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A satellite-based mobile warning system to reduce interactions with an endangered species

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Abstract. Earth-observing satellites are a major research tool for spatially explicit ecosystem nowcasting and forecasting. However, there are practical challenges when integrating satellite data into usable real-time products for stakeholders. The need of forecast immediacy and accuracy means that forecast systems must account for missing data and data latency while delivering a timely, accurate, and actionable product to stakeholders. This is especially true for species that have legal protection. *Acipenser oxyrinchus oxyrinchus* (Atlantic sturgeon) were listed under the United States Endangered Species Act in 2012, which triggered immediate management action to foster population recovery and increase conservation measures. Building upon an existing research occurrence model, we developed an Atlantic sturgeon forecast system in the Delaware Bay, USA. To overcome missing satellite data due to clouds and produce a 3-d forecast of ocean conditions, we implemented data interpolating empirical orthogonal functions (DINEOF) on daily observed satellite data. We applied the Atlantic sturgeon research model to the DINEOF output and found that it correctly predicted Atlantic sturgeon telemetry occurrences over 90% of the time within a 3-d forecast. A similar framework has been utilized to forecast harmful algal blooms, but to our knowledge, this is the first time a species distribution model has been applied to DINEOF gap-filled data to produce a forecast product for fishes. To implement this product into an applied management setting, we worked with state and federal organizations to develop real-time and forecasted risk maps in the Delaware River Estuary for both state-level managers and commercial fishers. An automated system creates and distributes these risk maps to subscribers' mobile devices, highlighting areas that should be avoided to reduce interactions. Additionally, an interactive web interface allows users to plot historic, current, future, and climatological risk maps as well as the underlying model output of Atlantic sturgeon occurrence. The mobile system and web tool provide both stakeholders and managers real-time access to estimated occurrences of Atlantic sturgeon, enabling conservation planning and informing fisher behavior to reduce interactions with this endangered species while minimizing impacts to fisheries and other projects.

Key words: dynamic management; ecosystem forecasting; interactive mobile/web application.

INTRODUCTION

Forecasting species' distributions is essential to sustainable management in marine systems. However, the forecast's scale, skill, delivery, and continuity are dependent on the ecological decision framework that is being addressed (Hobday et al. 2019). To optimize the utility of species distribution models (SDMs) for use in dynamic management, they should operate in near real-time and

the products should be readily and consistently accessible to stakeholders (Hazen et al. 2018, Welch et al. 2018, Hobday et al. 2019). Often, these tools are successfully implemented, but it can be difficult to assess their utility toward management (Howell et al. 2008, Barnes-Mauthe et al. 2013). The performance of marine SDMs is highly dependent on the spatial and temporal scales of the environmental covariates. If the species responds to high frequency environmental dynamics, the quality and immediacy of environmental covariates needed for accurate forecasts are also important. Scales et al. (2016) analyzed how satellite observations on different spatial and temporal scales affected the skill of simulated SDMs and recommended

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the use of higher resolution, contemporaneous data on daily to weekly scales. However, missing satellite data due to factors such as cloud contamination, aerosols, low sun angle, or data delivery failure can reduce SDM performance and usability. In this manuscript, we describe and evaluate a satellite-based dynamic management framework that incorporates (1) daily, actionable forecasts at a kilometer scale in the Delaware Bay, USA and coastal ocean, (2) methods to deal with consistent missing data, and (3) satellite products that will likely be available in the coming decade.

Protected under the Endangered Species Act since 2012, *Acipenser oxyrinchus oxyrinchus* (Atlantic sturgeon) need management strategies to reduce interactions with various industries (USOFR 2012). Atlantic sturgeon were once plentiful along the Eastern Seaboard of the United States with the Delaware River supporting the largest commercial harvest in the late 19th and early 20th centuries (Cobb 1900, Borodin 1925, Smith and Clugston 1997). As a result of overfishing and poor water quality in spawning rivers, Atlantic sturgeon populations plummeted in the early 20th century (Borodin 1925) and have not recovered (Secor and Waldman 1999). Although targeted catches of Atlantic sturgeon have been prohibited for the last two decades, population recovery has not been realized with major impacts still experienced from ship-strikes, habitat degradation, hypoxia, pollution, and incidental bycatch in commercial gillnet fisheries (Collins et al. 2000, Stein et al. 2004, ASMFC 2017). Future bycatch take limits, such as those in the Delaware State Habitat Conservation Plan under construction, are expected to increase regulatory pressure on the Delaware Bay commercial fishing industry. Furthermore, when Atlantic sturgeon interact with gillnets, they can cause significant damage to gear that results in costly downtime for commercial fishers. Therefore, the commercial fishing industry has strong regulatory and economic incentive to avoid Atlantic sturgeon as part of their daily operational decision framework. State managers are also tasked with implementing measures to reduce incidental take of Atlantic sturgeon that occur in non-federally regulated activities, including commercial fishing and shoreline development. Therefore, Atlantic sturgeon occurrence information is included in permitting decisions, and time-of-year activity restrictions in Delaware waters.

Atlantic sturgeon in the mid-Atlantic make northerly spring migrations to foraging grounds near estuaries and spawn within natal rivers. In the fall, the pattern is reversed with mainly southerly and offshore migrations (Dovel and Berggren 1983, Smith 1985, Collins et al. 2000, Erickson et al. 2011). These migrations are linked to seasonally dynamic processes that are reflected by water temperature and ocean color (Breece et al. 2016, 2018). Coincidentally, anthropogenic interactions increase during these migration events as sturgeon move into coastal waters and estuaries, creating a significant source of mortality (Stein et al. 2004, ASMFC 2017, Melnychuk et al. 2017).

Breece et al. (2018) modeled the presence and absence of Atlantic sturgeon in the Delaware Bay and surrounding waters using a generalized additive mixed model. However, persistent satellite data loss due to cloud cover over the model domain limited the usefulness of the Atlantic sturgeon occurrence model (ASOM) for operational decisions by commercial fishers and state managers. Although it was a powerful research tool, it was not actionable because of missing data. Many image composite techniques have been utilized to overcome lack of data due to cloud cover. These composites are typically time averaged, utilizing 3, 5, or 8 d of data for a given pixel that allow days without clouds to fill in for days where no data exist (reviewed by Kohrs et al. 2014). In rapidly changing environments like coastal oceans, this can lead to composites that are “patchy,” as conditions from earlier in the composite time are juxtaposed to conditions from later in the composite time. Monthly averages and historic climatologies from the entire satellite record can also be utilized to make composite images. However, extensive averaging over many satellite passes does not guarantee completely filled in composite images (Racault et al. 2014), and may not be appropriate for highly mobile species responding to fine-scale and ephemeral features. Additionally, long-term averaging can result in variable data densities across pixels (e.g., in monthly averages, pixel values may be calculated across one to potentially 31 daily data points), also creating patchy composites (Breece et al. 2018). Climatologies can do well at resolving parameters such as SST during years and times that are close to mean conditions; however, during anomalous years, climatologies can be significantly different than contemporary conditions.

Data interpolating empirical orthogonal function (DINEOF) is a technique that has been used to statistically fill in satellite data sets suffering from cloud cover. DINEOFs rely on the patterning of past data to reconstruct missing contemporary data and have the ability to resolve finer scale features in the data sets if given a sufficient amount of historic points (Beckers and Rixen 2003, Alvera-Azcárate et al. 2007). By using cross-validation to estimate the optimal number of EOFs needed to minimize the differences between observed and predicted values, DINEOFs can reconstruct spatial data sets with significant missing data (Alvera-Azcárate et al. 2009). Liu and Wange (2018) revealed that DINEOF can successfully reconstruct satellite ocean color data to estimate meso- and large-scale features. DINEOF has also been utilized to track and forecast harmful algal blooms to predict the threat of domoic acid to humans and wildlife (Anderson et al. 2016). While DINEOF can create complete data fields that are attractive for decision-making, it is not known if these reconstructed data fields improve the performance of SDMs. In this manuscript, we describe the process of operationalizing and delivering the ASOM to Delaware Bay stakeholders, evaluate the impact of gap-filling satellite products on the ASOM predictions, and survey the stakeholder usage of the operationalized product.

