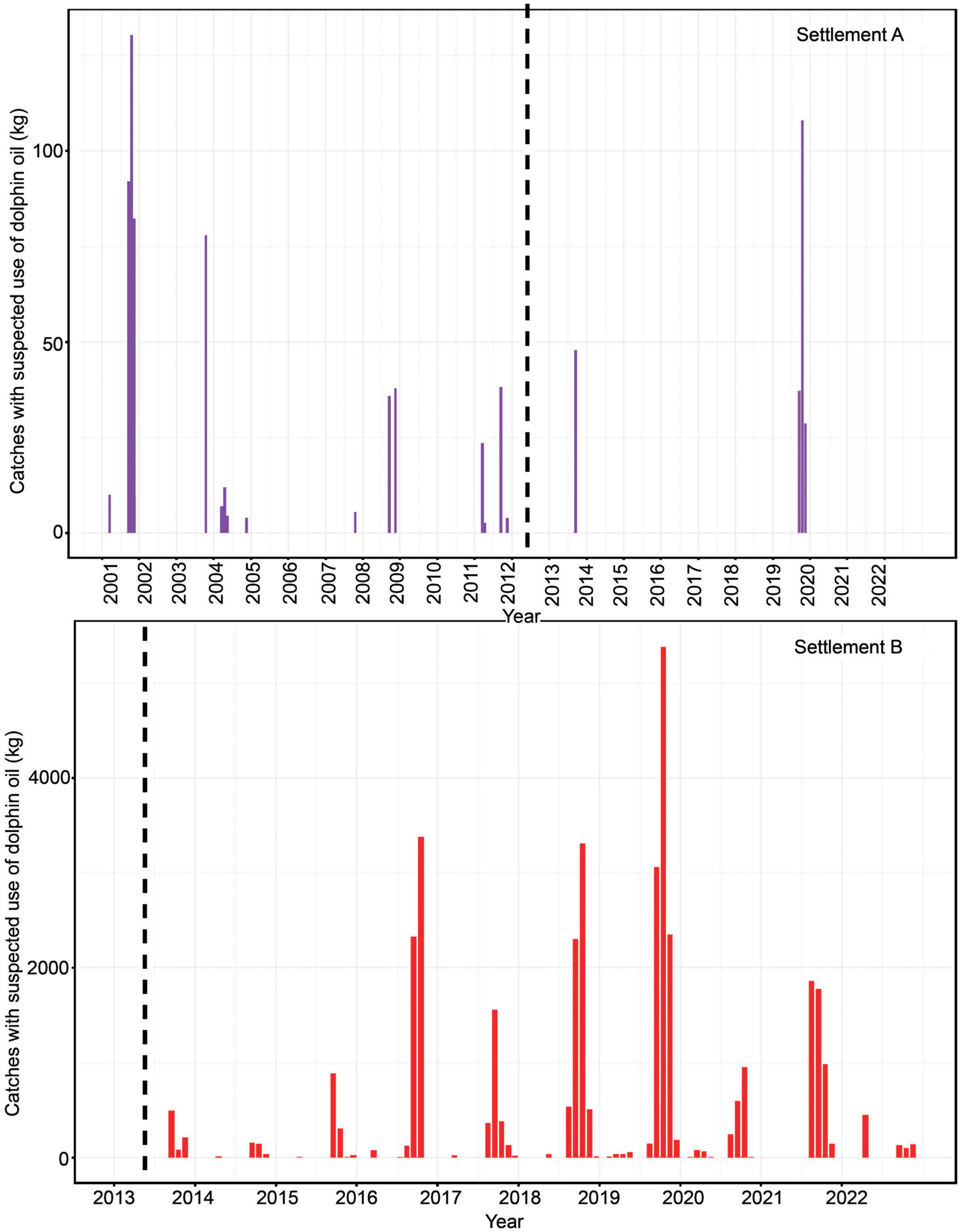


Figure 9. Estimates of oil-bait fishing practices for Settlements A and B. Since 2020, there were no recorded oil-bait catches at Settlement A. We received three unconfirmed reports of oil use in the post-monsoon season 2020–21. At Settlement B, oil-bait catches were estimated to be much higher and directly related to total *Clupisoma* yields. Dashed line indicated the start of a programme in 2013 involving selected fishers to report illegal fishing practices.

