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Overlap between Atlantic bluefin tuna spawning grounds and observed Deepwater Horizon surface oil in the northern Gulf of Mexico

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ABSTRACT

The 2010 Deepwater Horizon oil spill impacted the northern Gulf of Mexico (GOM) during the spring spawning season of Atlantic bluefin tuna (BFT). Overlap between BFT spawning habitat and surface oil in the northern GOM was examined using satellite-derived estimates of oil coverage, and spawning habitat models. Results suggested that although eggs and larvae were likely impacted by oil-contaminated waters in the eastern GOM, high abundances of larvae were located elsewhere, especially in the western GOM. Overall, less than 10% of BFT spawning habitat was predicted to have been covered by surface oil, and less than 12% of larval BFT were predicted to have been located within contaminated waters in the northern GOM, on a weekly basis. Our results provide preliminary but important initial estimates of the effects of the spill on larval BFT mortality, as concern continues over the appropriate management responses to impacts of the spill.

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1. Introduction

On April 20th, 2010, the Deepwater Horizon oil rig exploded while drilling on the Macondo prospect in the Gulf of Mexico (GOM). During this incident, the wellhead was damaged, and oil began leaking into the water column. Initial efforts to seal the well were unsuccessful until achieved in September 2010, by which time an estimated 4.9 million barrels of oil were discharged into the ocean environment (Camilli et al., 2010; Crone and Tolstoy, 2010).

The GOM marine and coastal environment is biologically diverse, and supports a variety of commercial and recreational fisheries. Many species use the GOM for spawning or nursery habitat, and there has been considerable concern regarding the impact of the spilled oil, petroleum byproducts and dispersants on marine life. Particular attention has been focused on the Atlantic bluefin tuna (BFT), a large, highly migratory species that spawns in the GOM during spring (Richards, 1976, 2010; Scott et al., 1993). Despite the pan-Atlantic range of BFT, the GOM is the only confirmed, major spawning location for the western Atlantic stock (Richards, 1976; Scott et al., 1993). Spawning occurs predominantly from April to June, with a peak in May (Muhling et al., 2010). Due to their high

value as a food fish, BFT have been heavily exploited historically, and they are currently considered to be undergoing overfishing (McAllister and Caruthers, 2007). In addition, recent attention was given to the possibility of listing BFT under the CITES convention, which would prohibit international trade in the species. To accurately assess whether this action is justified, and to evaluate the effects of the oil spill on stock recruitment, information on the likely effects of the oil spill on the early life history stages of BFT in the GOM is required.

Both crude oil and weathered oil byproducts are highly toxic to fish eggs and larvae (Incardona et al., 2004). Oil contamination may cause increased mortality of eggs and larvae even at low concentrations (Carls, 1987; McGurk and Brown, 1996), and the addition of dispersants is likely to increase this effect (Couillard et al., 2005). Exposure to oil and oil byproducts also leads to a range of sub-lethal effects on fish eggs and larvae, including premature hatching (Carls et al., 1999), morphological malformations (Hose et al., 1996; Norcross et al., 1996) and genetic damage (Norcross et al., 1996). Low levels of dissolved oil hydrocarbons may also slow larval growth rates, and affect swimming and feeding behaviors (Tilseth et al., 1984). Mortality rates on malformed, premature or slow-growing larvae are likely to be extremely high (Carls et al., 1999; Rice et al., 1993).

In this study, the overlap between predicted BFT spawning habitat and surface oil in the northern GOM was estimated using

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satellite data for April and May, 2010. Spawning habitat was defined using a habitat model trained with archival data collected from previous spring ichthyoplankton cruises, and surface oil extent was estimated using a suite of satellite products. In addition, a preliminary product examining potentially contaminated water was developed. Overlap between spawning habitat and both surface oil, and potentially contaminated water, was quantified on a weekly basis between 19th April and 30th May, 2010.

2. Methods

2.1. Extent of surface oil and contaminated water

The Deepwater Horizon surface oil spill had many characteristics that permitted tracking the oil spreading on the ocean surface by means of satellite remote sensing. These included changes in surface reflectance due to the color of the oil, changes in surface wave dampening characteristics, and effects on sea surface temperature (SST).

Several satellite-derived products and analyses were generated using infrared and visible (red/green/blue – RGB and chlorophyll plus colorized dissolved organic material) data, as well as microwave radar observations. These were derived from polar orbiting NOAA (NOAA_15, 16, 17, 18, 19), NASA (Aqua and Terra) and European (Metop_A) satellites. These satellites provided at least 16 synoptic images in infrared and two images in visible ocean color every 24 h, depending on cloud cover. The Envisat (European Space Agency) satellite provided additional ocean color data. To overcome the issue of cloud interference, daily composite images of the infrared and ocean color imagery were used. Observations were also obtained from several international satellite based synthetic aperture radar (TerraSARX, Envisat, Radarsat1, Palsar, Ers2 and CosmoSkymed_1, _2, _3) sensors, with a variety of spectral and spatial resolutions (75 m–1 km). Due to the large area of the spill, individual satellite Synthetic Aperture Radar (SAR) coverage of the spill was incomplete. To address this limitation, daily SAR composite images were constructed using all available daily SAR passes.

Surface oil was identified using a combination of SAR and visible–RGB with and without sun glint (Mariano et al., 2011). The presence of surface oil was verified using NOAA Marine Pollution Surveillance Reports (MPSRs) and observations from different research vessels sampling in the GOM at the time of our analyses (e.g. personal communications J. Franks, Gulf Coast Research Laboratory, R.V. Tommy Munro, M. Woods, NOAA-AOML, R.V. Walton Smith). Separate weekly summaries of the obvious surface oil and contaminated water masses were derived and converted into shape files using ESRI ArcGIS software.