METHODS

Study region

The study area for this project is the Delaware Bay and lower Delaware River, USA and nearshore coastal waters of the Atlantic Ocean (Fig. 1). From 2009 to 2013, an array of VEMCO acoustic hydrophones (VEMCO/Innovasea, Bedford, Nova Scotia, Canada) were maintained in this area to collect location information on over 300 telemetered Atlantic sturgeon (Fig. 1). These acoustic detections along with environmental data from NASA's MODIS Aqua (Moderate Resolution Imaging Spectroradiometer) were the basis of the ASOM that accurately estimated the occurrence of Atlantic sturgeon in this study area (Breece et al. 2018) as a research product. The ASOM utilized sea surface temperature (SST), ocean color (absorption at 443 nm [A443]), water depth, and day of year to correctly identify >88% of biotelemetry observations and ~90% of fisheries observations during sturgeon seasonal migrations.

Stakeholder needs to operationalize the ASOM

We worked with the Delaware Department of Natural Resources and Environmental Control (DNREC) and local commercial fishers to operationalize the ASOM. These are two distinct but related user groups that each

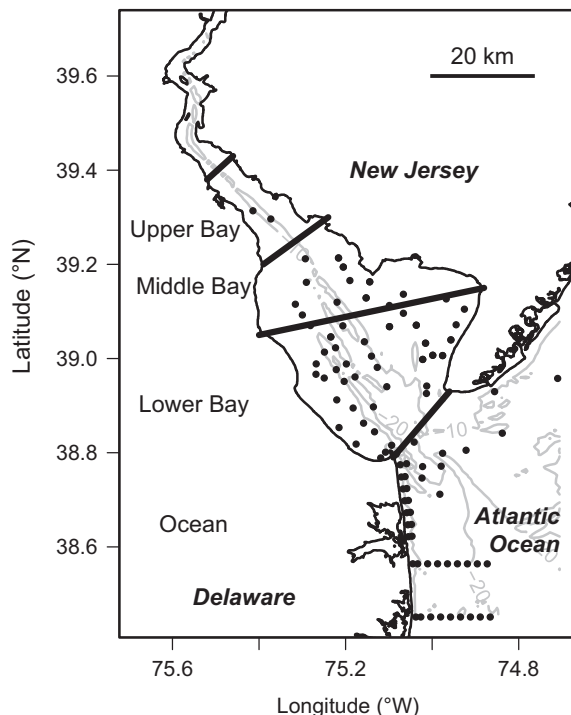


FIG. 1. Map of Delaware Bay and adjacent coastal ocean divided by reporting regions known to stakeholders and fishers. Black dots indicate acoustic receiver locations in 2013. Depth contours are shown in meters.

interact with the Delaware Bay differently. To understand their needs, we held a series of informal meetings and phone calls with DNREC and local commercial fishers. We also attended and presented at three Atlantic States Marine Fisheries Council (ASMFC) meetings where bycatch avoidance was discussed to get community feedback and information. The Fish and Wildlife division at DNREC already had strong relationships with commercial fishers, so both of these groups generally understood each other's regulatory and operational needs. This positive existing relationship facilitated product development at the appropriate resolution and time and length scales.

The decision time and spatial framework as it relates to Atlantic sturgeon for both DNREC and the commercial fishers were distinct, but critical for operationalization. To comply with section 10 of the Endangered Species Act, DNREC issues time-of-year restrictions for certain activities including dredging and coastal development that potentially affect the recovery of the Atlantic sturgeon. These permits are usually issued months in advance for different regions of the estuary. Therefore, DNREC requested climatological or seasonal predictions be included in the tool as a reference guide. For commercial fishers in the bay, fishing trips occurred daily on boats <15 m in length and are typically planned only a few days in advance given weather patterns. Commercial fishers generally used the bay in three distinct sections, which is reflected in the 2016 ASMFC Delaware River Sustainable Fishing Plan for American Shad: Upper Delaware Bay, Mid Delaware Bay, Lower Delaware Bay, and Atlantic Ocean (ASMFC 2016) (Fig. 1). These are recognizable and meaningful regions for commercial fishers in Delaware Bay. Depth is a major factor in fishing location decision-making by fishers. Many fishers use gill nets that have a length equal to or <1 km.

Based on these discussions with DNREC and the fishing community, the operationalization should have a seasonal or climatological component, have a forecast window of a few days, and a grain size of 1 km, but be regionalized based on depth and existing ASMFC fishing area designations. In contrast to DNREC managers in a state office, many commercial fishers do not have broad-band internet access on the water or at home, therefore forecasts should be accessible across different kinds of desktop and mobile platforms. Commercial fishers and natural resource managers were polled at the end of the project period to assess message delivery preferences. Respondents were asked a series of five questions through an anonymous polling software application (SurveyMonkey) and permitted to respond with only one answer from a list of available options except for an open-ended question at the end, including the following:

1. Are you a commercial fisher? (answer choices: yes, no)
2. I prefer to get my Atlantic sturgeon warnings as (answer choices: text, map, either, both).

3. I prefer depth in feet vs. meters (answer choices: yes, no).
4. I think the current population level of Atlantic sturgeon in the Delaware River Estuary is (answer choices: very low, never saw any sign of sturgeon this year; low, never saw any sign of sturgeon, but have heard of at least one other netter who saw sturgeon while fishing his nets this year; moderate, saw less than three sturgeon and heard the same from other netters this year; high, saw more than three, but less than 10, sturgeon and heard the same from other netters this year; very high, saw sturgeon most days I was at my nets and heard the same from other netters this year).
5. Are there any changes you would like to suggest to improve the warning system messages? (answer choices: open ended)

Satellite observations

Coastal ocean scientists have relied heavily on the MODIS-Aqua sensor for SST and ocean color estimates since its deployment in 2002. MODIS-Aqua's coverage, resolution, and reliability have made it an important asset for monitoring many oceanographic processes and demonstrate that satellite radiometers can provide reliable data sets for model development that can be used in daily decisions (Howell et al. 2008, Liu et al. 2014, Hazen et al. 2018, Welch et al. 2018). Unfortunately, MODIS-Aqua is well past its expected mission duration and confidence in its longevity is diminishing. Fortunately, a replacement sensor platform, Visible Infrared Imaging Radiometer suite (VIIRS) on board Suomi-NPP, was launched in 2011 in a combined effort between NASA and the National Oceanographic and Atmospheric Administration to extend and improve MODIS data products into the foreseeable future through continued launches of similar sensors on future satellites through the Joint Polar Satellite System. Therefore, SDMs built on satellite products developed using MODIS-Aqua have the potential for sustained future use by managers, stakeholders and practitioners. However, it is important to test the transferability of SDMs from MODIS to VIIRS, as significant downstream impacts to operational research tools have been demonstrated (Welch et al. 2020).