DISCUSSION

Applications and significance

Our method provides a new tool to monitor the use of Ganges river dolphin oil in fishing activities. We successfully used image analyses and visual tests to distinguish between samples of the catfish *Clupisoma garua* known to be caught both with and without dolphin oil, with strong statistical significance in our results. This method can support the efficient detection of dolphin-oil use based on observations of fish catches during market surveys. It is possible that similar studies could be useful for river dolphin species in the Amazon, where the use of carcasses as fishing bait is still a significant threat (Beltrão *et al*., 2017; Franco *et al*., 2016; Brum *et al*., 2015).

This new method is based on simple rules and can be easily implemented by monitoring agencies, such as state or district-level wildlife and fisheries departments. Indirect and low-cost methods based on visual inspection of fish catches have not been explored before, even though costs are a critical consideration for state-level monitoring agencies. Genetic and advanced chemical studies are the only alternative, but these are often expensive and require specialised inputs. Our method can be applied in remote locations. Approaching the problem from the fisheries perspective may have further advantages: (1) it can make the collection of evidence easier and more robust; (2) it can provide some level of anonymity to the person gathering data and reduce the risk of community conflicts; and (3) it can make the identification of fishers engaged in illegal activities more targeted. In India, conviction rates for wildlife crimes, including hunting, trade and use of wildlife products, are extremely low (Malaviya, 2018) – perhaps as low as 2–3% (The Hindu, 2019). This points to a lack of detection and/or weak enforcement, despite high levels of illegal activity in some regions.

Including local fishers

Importantly, our method is based on the scientific testing of local fishers' understanding that fish caught with dolphin oil display faster discoloration than others. The inclusion of local knowledge and expertise can help reduce bycatch (Zollett, 2008), providing additional information on the use of both river dolphin and alternative oils, which can also contribute to threat assessment methods. While this new technique draws on a specific source of local knowledge, we understand that our method currently relies on visual tests alone and will be best deployed as a rapid check in sites that would benefit from stronger surveillance. If deemed necessary, future studies can confirm the robustness of our method, including chemical analyses through lab tests on fish samples suspected and known to be captured with dolphin oil, based on the fatty acid profile and oil composition (Pilleri *et al*., 1971; Tsuyuki & Itoh, 1972) or other genetic methods. These tests fell beyond our available resources. It is also important to recognise that this method only applies where dolphin oil is used as bait. In other areas, dolphin oil is traded for its alleged medicinal properties and this method cannot be applied.

Dolphin oil has various possible applications as bait. Fishers described some possible applications which we could not find in the existing literature. For example, fishers reported that dolphin oil is poured close to set gillnets in order to attract *Clupisoma*. Fishers also reported that dolphin oil is used to attract catfish species such as *Mystus* and *Wallago*. For the *Eutropichthys* species of catfish, fishers indicated that vegetable oil (locally called *Dalda*) can also be used to great effect. Between 2013–17, fishers also experimented with mixtures of palm and fish oil in our study area but did not find these to be as effective. Our informants also shared a new method where dolphin oil is mixed with mud in and around mosquito-net barricades to attract and capture *Mystus* catfish. With such a diverse range of applications, it is clear that fish catches are not always simple to define, reinforcing the need for concerted monitoring to improve the precision and accuracy of detecting dolphin-oil exploitation. In addition, a combination of stronger regulations and incentives may help break the market chain which is crucial to reducing this illegal trade (Oyanedel *et al*., 2022).