Water masses which passed through the surface oil were identified by their characteristic SST and color properties. The current direction was identified by tracking the water masses using sequential image analysis. Surface circulation patterns were verified from drifting buoy tracks compiled by the NOAA Atlantic Oceanographic and Meteorological Laboratory and Horizon Marine Inc. and using acoustic doppler current profilers available from NOAA's National Data Buoy Center. Complementary data derived from space borne altimeters (NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML)–CoastWatch data portal: <http://www.aoml.noaa.gov/phod/dataphod/work/trinanes>) were also used to validate the current direction. Water that was either covered in visible surface oil, or was observed to have passed through surface oil was “tagged”, and considered to be potentially contaminated (PCW). The estimated surface area (km²) of these weekly observed surface oil and weekly PCW extents were then calculated in ArcGIS. Boundaries of potentially contaminated water masses were identified from SST and ocean color properties.

The satellite observations of anomalous surface light reflectance, temperature and roughness, combined with *in situ* observations, reduced our uncertainty in defining the location of oil contamination. Unfortunately, there was no mechanism to estimate oil concentration in the areas identified as suspected of containing contaminated water. However, because the oil–dispersant mixture is considered toxic at very low concentrations, we assumed that eggs and larvae located within these water masses could be negatively impacted.

2.2. Spawning habitat model

Relationships between occurrences of larval BFT and environmental conditions were defined using a combination of historical cruise data, and remotely sensed satellite products. Larval BFT data from the surveys were available from the National Marine Fisheries Service Southeast Area Monitoring and Assessment (SEAMAP) Program. Oblique bongo net tows were completed across a $1 \times 1^\circ$ grid of stations (the SEAMAP grid) in the northern GOM each year, in late April through to the end of May, with sampling continuing into June in some years (Scott et al., 1993). Bongo nets were 61 cm in diameter, fitted with 333 μ m mesh, and towed obliquely as described in Scott et al. (1993) and Richards et al. (1993), from 200 m depth or within 10 m of the bottom in shallower water. Samples from one side of the bongo net were sorted, and larvae were identified to the lowest possible taxa at the Sea Fisheries Institute Plankton Sorting and Identification Center, Gdynia and Szczecin, Poland. Identifications of scombrid larvae were validated at the Southeast Fisheries Science center in Miami, Florida (W.J. Richards, NOAA-NMFS, pers. comm.). In addition, observations of adult BFT in the GOM by date, from 1992 to 2009, by government observers on longline fishing vessels targeting other species were used.

Simple preference models were used to explore relationships between environmental variables and occurrences of bluefin tuna larvae. Each environmental variable was divided into 15–20 bins, and the proportion of stations within each bin that contained bluefin tuna larvae was calculated from historical data collections. All data were then combined into a spawning habitat model which used *in situ* environmental data to predict BFT larval occurrences (Muhling et al., 2010). The model was then used to forecast spawning habitat using only remotely sensed environmental data: sea surface temperature, surface chlorophyll, surface height and surface current velocities. For these analyses, SST data were derived from NOAA 15–19, NASA Aqua and Terra and European (MetOp-A) satellites, while chlorophyll was estimated primarily from the Aqua satellite, as described in the previous section. Sea surface height data were obtained from AVISO (multiple satellites), while estimates of total current velocities were available from the Hycom consortium's GOM ocean model (<http://www.hycom.org>). Historical values for each of these environmental variables were extracted at the location of each plankton sampling station, for the day it was sampled. The Hycom model commenced in 2003, therefore only data from cruises completed in 2003–2009 were used to train the model. The four environmental variables, in addition to day of the year, were combined into a multilayer perceptron neural network model, which predicted the probability of occurrence of BFT, and attempted to define environmental conditions where larvae have been most likely to be collected historically.

Artificial neural network models are useful and accurate predictive techniques which make no prior assumptions regarding data distribution, and can model highly nonlinear functions. They have been shown to perform as well, or better, than other leading non-parametric methods such as generalized additive models (Segurado and Araujo, 2004). Multilayer perceptrons consist of systems of interconnected nodes, connected by nonlinear transfer functions (Gardner and Dorling, 1998). To avoid overfitting, 20%

of the training data were withheld from the model fitting process, and each iteration of the model was evaluated against the withheld data. The model parameters which generated the lowest error on the withheld data were selected for use (Sherrod, 2003). A misclassification cost of 3.5 was included to account for inefficiencies in sampling of larvae due to gear avoidance, and set at the lowest possible value at which model sensitivity remained above 80% (Muhling et al., 2010).

To assess likely spawning areas for BFT during spring 2010, SST, chlorophyll, height and current velocities were extracted at weekly intervals from April 19th to May 30th, 2010, at 0.1° resolution. These data were run through the neural network habitat model trained using archival data, generating maps showing probabilities of larval BFT occurrence in the northern GOM at the time of the oil spill incident.

The SEAMAP ichthyoplankton survey in spring 2010 was conducted in the northern GOM between April 26th and May 23rd. The cruise was terminated a week early to allow re-deployment of the ship to research other aspects of the spill. These samples were collected using standard SEAMAP protocols (Scott et al., 1993), with the addition of a new sampling net, the shallow subsurface tow. This was a 505 μm mesh net attached to a standard 1 \times 2 m neuston frame, towed from the surface to a depth of 10 m, and back to the surface in an undulating fashion for 10 min. Similarly to the bongo net, the shallow subsurface net was fitted with a flowmeter, which allowed the estimation of larval densities per m^3 of seawater filtered. This new gear was added to target the upper mixed layer, where larvae of BFT and other scombrids are thought to be most abundant (Davis et al., 1990; Leis et al., 1991). Larval occurrences from all three gears in spring 2010 were used to validate the predictions of the spawning habitat model, and to assess the spatial extent of spawning activity of BFT in the GOM in late April and May. All larvae collected were measured, to the nearest 0.1 mm total length.