Near real-time SST and ocean color absorption from MODIS-Aqua and VIIRS is acquired from the University of Delaware satellite receiving station, processed to 1 km resolution, and made available to the public on a THREDDS and ERDDAP server (see *Open Research*). All satellite passes were automatically backfilled from NASA Ocean Color Biology website if needed due to incomplete data transfers. To ensure VIIRS data products are a suitable replacement for MODIS-Aqua, we compared values at acoustic receiver locations on days when neither MODIS-Aqua nor VIIRS platforms were obstructed by cloud cover using a model 2 regression, R

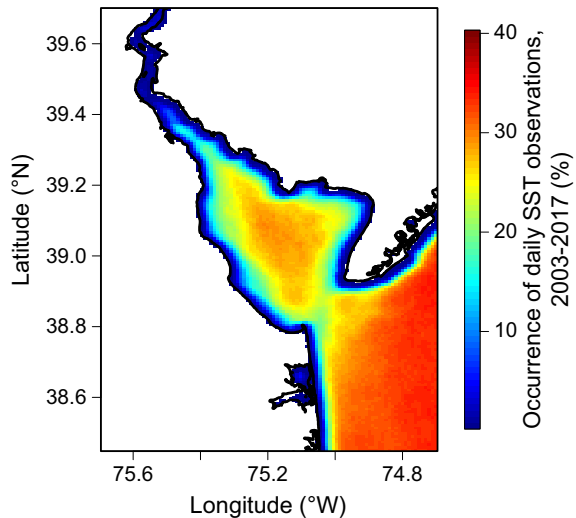


FIG. 2. Occurrence of cloud free sea surface temperature observations from 2003 to 2017 by the MODIS-Aqua satellite.

package *Lmodel2* (Legendre 2014, R Core Team 2017). We restricted this analysis to these acoustic receiver locations so that we could later validate the ASOM predictions against known presence and absence locations of Atlantic sturgeon.

Gap-filling satellite observations

Cloud coverage is a persistent problem in Delaware Bay, resulting in up to a 90% loss in data coverage near the coast (Fig. 2). Clouds are not random events and can completely cover the study area for extended periods of time. The median time between satellite passes with at least 50% coverage of the study area was 3 d. These high cloud cover days corresponded to storm events that were in line with local fishers' experience of storm frequency. This informed our implementation of gap-filling techniques. To gap fill SST and A443, we utilized the DINEOF algorithm from the GeoHydrodynamics and Environment Research group of the University of Liège in Belgium (Alvera Azcarate et al. 2009, Video S1; algorithm *available online*).⁹ Delaware Bay is characterized by large seasonal swings in water temperature. Summer temperatures can exceed 30°C, while approaching the freezing point (−2°C) of seawater in the winter. To capture this major mode of variability, the preceding 365 d of 1-km satellite data were used as input to the algorithm. The DINEOF initialization parameters were left at the default values contained within the algorithm with the following exceptions: the *numit* parameter, controlling the reach of the filter, was set to 23, which is equivalent to smoothing data at a 3-d frequency, and the number of EOF modes and maximal size of the Krylov space were set to 50 and 55, respectively (Alvera Azcarate et al.

⁹ <http://modb.oce.ulg.ac.be/mediawiki/index.php/DINEOF>

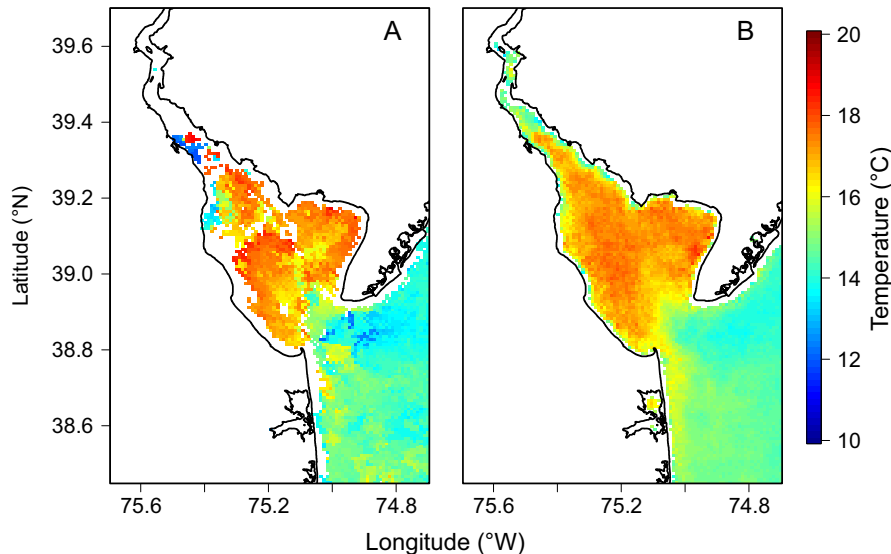


FIG. 3. Example (A) 15-yr composite climatology for SST vs. (B) 15-yr DINEOF gap-filled climatology for SST for 20 May. Even though 15 yr of data are used, significant spatial gaps still exist in the coverage of Delaware Bay.

2009). One benefit of the DINEOF is that it can be extrapolated over completely empty data fields into the future. To capitalize on this, we extended the DINEOF outputs for 3 d past the current satellite pass as an attempt to statistically forecast SST and A443 based on the DINEOF analysis. This forecast window was based on the median time between satellite passes with at least 50% coverage of the study area, so that there was reasonable expectation that a DINEOF 3-d forecast was based on relatively recent data. In addition to creating nowcasts and gap-filled forecasts, we created a daily, 15-yr climatology (2003–2017) of MODIS-Aqua SST and A443. However, even these 15-yr daily climatologies show significant effects from clouds (Fig. 3). Therefore, we used DINEOF to gap fill and smooth the climatology. The gap-filled, forecasted, and climatological SST and A443 forecasts were then compared to MODIS-Aqua and VIIRS satellite measurements using root mean squared error (RMS) when measured satellite passes had >50% coverage in our study region.

Atlantic sturgeon occurrence on gap-filled data

After MODIS and VIIRS data were gap-filled, they were used as inputs for the projection of ASOM (Breece et al. 2018) over the entire study area for each day of 2013, the only full year with overlapping coverage from MODIS, VIIRS, and Atlantic sturgeon telemetry data. Additionally, 1-, 2-, and 3-d probability forecasts, as well as daily climatologies based on the DINEOF gap-filled data as inputs to the ASOM, were made every day for each platform. These ASOM probabilities were then compared against the original biotelemetry data from Breece et al. (2018) to determine sensitivity (correctly

predicted Atlantic sturgeon presences) as a whole but also by astronomical season and region within the greater study area.

To operationalize daily real-time ASOM estimates and forecasts to fishers, we partnered with conservation managers, scientists, and other stakeholders to create a warning system that reflected the knowledge base of the users (Welch et al. 2018). In addition to providing a 1-km pixel estimate of encounter risk, we aggregated pixels into regions that were already known to the Delaware Bay community. The study area was divided into four regions based on the 2016 ASMFC Delaware River Sustainable Fishing Plan for American Shad: Upper Delaware Bay, Mid Delaware Bay, Lower Delaware Bay and Atlantic Ocean (ASMFC 2016). The regions were further divided into 5-m depth bins. These divisions created a manageable number ($n = 22$) of subregions for assignment of an encounter risk, which simplified the interpretation of these warnings. Based on feedback from state managers and desire to avoid Atlantic sturgeon captures, we chose a conservative approach to classify each depth-defined subregion as high or medium risk if more than 5% of the pixels of the subregion met the high or medium risk criteria. Low risk was defined as a probability of occurrence less than the presence/absence threshold value of 0.01 that was calculated during the ASOM model-building process (Breece et al. 2018). Medium risk was defined as between that threshold value and five times that value (0.05). High risk was defined as a probability of occurrence greater than five times the threshold. (Fig. 1). This makes these categorical risk maps more risk averse than their pixel by pixel counterparts, as only 5% of the pixels within each subregion needed to be classified as medium or high risk for the entire subregion to

carry the increased risk warning. Risk maps were overly sensitive to thresholds below 5% of the pixels while above 5% created stable predictable risk maps while ensuring the conservative approach desired by stakeholders.