Biochemical research

The observed discoloration of *Clupisoma* fish could be due to changes in the concentration of neurohumors upon contact with or exposure to dolphin oil. Parker (1940) noted such an effect on catfish injected with oil in the laboratory. Docosahexanoic acid is a known constituent of Ganges dolphin oil (Tsuyuki & Itoh, 1972) and inhibits melanin synthesis in laboratory mice (Balcos *et al*., 2014). Fatty acid volatiles could help reduce melatonin or trigger chromatophore redistribution and motility so that discoloration could then result from stress-induced pigmentation changes upon exposure to oil (Souza *et al*., 2019; Cole, 1954). In contrast, higher redness of gillnet-caught fish could occur from stressors, such as entanglement (Sabzipour *et al*., 2019). Further investigation is required to determine the exact mechanism(s) of discoloration. Experimental and biochemical profiling studies of different oils could help identify improvements to proposed alternatives to dolphin oil, such as fish scrap, shark or palm oil (Lal Mohan *et al*., 1996; Sinha, 2002). It has been found that the uptake of alternative oils is not adequate to prevent the continued use of dolphin oil (Kolipakam *et al*., 2020). Exploring the active ingredients in dolphin oil could therefore enable alternative oils to be developed. Furthermore, it has also been noted that the effectiveness of alternative oils may vary between regions and seasons and/or in relation to the combination of bait (Das *et al*., 2019). Our study therefore makes a case for further biochemical research into effective alternative oils that could provide stable catches of *Clupisoma* and maintain the shelf life of fish, thereby raising the sale price and providing wider advantages for fishing and conservation.

Implications of estimated mortality rates for conservation

Our estimates of five to seven dolphins used or removed per year from one settlement with 100–200 fishers are alarming, especially as they amount to 3–4% of the most recent dolphin abundance estimate of 200 (CV = 5%) in the study area (Kelkar *et al*., 2022a). While our estimate is likely to be conservative, it is still higher than the Potential Biological Removal threshold for this species (Wade *et al*., 1998; Moore, 2013; Moore *et al*., 2013; Punt *et al*., 2021). Furthermore, the availability of dolphin oil in a particular location is not only related to mortality but also trade with nearby fishing areas. Investigating these trade networks is essential, in addition to the design and implementation of a systematic enforcement plan. In order to focus on fishers engaged in illegal activities, a precise approach is needed. We hope this new method can provide a starting point. There are several multi-scale river dolphin conservation initiatives underway in India, mostly through programmes which engage fishing communities as river dolphin 'stewards'. Unfortunately, we know of cases where some 'stewards' are exploiting these programmes to disguise the continued use of dolphin oil, which suggests that these programmes should still be combined with effective monitoring and enforcement. Our fisheries data analyses indicate that use of dolphin oil in the *Clupisoma* fishery is not yet resulting in diminished catches. Fishers are therefore likely to continue with this illegal practice, but catches may fluctuate due to environmental variability and the availability of dolphin oil.

Future directions

While this new method helps address the problem of river dolphin bycatch, the problem still needs to be understood and tackled at broader and higher levels. The reporting of accidental bycatch is almost absent, while socioeconomic incentives to report accidental bycatch should be stronger in order to compete with the lucrative illegal trade (Teh *et al*., 2015). In India, a bycatch policy framework is needed to develop a tiered system of measures, which could include penalties, fines, sanctions and net confiscations, proportionate to the frequency of accidental bycatch. This may provide fishers who occasionally bycatch a dolphin with an opportunity to alter their fishing practices, either by changing gear, timing or location, while fishers who repeatedly bycatch dolphins could be penalised in accordance with existing legislation. It must also be highlighted that these systems depend on effective monitoring of fishing boats operating in river dolphin habitats. Riverine capture fisheries in India are highly informal, with almost no barriers to entry and exit (Kelkar & Arthur, 2022). This means fishing gear, practices, vessel type and effort are rarely registered or monitored. These data gaps point to the need for larger policy changes to improve decision making and reduce fishing-induced mortality of Ganges river dolphins.