2.3. Predicted rates of larval mortality

In order to estimate the percentage of BFT larvae potentially impacted by oil in the northern GOM, larvae collected in shallow subsurface tows during the National Marine Fisheries Service Spring Ichthyoplankton Survey conducted in April and May, 2010 were enumerated. To estimate the number of larvae under one square meter of sea surface, larval densities (per m^3) were multiplied by 10 (the depth of the net tow). Spawning habitat in the northern GOM through spring 2010 was estimated on a weekly basis using the aforementioned habitat model. Habitat suitability was divided into four categories, based on the chance of occurrence of larval BFT: “poor” (<10% chance of occurrence), “fair” (10–20%), “good” (20–30%) and “very good” (30–40%). Overlap between weekly extent of each habitat category and both observed surface oil and PCW were quantified using ArcGIS batched tools. Mean larval densities (number under 1 m^2) were then multiplied by the area of poor, fair, good and very good BFT spawning habitat, to estimate the number of larvae of a size collected by our sampling gear in the northern GOM which may have been affected by surface oil, or PCW.

3. Results

Initial examination of relationships between larval BFT occurrences and environment found that BFT larvae were historically most likely to be collected in areas of moderate (~ 24 – 27°C) surface temperature, and lower (<40 cm) surface height (corresponding to areas outside the Loop Current, and warm-core eddy features) (Fig. 1). Surface chlorophyll and surface current velocities showed weaker, negative relationships.

Spawning activity was strongly related to day of the year, with the probability of occurrence of larvae historically increasing from mid April through to the end of May, and declining into June and

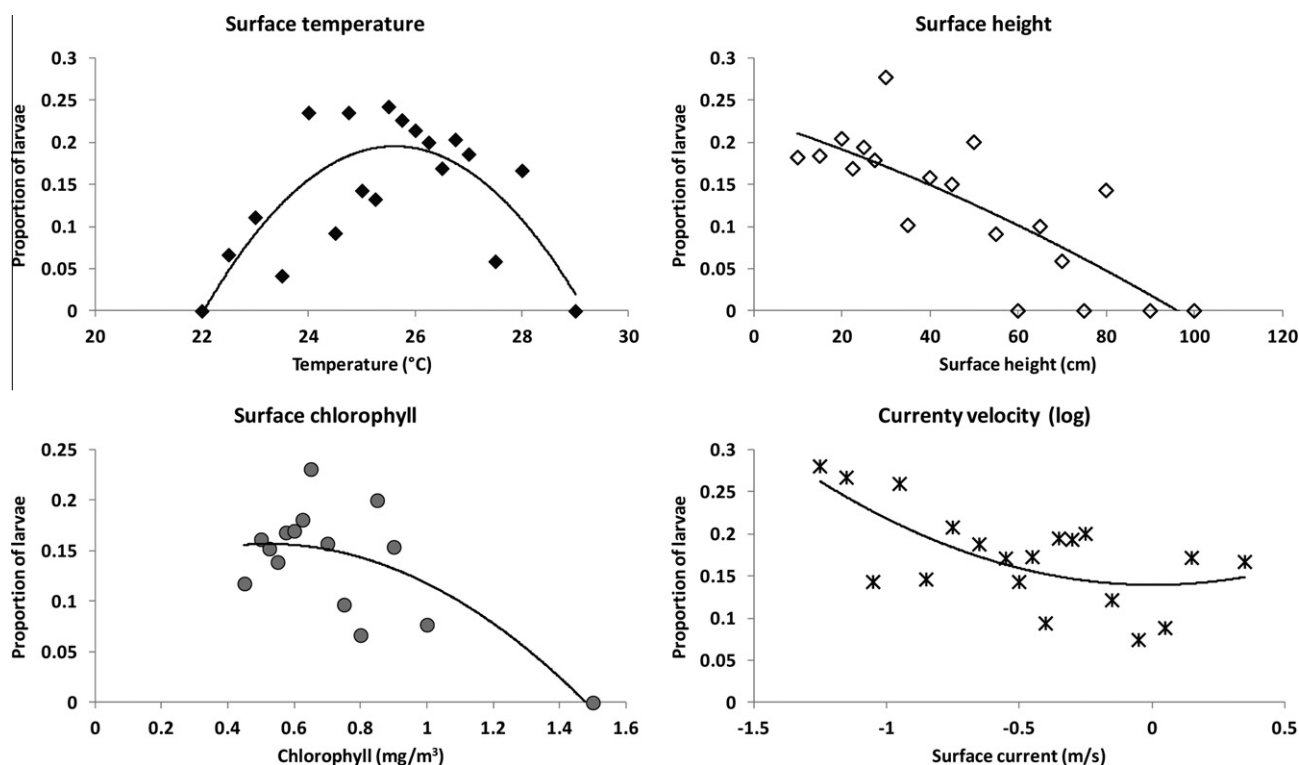


Fig. 1. Historical probabilities of collecting larval bluefin tuna in the northern Gulf of Mexico, 2003–2009, in relation to four remotely sensed environmental variables. First-order polynomial lines of best fit are also shown.