Automated operational forecast dissemination

The automated delivery of Atlantic sturgeon risk of occurrence warnings was operationalized in January 2018 and enabled quick dissemination to users via the three delivery platforms. The first is an online web application that displays the categorical warning maps, as well as the pixel by pixel results of the ASOM produced by the Shiny package in R (Chang et al. 2017). The integrated web application has three main tabs (Fig. 4 and Appendix S1: Fig. S1) that can be viewed in full *online*.¹⁰ The first tab shows tiled maps for the current date as well as the three future forecast days. Users can select the date to view the encounter risk and predicted forecast. The second tab gives model details including the current encounter risk, continuous probability of occurrence from the ASOM, gap-filled SST, and a risk climatology. The final tab displays climatologies for SST, the ASOM, risk categories, and example SMS text warning for any day of the year the user selects, as requested by our DNREC partners. Additionally, the application has embedded links directing the user to the data sources used to build the ASOM and gap filling. Critically, the application warns users if there have been more than three days without satellite data, due to continued cloud cover, via a warning issued on the main page of the web application, and in the SMS text messages instructing recipients to use the climatological predictions rather than the most current forecasts.

The second platform is an auto-generated online flyer that contains the warning map of the study area with each subregion colored by risk of encounter (green, low; yellow, medium; red, high). The file size of the flyers that were linked in the text messages was small (~500 kb), so that they could be loaded quickly by a smartphone over cellular service (Fig. 5). The flyer also contained a reference to Brece et al. (2018), a brief description of the project and contact information for participants who needed more detail. The third platform is a simple automated SMS text message to subscribers that includes links to the other two platforms. The daily generated SMS messages list subregions of medium risk followed by subregions of high risk for the given day in text format. If low risk is indicated by the model for the entire region then no text message is delivered. The SMS text messaging system was intended for fishers in the field who have low internet accessibility but do have cellular phone service. If fishers on the water know their depth and which region they are in, they can easily derive their risk level of encountering an Atlantic

sturgeon based on the SMS messages. We assessed the warning system with an end-of-season survey with our partners at DNREC.

The web application and links to the flyers typically updated within several hours of the daily midday satellite pass and text messages were constructed shortly after. At the request of the participants, text messages were delivered to subscribers twice weekly (Appendix S1: Fig. S2) and included the three forecast days for planning purposes.

RESULTS

Comparison of Modis-Aqua and VIIRS in study region

MODIS-Aqua and VIIRS overlapped with the deployment of acoustic receivers and collection of Atlantic sturgeon detections for 2013. At acoustic receiver stations, SST and \log_{10} -transformed A443 were similar between the two sensors. Model 2 regression analysis showed that MODIS-Aqua and VIIRS SST had a very high R^2 (0.98) and a slope not significantly different than the one to one line (1.002 ± 0.008 [mean \pm SE]), while A443 had a lower but still acceptable R^2 (0.51) and a slope near the one to one line (0.918 ± 0.043) showing that VIIRS is a suitable substitute for MODIS SST and ocean color in this region (Arnone et al. 2013; Fig. 6).

Predictive skill of gap-filled satellite observations

Root mean squared error was lowest for the gap-filled SST and A443 nowcast but increased with forecast duration. For MODIS-Aqua SST, the gap-filled forecasts performed better than the gap-filled climatology. However, in the case of VIIRS SST, the gap-filled climatology performed better than the 2- and 3-d gap-filled forecast (Table 1). For A443, the gap-filled forecast was not better at predicting conditions compared to the gap-filled climatology (Table 1), therefore we used gap-filled forecasts of SST, but gap-filled climatologies for A443 as inputs for the operational ASOM model.

The gap-filled satellite data allowed many more sturgeon observations to be matched to Atlantic sturgeon occurrence predictions. For example, in 2013, 147 Atlantic sturgeon presences were matched to non-gap-filled satellite data. Over the entire year, the Atlantic sturgeon model nowcast predictions (predictions based on non-gap-filled data) had similar performance when using either MODIS or VIIRS SST and A443; correctly classified presences was 0.95 for both platforms (Fig. 7A). After gap filling, the number of matched sturgeon observation was >4,000. As such, a much larger number of observations were matched to values reconstructed by DINEOF. The gap-filled SST and A443 data used for the ASOM nowcast predictions for both MODIS-Aqua and VIIRS had decreased sensitivity (0.90) for both MODIS-Aqua and VIIRS) on a per 1-km pixel basis. This trend continued for both MODIS-Aqua and VIIRS

¹⁰ <http://robots.ceoe.udel.edu/shiny/sturgeon/>

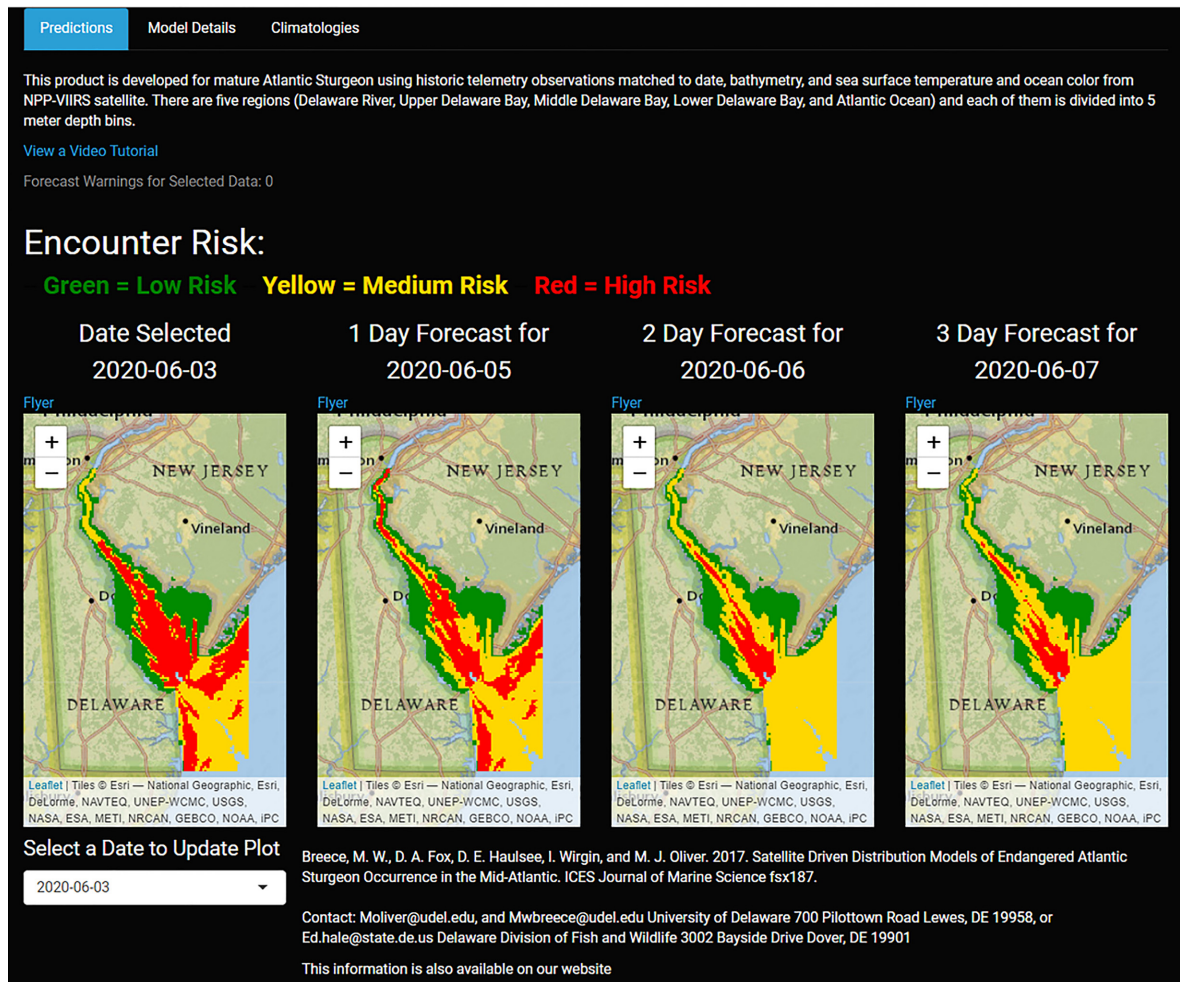


Fig. 4. Screenshot of the prediction tab from the R-Shiny web application. See Appendix S1: Fig. S1 for the model details and climatology tabs.