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AUTHOR CONTRIBUTION

Conceptualisation – NK, SD. Data curation – NK, SD. Formal analysis – NK. Funding acquisition – NK. Investigation – NK, SD. Methodology – NK. Project administration – NK, SD. Resources – NK. Software – NK. Supervision – NK. Validation – NK, SD. Visualisation – NK. Writing: original draft – NK. Writing: review and editing – NK, SD.

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Supplementary Material

Figure S1. (A–B) A local fisher catching *Clupisoma garua* with dolphin oil and chicken offal as bait. (C–D) Dolphin oil is poured into the water and fish are hooked with baited lines. (E) *Clupisoma* are also caught in gillnets. (F) Catfish in a fish market.

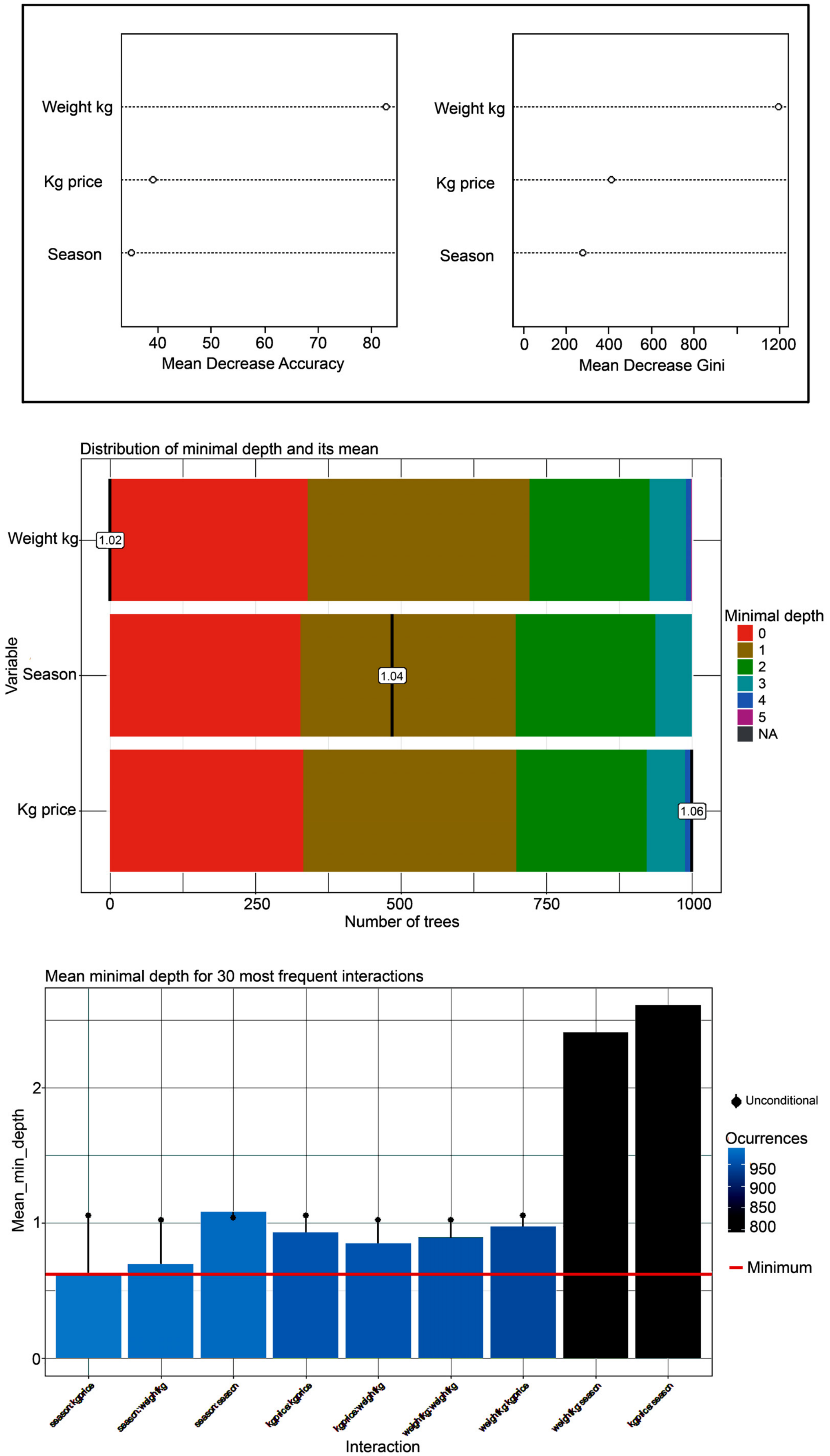

Figure S2. Diagnostic tests of Random Forest classification models: (1) variable importance plots; (2) distribution of minimal depth; (3) mean minimal depth of variable interactions.

Assessment (Model: Model1, Node: OilCatch)

Parent Node(s)				OilCatch			
Appearance	**PriceOfCatch**	**WeightOfCatch**	**Season**	**Yes**	**No**	**Not sure**	bar charts
White or pale appearance	Above 120 Rs/kg	Above 10 kg	ASON	0.99	0.01	0.0	
			DJF	0.65	0.35	0.0	
			MAM	0.85	0.15	0.0	
			JJ	0.4	0.6	0.0	