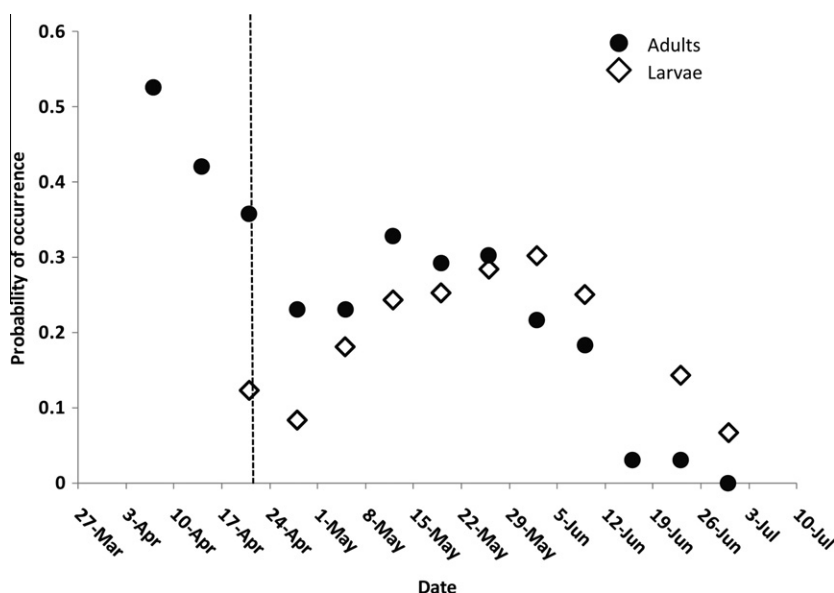


Fig. 2. Probability of occurrence of adult and larval BFT during spring, derived from plankton surveys (1982–2009) and longline catch data (1992–2009).

July (Fig. 2). Adult BFT were generally captured from the commercial longline fishery from early spring, suggesting that some may be present before spawning commences. However, catches generally fell as spring progressed and the GOM became warmer, becoming zero by the end June.

In total, 1051 larval bluefin tuna were collected in the spring 2010 survey, with the majority (1005) being collected in the shallow subsurface tow (Fig. 3). Relatively few larvae were collected east of 86° W by any of the gears used. Larval abundances were greatest west of 89° W, and the highest number catches concentrated around 94° W. As smaller larvae are more likely to be found close to actual spawning sites, larval distributions were also separated by size class (Fig. 4). The smallest larvae (less than ~5 days old: Brothers et al., 1983) were concentrated at two locations in the western and middle GOM, with some additional collections in the eastern GOM and east of the Yucatan Peninsula. Most larvae collected were between 2.5 and 5.0 mm in length.

Results of the neural network habitat model for spring 2011 highlighted the effects of day of the year, and surface temperature (Fig. 5), with probabilities generally increasing with time. Water masses with high sea surface height, such as the Loop Current, showed generally low probability of occurrence, and inshore waters with higher chlorophyll concentrations were also predicted to be less suitable. Larval sampling took place in the northern GOM from mid April through to May 22nd, therefore no information is available from the late part of May for larval bluefin abundance or distribution. Although sampling was not synoptic across the GOM through this time, larval distributions show general agreement with the predictions of the habitat model. BFT larvae were collected in and around what is very likely to have been oil contaminated waters, however extensive spawning also appeared to be taking place in the western GOM.

These results suggest that some BFT spawning habitat was likely to have been impacted by oil and oil-contaminated water during the spawning season. To quantitate this effect, the proportion of poor, fair, good and very good spawning habitat (as defined by probability of larval occurrence) covered by oil or contaminated water was determined (Fig. 6). The spatial extent of good (>20% probability of larval BFT occurrence), and very good habitat (>30% probability of occurrence) increased through time (Fig. 6), as did the spatial extent of surface oil. However, the proportion of spawning habitat

impacted by oil was generally predicted to be small (<10%). By the end of May, a considerable proportion of habitat in the eastern GOM was impacted by oil or contaminated water, however the western GOM remained largely unaffected.

Abundances of BFT larvae (fourth-root transformed) were well correlated with probabilities of occurrence generated by the neural network model (linear regression $R^2 = 0.42$, $p < 0.001$). Mean abundances for poor habitat were 0, although only one station was sampled in this habitat category, with 0.0015 larvae/m² in fair habitat ($n = 48$), 0.21 larvae/m² in good habitat ($n = 52$), and 0.33 larvae/m² in very good habitat ($n = 25$).

The percentage of larval BFT, of a size typically collected by the sampling gear used, predicted to have been impacted by oil increased from mid April through late May, 2010 (Table 1). On a weekly basis, up to 5.12% of larvae present were predicted to have been affected by visible surface oil, and up to 11.09% were potentially affected by contaminated waters.

4. Discussion

The Deepwater Horizon oil spill is considered to be the largest offshore oil spill in history (Camilli et al., 2010). The effects of the spill on the GOM ecosystem are likely to be complex, difficult to assess, and may remain largely unknown for many years. While direct exposure to oil, oil byproducts and dispersants almost certainly resulted in increased rates of mortality for many organisms, the effects of the incorporation of the oil into marine food webs are still to be determined. Despite this, soon after the oil spill, public and scientific attention focused on the potential impacts on important fisheries stocks, especially BFT.