as the forecast extended 3 d into the future (Fig. 7A). Seasonal performance of the ASOM predictions utilizing both gap-filled MODIS-Aqua and VIIRS SST data show a similar trend with the non-gap-filled data performing best and then decreasing performance as ASOM forecasts extended out to 3 d (Fig. 7B–D). Notably, the ASOM has poor performance in the fall, which is a known limitation of the model (Breece et al. 2018).

When the study area is divided by ASMFC region (Fig. 1), we again see the similar pattern of decreasing correct classifications with extended forecast. This is most visible in the Upper Delaware Bay (Fig. 8) where satellite coverage is the poorest (Fig. 2). Interestingly the model using the SST climatology performs slightly better in this region than both MODIS-Aqua and VIIRS gap-filled SST (Fig. 8). In both the seasonal and regional analysis, the 3-d forecast was very close to or worse than the climatological forecast for VIIRS, indicating that a

3-d forecast was no better than the climatological forecast.

Warning maps

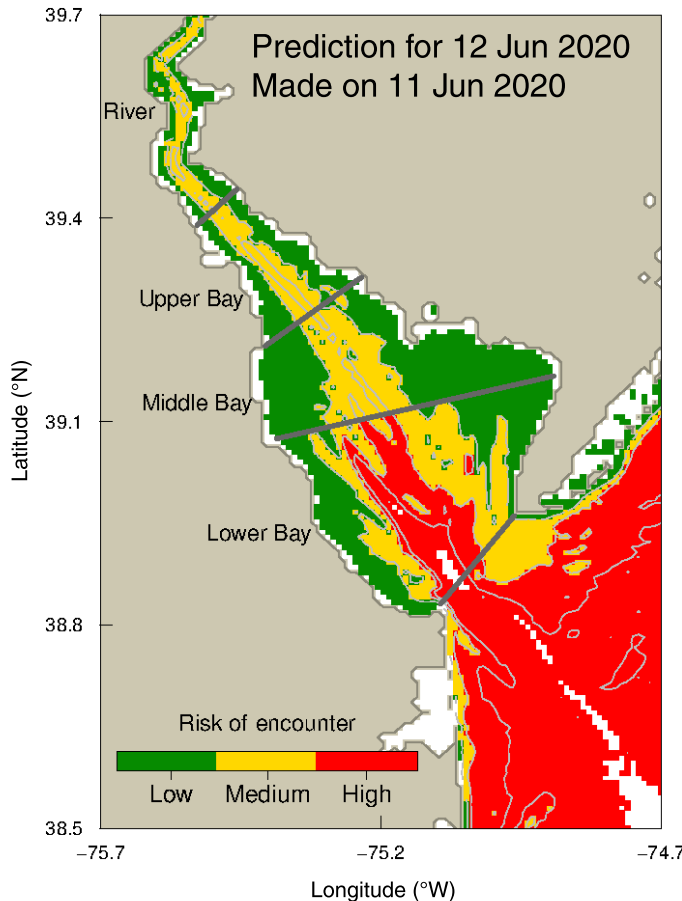
Warning maps aggregated the risk of encountering an Atlantic sturgeon by the ASMFC regions along with depth bin intervals and classified as low, medium or high risk. Two things were accomplished by this aggregation. The first is that it made it possible to communicate the warnings via text message alone, if the user knew their water depth, and if they were in the upper, middle, or lower bay. This meant that warning messages could be delivered to mobile devices with limited cellular coverage. The second is that it made the warning system more risk averse. If 5% of the 1-km pixels in a subregion had a risk for a sturgeon occurrence, then the entire subregion was designated as higher risk. This aggregation of risk

Atlantic sturgeon predicted occurrence

Green indicates low risk of encountering Atlantic sturgeon

Yellow indicates medium risk of encountering Atlantic sturgeon

Red indicates high risk of encountering Atlantic sturgeon



This product is developed for mature Atlantic sturgeon using historic telemetry observations matched to date, bathymetry, and sea surface temperature and ocean color from NASA’s MODIS AQUA and VIIRS satellites. The five regions (Delaware River, Upper Delaware Bay, Middle Delaware Bay, Lower Delaware Bay, and Atlantic Ocean) are divided into 5m (16 foot) depth bins.

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FIG. 5. Operational distribution of flyer with subregions and risk factors linked from the SMS text message. Each flyer indicates when the prediction was made, and what date the prediction is for.

improved the ASOM correctly classified Atlantic sturgeon presences both seasonally (Fig. 9) and by subregion (Appendix S1: Fig. S3). To understand how the warning maps based on gap-filled nowcast, 1–3-day forecasts and daily climatology varied over the year and differed with each other, we estimated the area of the study region each risk category occupied during 2013. The area of low risk region for the gap-filled nowcast, 1–3-d forecast, and climatology showed a clear seasonal signal highlighting peak migration times in the spring and fall (Fig. 10). While there was a clear seasonal signal in the medium and high-risk category, there was more divergence between gap-filled products during the late spring and early summer.

Stakeholder usage

For the stakeholder survey, we had 24 total voluntary participants, seven were commercial fishers and 17 were natural resource managers and scientists working for state and federal agencies. There are approximately 40 active commercial gill netters in Delaware Bay (G. Glenden, *personal communication*), many of which hold multiple permits. The seven commercial fishers in our group represented 17.5% of the active gill net fishers in Delaware Bay and 6.3% of the total number of permitted gill net fishers. Our partners at DNREC surveyed their stakeholders, 11 managers and five commercial fishers responded. The managers did not show a clear

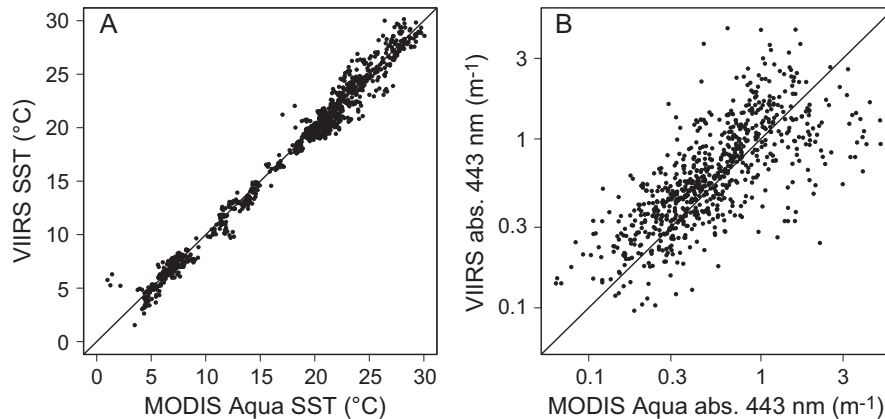


FIG. 6. Comparison of (A) sea surface temperature and (B) absorption (abs.) at 443 nm between MODIS-Aqua and VIIRS at the acoustic receiver locations during 2013. The black line indicates the 1:1 line.