		5-10 kg	ASON	0.9	0.1	0.0	
			DJF	0.5	0.4	0.1	
			MAM	0.75	0.25	0.0	
			JJ	0.4	0.5	0.1	
		0-5 kg	ASON	0.8	0.2	0.0	
			DJF	0.6	0.25	0.15	
			MAM	0.7	0.25	0.05	
			JJ	0.3	0.6	0.1	
	Below 120 Rs/kg	Above 10 kg	ASON	1.0	0.0	0.0	
			DJF	0.7	0.2	0.1	
			MAM	0.95	0.05	0.0	
			JJ	0.6	0.3	0.1	
		5-10 kg	ASON	0.95	0.05	0.0	
			DJF	0.7	0.3	0.0	
			MAM	0.95	0.05	0.0	
			JJ	0.5	0.4	0.1	
		0-5 kg	ASON	0.8	0.2	0.0	
			DJF	0.6	0.4	0.0	
			MAM	0.75	0.25	0.0	
			JJ	0.4	0.6	0.0	
Grey colors, reddish appearance	Above 120 Rs/kg	Above 10 kg	ASON	0.2	0.8	0.0	
			DJF	0.1	0.9	0.0	
			MAM	0.15	0.85	0.0	
			JJ	0.05	0.95	0.0	
		5-10 kg	ASON	0.15	0.85	0.0	
			DJF	0.05	0.9	0.05	
			MAM	0.1	0.9	0.0	
			JJ	0.05	0.95	0.0	
		0-5 kg	ASON	0.05	0.9	0.05	
			DJF	0.03	0.9	0.07	
			MAM	0.01	0.9	0.09	
			JJ	0.01	0.89	0.1	
	Below 120 Rs/kg	Above 10 kg	ASON	0.25	0.75	0.0	
			DJF	0.12	0.88	0.0	
			MAM	0.2	0.8	0.0	
			JJ	0.1	0.9	0.0	
		5-10 kg	ASON	0.2	0.8	0.0	
			DJF	0.08	0.9	0.02	
			MAM	0.15	0.75	0.1	
			JJ	0.05	0.85	0.1	
		0-5 kg	ASON	0.05	0.95	0.0	
			DJF	0.01	0.99	0.0	
			MAM	0.025	0.975	0.0	
			JJ	0.01	0.99	0.0	

Figure S3. An example of a Conditional Probability Table (CPT) used in the software MSBNx to construct the Bayesian network, based on the rules identified by the Random Forest model.