BFT appear to spawn only during a short time window, and largely in the northern GOM, with some activity occurring in the north-western Caribbean (Muhling et al., 2011). Spawning is initiated by water temperatures of approximately 24 °C (Schaefer, 2001), with larval BFT development optimal at around 25 °C (Miyashita et al., 2000). Adult BFT likely find water temperatures of >28–30 °C physiologically stressful (Blank et al., 2004), and it has been hypothesized that observed deep diving behavior of adults in the GOM is for thermoregulatory purposes (Teo et al., 2007). Bycatch records from longline fishing vessels show declining occurrence of adult

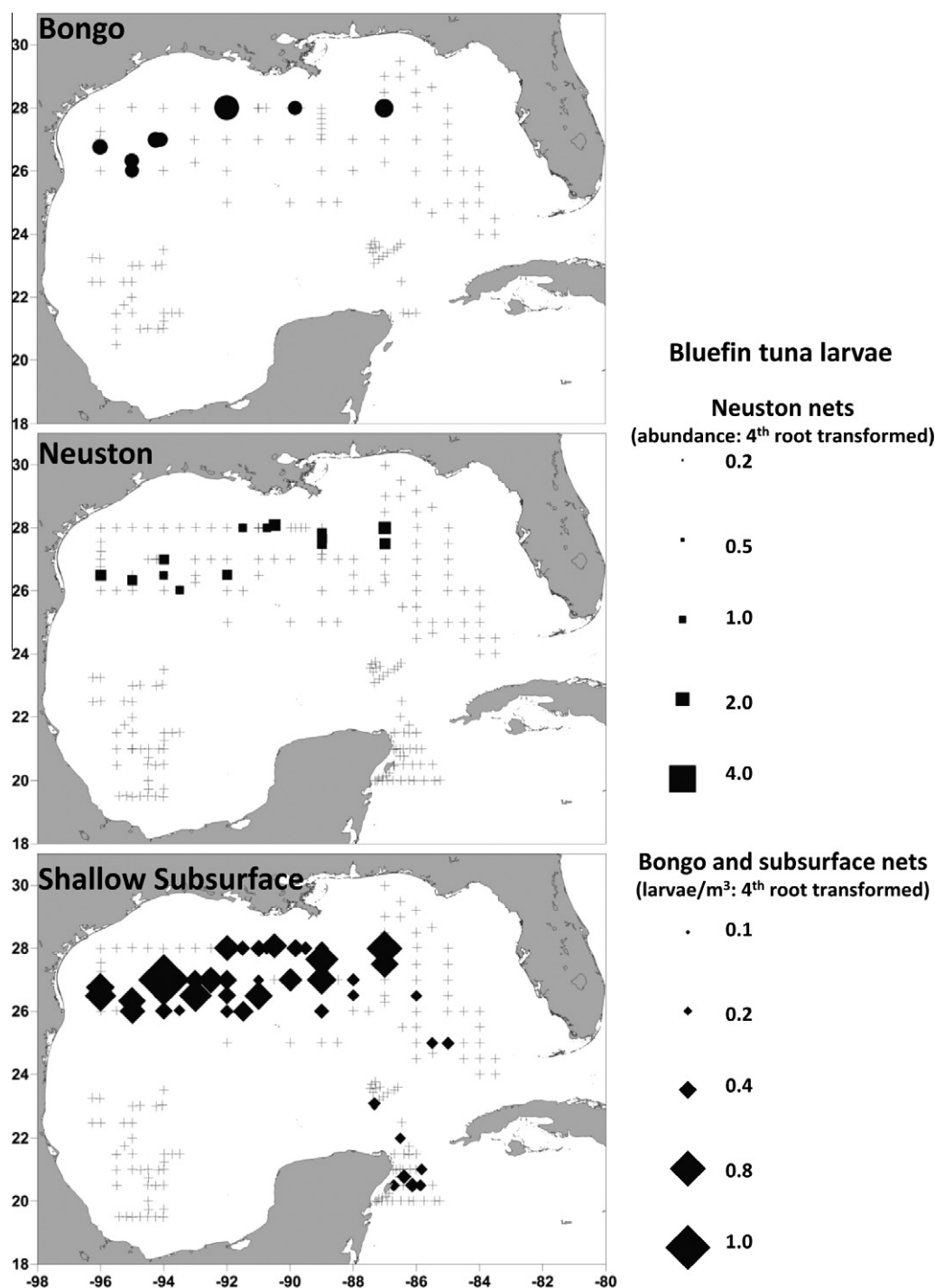


Fig. 3. Larval bluefin tuna collections by gear in the Gulf of Mexico, April 19th–May 23rd, 2010. Abundances have been 4th root transformed for clarity. Bongo and neuston nets are standard SEAMAP gear. The shallow subsurface tow is a 1 × 2 m standard neuston frame with a 505 µm mesh net, which samples from the surface to a depth of 10 m.

BFT through June, with none caught in July since 1992. If commencement of spawning requires a minimum water temperature, and adult BFT are unable to tolerate waters above a maximum temperature limit, then a specific temperature window exists for spawning activity. Any large-scale event that affects the northern GOM in spring thus has the potential to affect recruitment of entire year classes.

This study aimed to contribute to the understanding of potential impacts of the oil spill on BFT by examining the spatial and temporal overlap between surface oil, potentially oil-contaminated water,

and suitable habitat for BFT spawning. Estimates of spawning areas from remotely sensed data were consistent with those from previous studies using *in situ* environmental variables as predictors (Muhling et al., 2010). Larval BFT were predicted to be found across the northern GOM, with the exception of Loop Current waters and warm core eddy features, and continental shelf waters with high chlorophyll concentrations.

Due to the wind and circulation patterns present at the time of the spill, surface oil was primarily confined to an area immediately east of the Mississippi river delta, and north of the Loop Current.