TABLE 1. Root mean square (RMS) errors between measured sea surface temperature (SST) and ocean color (absorption at 443 nm, A443) with >50% coverage over the study region for gap-filled (GF) nowcast, forecasts, and climatology.

| Model | GF nowcast | GF 1-d forecast | GF 2-d forecast | GF 3-d forecast | GF MODIS-Aqua climatology |
|-------------------------|------------|-----------------|-----------------|-----------------|---------------------------|
| MODIS-Aqua SST (°C) | 0.28 | 0.76 | 0.82 | 0.98 | 1.02 |
| VIIRS SST (°C) | 0.25 | 0.93 | 1.18 | 1.41 | 1.15 |
| MODIS-Aqua A443 (per m) | 0.57 | 1.28 | 1.34 | 1.49 | 0.78 |
| VIIRS A443 (per m) | 0.32 | 0.58 | 0.65 | 0.66 | 0.38 |

preference for one of the three delivery methods. However, the commercial fishers overwhelmingly (80%) preferred the text delivery system over the flyer maps and web application. All survey respondents preferred depth bins to be reported in feet vs. meters. The natural resource managers thought that the current population level of Atlantic sturgeon in the estuary ranged from low to high, with most choosing low ($n = 3$) or moderate ($n = 3$) and four respondents choosing to not answer the question. However, the commercial fishers had a broader range of where they thought the current population level of Atlantic sturgeon was presently, with responses ranging from very low to very high. The majority of commercial fishers that responded to the survey following project implementation were satisfied with the frequency and amount of information in the warnings. However, two of the commercial fishers did suggest a lower frequency warning would have been preferred. Similarly, roughly 27% of the natural resource scientists and managers that responded to the survey would have preferred less frequent notification.

DISCUSSION

Conserving Atlantic sturgeon requires a decision framework with accurate and spatially complete predictions of occurrence for managers, stakeholders, and practitioners to make daily decisions about their

activities. To engage with this framework, users have an expectation that these prediction systems will have continuity around which best practices can be developed (Hobday et al. 2019). These requirements create challenges when using satellite remote sensing in a region that changes rapidly, is often plagued by cloud cover, and can sometimes suffer from sensor failure. Operationalizing the Atlantic Sturgeon Occurrence Model (ASOM; Breece et al. 2018) given the constraints of the decision framework for stakeholders on Delaware Bay required that daily, spatially resolved forecasts be made that could be understood over text messages. Furthermore, the ASOM system needed to be successfully transitioned from the retiring (MODIS-Aqua) to the continuing satellite-borne sensors (VIIRS). We addressed these challenges by cross comparing MODIS-Aqua and VIIRS using DINEOF to gap fill the satellite data inputs for the ASOM and delivering these forecasts to stakeholders in multiple ways.

The longevity and reliability of MODIS-Aqua makes it an attractive platform for the development of SDMs without the complications of cross satellite calibrations. However, MODIS-Aqua is beyond life expectancy, therefore comparison between MODIS-Aqua and VIIRS was a critical step for operationalizing the ASOM to maintain future continuity. Overall the products from MODIS-Aqua and VIIRS were comparable in the Delaware Bay suggesting the tool will not be limited by

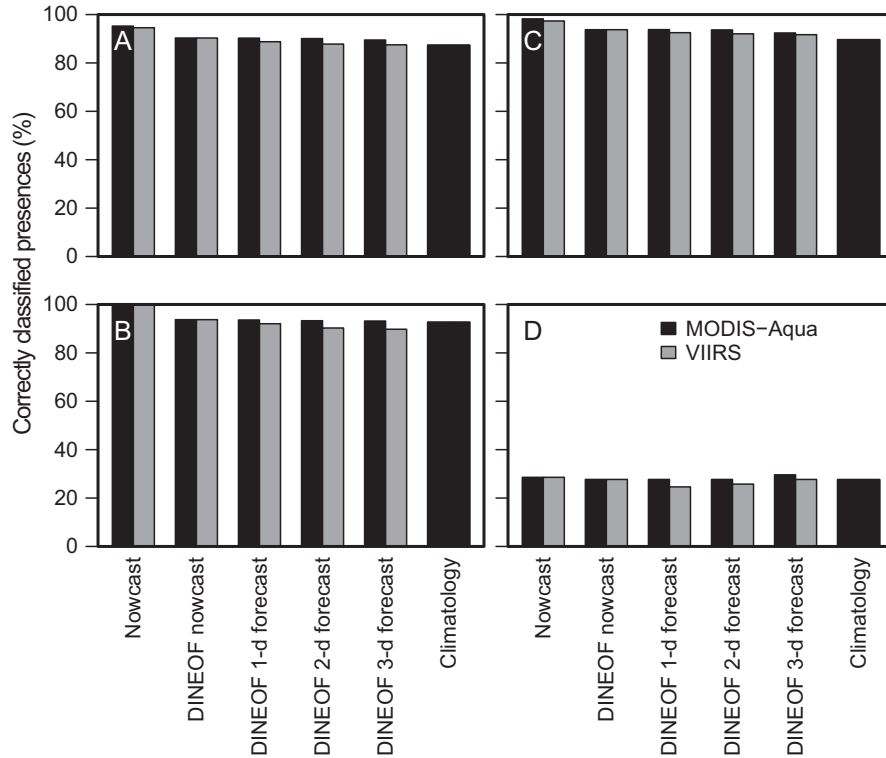


FIG. 7. Percentage of correctly classified Atlantic sturgeon presences (sensitivity) by (A) whole year, (B) spring, (C) summer, and (D) fall astronomical seasons. Winter had too few observations for meaningful comparison.

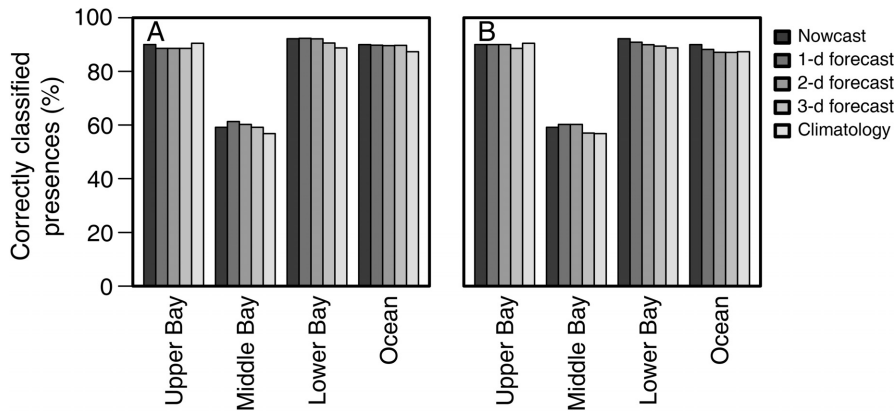


FIG. 8. Percentage of correctly classified Atlantic sturgeon presences by region for (A) MODIS-Aqua, and (B) VIIRS. The MODIS-Aqua gap-filled daily climatology performed better than any other gap-filled product.

MODIS-Aqua life span. Sea surface temperature compared favorably between the satellite platforms, which is consistent with previous studies (Liang and Ignatov 2013). The relationship of A443 between MODIS-Aqua and VIIRS was not as robust, and slight differences in the derived absorption products from these two sensors are consistent with previous comparisons (Ladner et al. 2014). Overall, the differences in the ASOM between MODIS-Aqua and VIIRS were small (<5% on average),

indicating that VIIRS data are suitable for the ASOM in our study region.

DINEOF was developed to gap fill satellite SST data (Alvera-Azcárate et al. 2009) and has been used to gap fill ocean color data (Liu and Wange 2018). In our study, DINEOF was better at statistically nowcasting and forecasting SST than A443 in the study region compared to climatologies (Table 1). SST shows large seasonal variability and seasonally persistent upwelling near the mouth

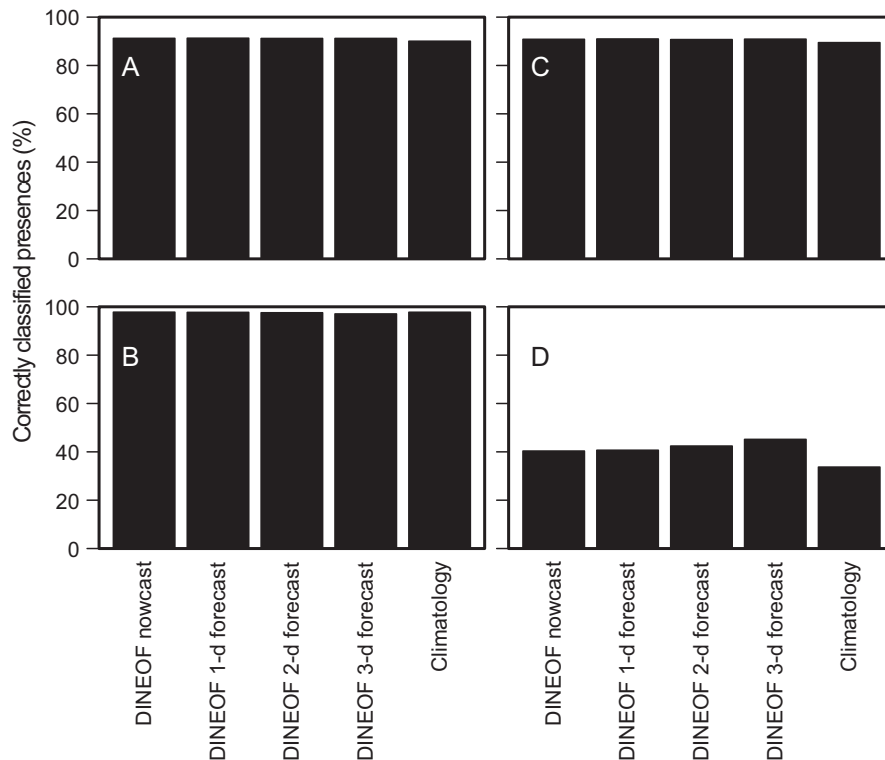


FIG. 9. Percentage of correctly classified Atlantic sturgeon presences (sensitivity) by (A) whole year, (B) spring, (C) summer, and (D) fall astronomical seasons based on the assigned categories using a 5% pixel threshold to indicate warning for the entire sub-region. Winter had too few observations for meaningful comparison.

of Delaware Bay (Voynova et al. 2013). However, because Delaware Bay is shallow, the temperature is strongly related to weather patterns and SST can be anomalously warm or cold depending on local weather conditions. Therefore near-real time forecasts of temperature could be better than gap-filled climatological predictions. Surprisingly, this did not appear to be true for A443. While the gap-filled nowcast of A443 performed about as well as the gap-filled climatology, the gap-filled forecasts were significantly worse than the climatology. Therefore, using DINEOF as a short-term statistical forecast with ocean color should be treated with care in this region. Because of these results, we used the DINEOF nowcasts and forecasts of SST and the gap-filled climatology of A443 as inputs to the ASOM model.

As expected, the non-gap-filled nowcast of Atlantic sturgeon occurrence performed better than the gap-filled products because these data were part of the original ASOM building process (Breece et al. 2018). However, the ASOM nowcasts, 3-d forecasts, and climatologies for the whole year, spring, and summer were quite good. In the fall of 2013, the non-gap-filled nowcast performed much worse compared to the entire year, spring, and summer. This is likely because in the fall of 2013, there were only seven observations of Atlantic sturgeon in the study area matched to non-gap-filled satellite data. By including gap-filled data, the number of matched Atlantic sturgeon

observations increased to 257. However, the number of matched Atlantic sturgeon observations in the fall was still a full magnitude lower than in the spring and the summer as Atlantic sturgeon have either left the study region by the beginning of astronomical fall or they are quickly migrating through the study area without maintaining residency for any period of time (Breece et al. 2018). In the spring and summer, when Atlantic sturgeon are heavily using our study region, the inclusion of DINEOF gap-filled data did not drastically reduce ASOM model performance.

There were also clear differences in model performance in each region. The middle bay had a much lower performance compared to the other regions (Fig. 8). This result may reflect a key conceptual weakness in the ASOM. Presence-absence models assume that matched environmental covariates approximate the preferred habitat of the modeled species. However, this key assumption can be violated if the species occurrence is not strongly related to its preferred environmental conditions but is coincidental as an organism travels through a region to achieve some other life history goal. An analysis of Atlantic sturgeon movements in Delaware Bay by Breece et al. (2017) showed that Atlantic sturgeon maintained residency in the upper and lower bay but were transient in the middle bay. This is consistent with the anadromous life history of Atlantic sturgeon, as