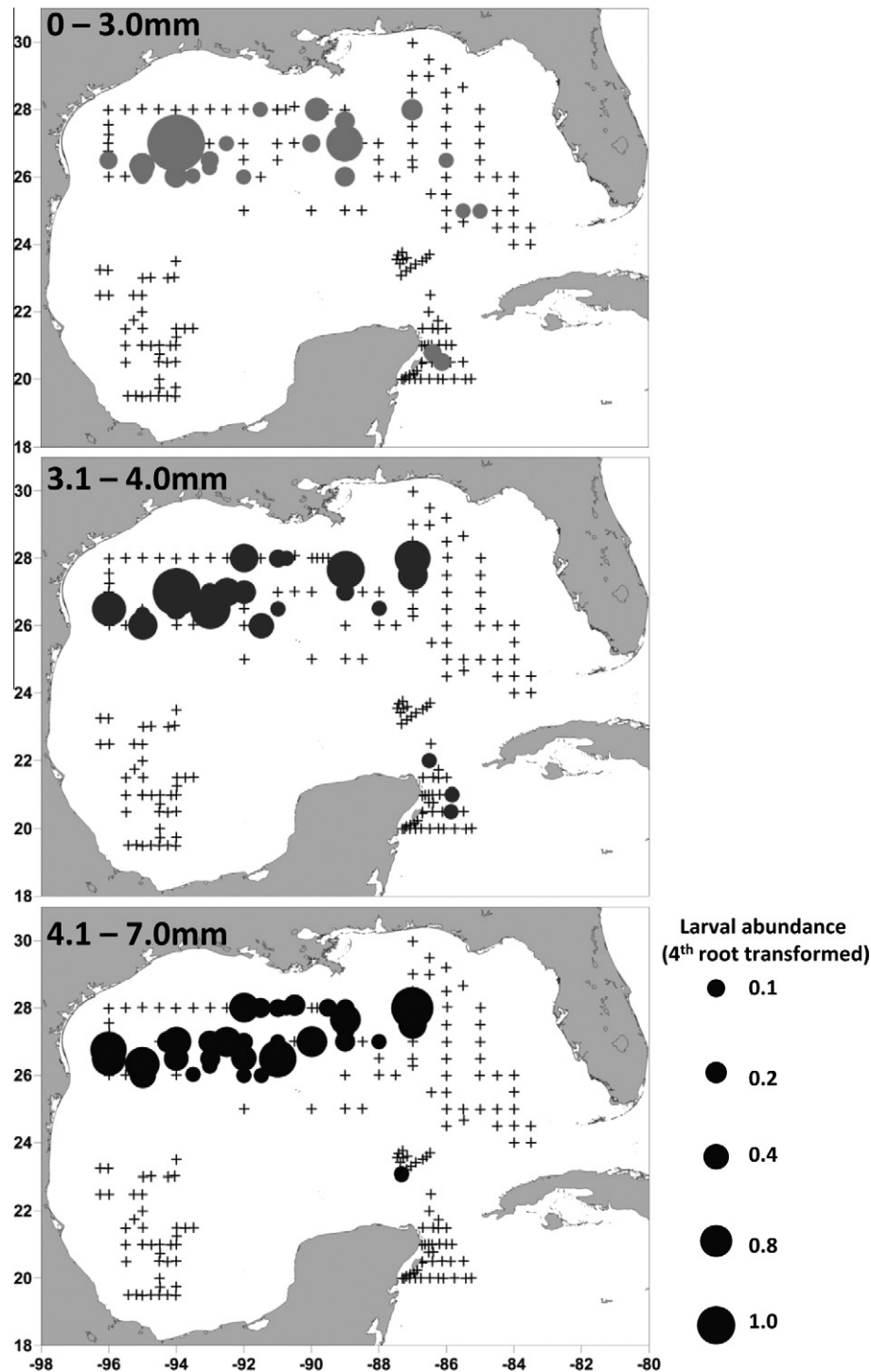


Fig. 4. Abundances of larval bluefin tuna by size class, collected in the Gulf of Mexico, April 19th–May 23rd, 2010. Abundances have been 4th root transformed for clarity.

Habitat modeling and larval survey results indicated that while some BFT spawning took place in the eastern GOM, near to and within oil-contaminated waters, considerable abundances of larvae were located in the western GOM, away from the influence of the spill. On a weekly basis, up to 5% of spawning habitat was likely to have been impacted by surface oil, with up to 11% potentially impacted by oil contaminated waters.

Our findings are inconsistent with some previous reports (e.g., Haas et al., 2010), which used higher surface chlorophyll values as proxies for favorable spawning habitat, and predicted that great-

er proportions of larvae spawned into the GOM may have been affected by oil contamination. Conversely, relationships described here between historical larval BFT catch locations and surface chlorophyll suggest that BFT generally spawn in low chlorophyll waters. These results indicate that while the oil spill may have significantly impacted BFT larval survival in spring 2010, it is likely that larvae spawned in the western GOM would have remained unaffected. In addition, any spawning activity in the southwestern GOM and the western Caribbean would have not been impacted by oil contamination. However, the extent of spawning activity in

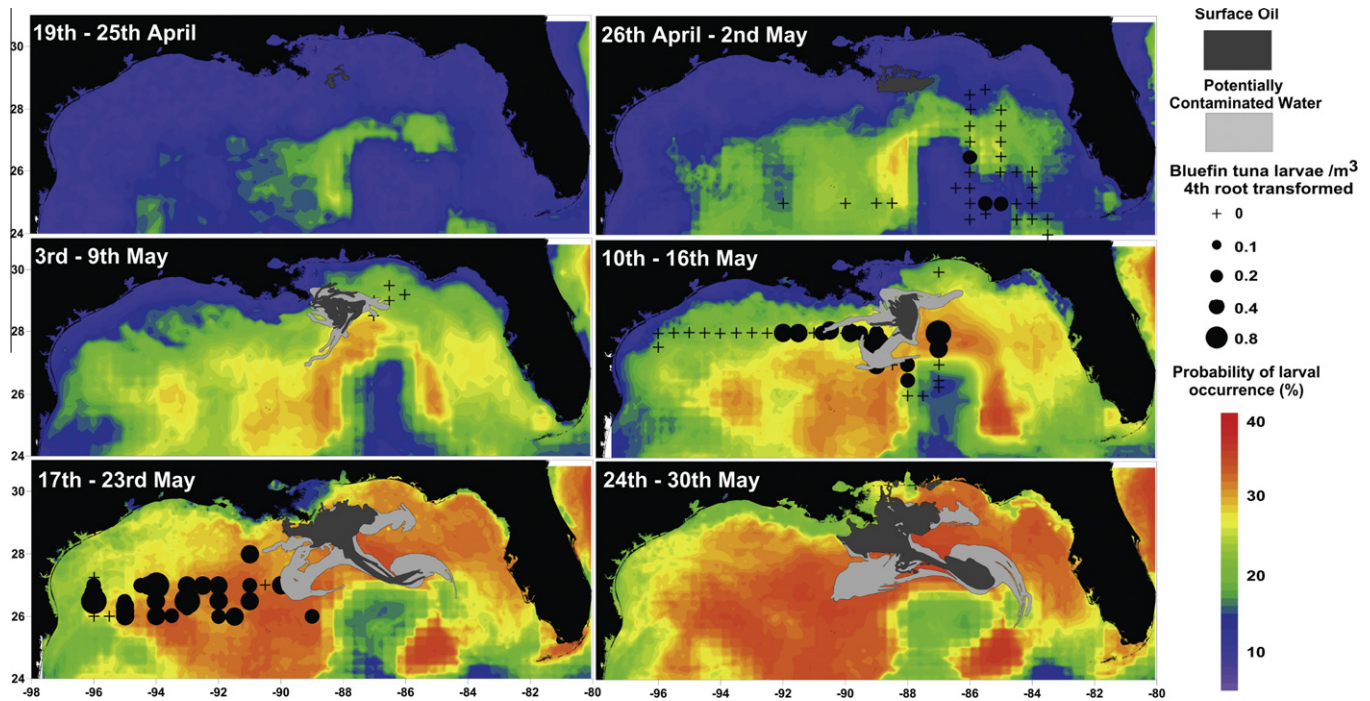


Fig. 5. Predicted probabilities of occurrence for larval bluefin tuna in the northern Gulf of Mexico on a weekly basis during spring 2010. Probabilities were derived from a neural network model trained using archival larval collection data. Oil extents are derived from satellite products. Catches of larval bluefin tuna from spring 2010 (April 19th–May 23rd), are also shown.

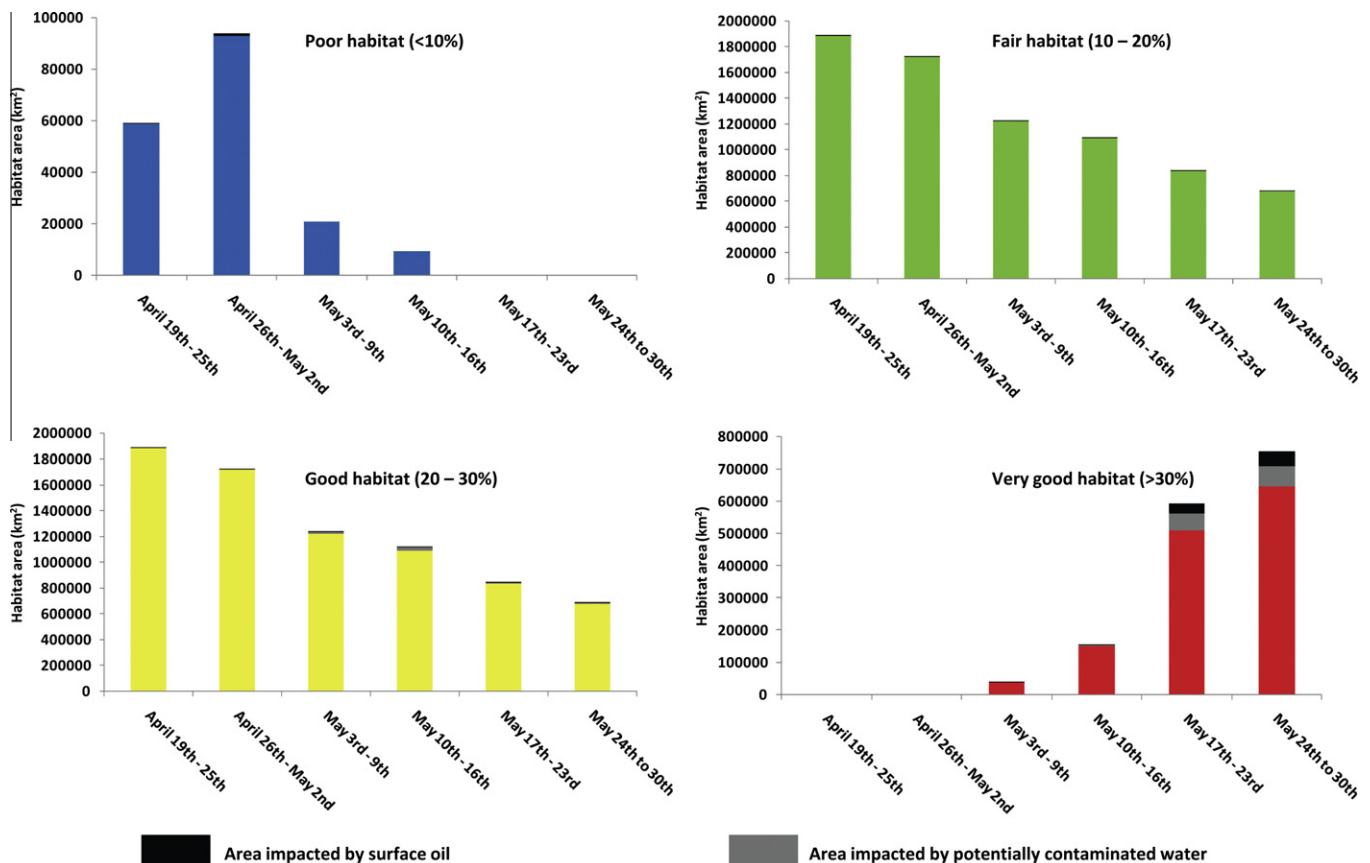


Fig. 6. Spatial extent in km² of poor (<10% probability of occurrence), fair (10–20%), good (20–30%) and very good (>30%) bluefin tuna spawning habitat in the northern Gulf of Mexico on a weekly basis during spring 2010. Suitability of habitat was defined using probabilities of occurrence of larval bluefin tuna from a neural network habitat model. The black portion of each column shows the amount of habitat affected by surface oil during each time period, and the gray portion shows habitat impacted by water that was likely to be contaminated.

Table 1
Overlap between larval BFT habitat and both observed surface oil, and potentially oil-contaminated water, calculated weekly from late April through May. Abundance estimates of BFT larvae impacted by surface oil, and potentially contaminated water, also shown.

	April 19th–25th	April 26th–May 2nd	May 3rd–9th	May 10th–16th	May 17th–23rd	May 24th–30th
Observed surface oil area	1954.15	10178.52	13385.02	11453.86	37287.36	59505.38
Potentially contaminated water (PCW) area	1952.94	10178.52	29887	43241.77	94786.56	125877.51
<i>Larval bluefin tuna habitat (km²)</i>						
Poor habitat (0–10% chance of occurrence)	58644.36	92811.68	20692.32	9256.43	0	0
Fair habitat (10–20% chance of occurrence)	1881879.78	1715529.02	1220028	1089191.57	833794.14	680056.54
Good habitat (20–30% chance of occurrence)	38688.05	177593.63	706773.07	729626.75	635834.06	659420.76
Very good habitat (30–40% chance of occurrence)	0.00	0	38440.94	151156.96	508091.29	646457.03
<i>Overlap between oil and larval bluefin tuna habitat (km²)</i>						
Surface oil and poor habitat overlap	152.48	919.19	0	0	0	0
Surface oil and fair habitat overlap	1801.67	9259.33	2834.88	966.87	550.32	14.82
Surface oil good habitat overlap	0.00	0	10539.91	10299.27	4454.13	12419.09
Surface oil and very good habitat overlap	0.00	0	10.22	187.71	32282.91	47071.48
PCW and poor habitat overlap	152.48	919.19	40.12	0	0	0
PCW and fair habitat overlap	1800.46	9259.33	5522.12	2962.57	613.25	14.82
PCW and good habitat overlap	0.00	0	24019.77	37860.49	8179.36	18120.01
PCW and very good habitat overlap	0.00	0	304.98	2418.72	85993.95	107742.68
Number of larvae in surface oil	2695298	13851958	2256713733	2260945482	11569139178	18131941558
Percentage in surface oil	0.02%	0.03%	1.37%	1.09%	3.81%	5.12%
Number of larvae in PCW	2693488	13851958	5234147734	8878998974	30029721207	39303218557
Percentage in PCW	0.02%	0.03%	3.17%	4.29%	9.88%	11.09%

these areas is not yet clear, due to the limited amount of data available from these areas.

Continuing effects of the oil spill in the GOM pelagic ecosystem are difficult to estimate. After the 1989 *Exxon Valdez* oil spill in Prince William Sound, extensive sublethal effects on larval fish were noted in 1989, but these were not detectable one year later (Hose et al., 1996). However, long-term effects of the spill on the entire ecosystem were evident many years later at higher trophic levels (Peterson et al., 2003), and detectable levels of pollutants in fish persisted for many years (Jewett et al., 2002). Longer term effects of the absorption of millions of barrels of oil into the GOM ecosystem on adult BFT, and the food webs upon which they rely while in the GOM, are presently unknown, and may not be apparent for years or decades to come.

Although we show that surface oil did not impinge on the majority of potential spawning habitat during spring 2010, the effects of eggs and larvae being advected into and concentrated in areas containing oil and weathered oil products are more difficult to quantitate. The circulation in the eastern GOM is a complex physical oceanographic regime dominated by the Loop Current, with influences from the Mississippi river outflow and numerous smaller sources of freshwater flow along the Mississippi and Florida coasts (Muller-Karger et al., 1991; Oey et al., 2005). Eventual dispersion of oil-contaminated waters is very difficult to assess, and will likely remain a challenge to the research community for some time.

In addition, while results presented here address overlap between oil and small larvae (<2 weeks old, Brothers et al., 1983), juvenile behaviors and patterns of migration out of the GOM for young fish are largely unknown. It is therefore beyond the scope of this research to quantitate the impacts of the oil spill on recruitment and spawning stock biomass. However, as future spring larval surveys are completed, and indices of one year old fish entering the western Atlantic stock become available, the eventual impacts of the 2010 oil spill on BFT will become more apparent. As controversy continues over fisheries practices and conservation efforts relevant to BFT, this information will be essential for informing fisheries managers and the international community of the most prudent actions to take.

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