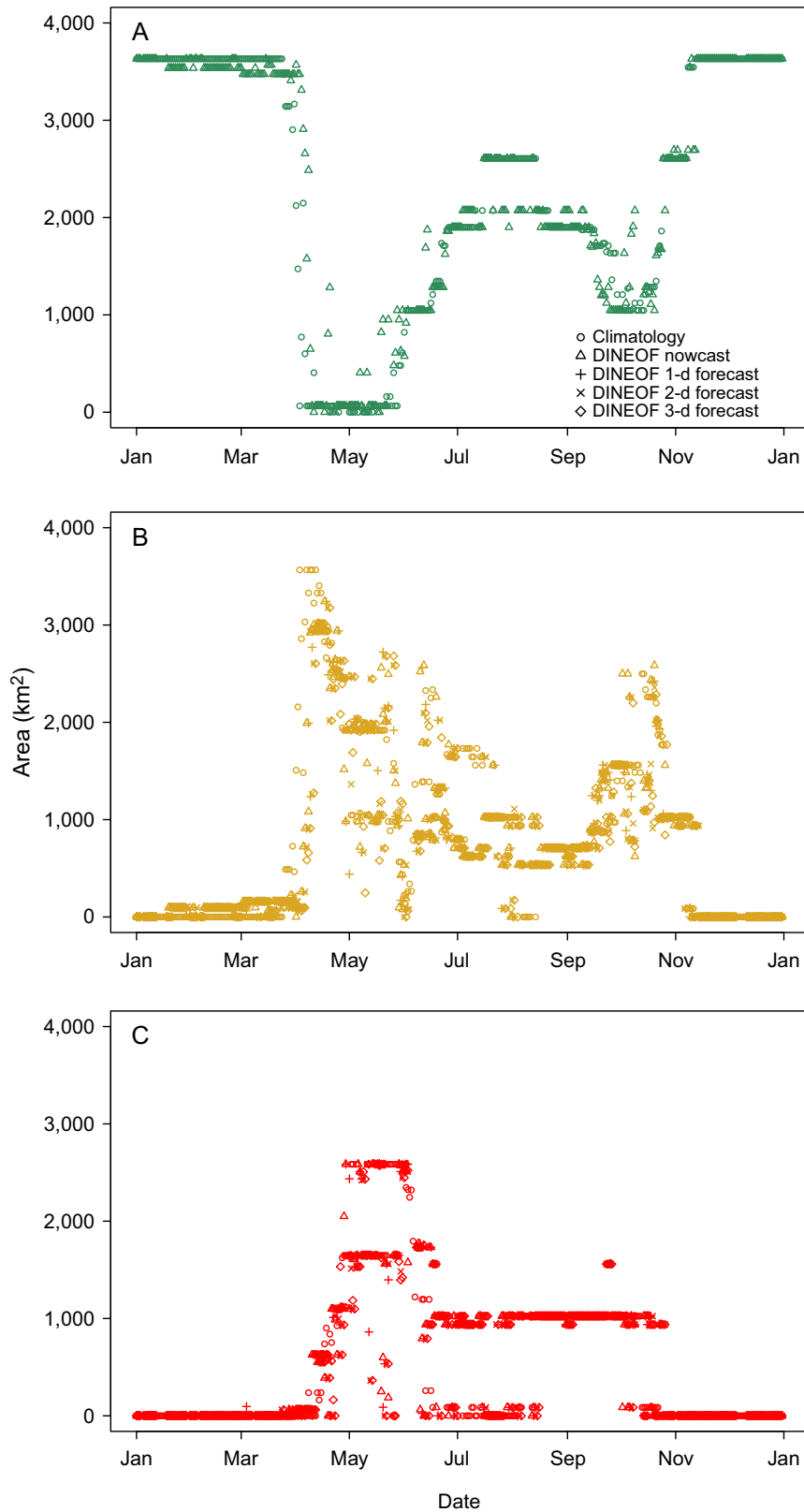


FIG. 10. Area of (A) low, (B) medium, and (C) high risk categories from the gap-filled MODIS-Aqua climatology. The area of low risk regions showed a strong seasonal signal and predictable signal.

spawning fish quickly migrate up the Delaware Bay to spawning and staging areas. At present, the ASOM does not account for these different behavioral switches, which limits performance in the middle bay subregion; however, the established framework can facilitate model adjustments easily to deploy a more accurate model for dissemination to stakeholders.

In a simulated study, Scales et al. (2016) showed that occurrence models performed best when contemporaneous data were used at the highest spatial and temporal scales and that climatological predictions of occurrence often performed poorly. Furthermore, missing data were a significant barrier to model performance. In this study, we tested this approach in a natural system with presence/absence data, and by filling missing data using DINEOF. In most cases, the contemporaneous nowcasts and short-term forecasts performed better than the climatologies. Surprisingly, the ASOM built only on the gap-filled climatologies still performed nearly as well (or better in a few cases) as gap-filled nowcasts and forecasts, irrespective of season or subregion (Figs. 7, 8). The primary purpose of the Scales et al. (2016) study was to understand the theoretical impact of averaging environmental predictors on a simulated pelagic organism responding to SST. The ASOM includes SST, as well as A443, water depth, and time of year. Because gap-filled forecasted A443 by DINEOF did not perform as well as gap-filled daily climatological predictions of A443, only SST was forecasted by DINEOF. Consistent with Scales et al. (2016), the most recent SST data, whether nowcasted or forecasted, produced better forecasts of Atlantic sturgeon occurrence than gap-filled climatological predictions. However, the difference in performance was relatively small. Given the dynamics of animal movement and Delaware Bay oceanography, this was surprising. This could be because Atlantic sturgeon occurrence in Delaware Bay is strongly correlated with both time of year and depth, which are captured in the climatology (Breece et al. 2018). Similar patterns have been observed for blue whales in the California Current where they track the climatological conditions during migration more closely than the contemporaneous conditions except in anomalous years (Abrahms et al. 2019). Once the risk of occurrence was aggregated into bay regions (ocean, lower, middle, upper) and by depth bins (at the request of our users), the differences between the gap-filled forecasts and gap-filled climatologies became even smaller. From a research perspective, there is a justified statistical inference to advocate for the most recent data to inform dynamic forecast habitat models. However, in this case, the user decision framework, risk tolerance, and communication needs, eventually led to a forecast warning system that was no different than climatological predictions seasonally (Fig. 9) or within the subregions (Appendix S1: Fig. S3).

Because the climatological predictions were nearly as good as the forecasts, the Shiny application directs users to them if there is more than 72 h without satellite data

over the study area (Fig. 9). However, there are sources of uncertainty in application that are not communicated to the user base. The differences between satellite sensors (Fig. 6) translate into slight differences in model performance (Figs. 7, 8), but the overall impact is small. There are also uncertainties introduced into the forecast because it is difficult to validate it with new data. Without new observations, it is unknown how climate change will affect the forecast over the long-term. The success of the climatological product suggests that year to year variation may be small, but this may change in future climates. Future deployments of acoustic receivers and tags should be used to verify this product.

Direct interactions between scientist, managers, and harvesters are crucial in the development of useful dynamic management tools (Payne et al. 2017, 2019, Welch et al. 2018). The Delaware Bay stakeholders' low appetite for risk was a major consideration that had to be taken into account during the development of this framework. State-level managers in our region saw the high performance of the gap-filled climatological risk maps as a strength of the ASOM forecast system. We found that resource managers and stakeholders are open to using the tool to evaluate permitting and activity requests in the future. For example, Fig. 10 shows how much of the study area would be climatologically classified as low, medium, and high risk. Because Atlantic sturgeon avoidance was the most critical management goal, the strong seasonal migration signal in the area of low risk categories could provide important information to inform time-of-year restrictions for certain activities including dredging and coastal development that potentially affect the recovery of the Atlantic sturgeon.

In addition to accurate predictions, dynamic management tools must be accessible, easy for users to interpret, and delivered in a consistent and timely manner at scales relevant to the decisions being made within the framework of the concerns of the community (Payne et al. 2017, Hazen et al. 2018, Hobday et al. 2019). There were three key stakeholder (both managers and fishers) concerns that drove the design of the final product. The first was overcoming stakeholder familiarity with technology and data transfer limitations due to user's service provider and limited cell phone coverage in the Delaware Bay. The second was the desire to be risk averse in the warning product, and the third was to balance inherent risk of unintended audiences targeting fishes for illegal profit. To try and mitigate these three issues, we effectively reduced the resolution by pooling the risk of individual pixels into the ASMFC regions (ocean, lower, middle, upper) and 5-m depth bins. This meant that warnings in the map could be communicated with four locations and a depth range, allowing for a text-based platform as the primary delivery mechanism and overcoming issues with low cellular bandwidth at sea. A consequence of pooling the risk into these subregions is that it made the model more sensitive to predicted presences. If a presence was predicted in 5% of the pixels in a subregion, then the entire subregion

received the higher risk. This was acceptable for the stakeholders to reduce unintended catches as much as possible. The risk of potential poaching was only partially mitigated. The reduced spatial grain size meant that, for high regions, as few as 5% of those pixels likely contained an Atlantic sturgeon. However, potential bad actors could still use the online web-application to get pixel-by-pixel estimates of the ASOM. Some of this concern could be further mitigated by putting the web application behind a subscription service, but these could also be circumvented. Currently and fortunately, there is no evidence of poaching in the study area as Atlantic sturgeon are not susceptible to hook and line captures (Collins et al. 1996) and therefore would need to be targeted via other means, gillnet or trawl; these methods would likely be noticed due to the limited number of participants and relatively few access points in the Delaware River estuary.

Ecological forecasting is becoming more common as data availability and computation have become more accessible to scientists (Dietze 2017), particularly those working in the marine environment (Payne et al. 2017, Tommasi et al. 2017). Ideally, these forecasts would be iterative, with a mechanism to update the underlying model based on new information and data (Dietze 2017, Welch et al. 2018); however, when predicting occurrence of rare cryptic species such as Atlantic sturgeon, new occurrence data are not typically immediately available as it is reliant on expensive passive acoustic telemetry arrays that are not maintained at necessary scales (Breece et al. 2018). Therefore, we must rely on historic data sets to create initial operational forecast that can only be updated if funding for future data collection is continued. While this approach is not ideal it has produced a reliable delivery system to warn stakeholders of their risk of encounter with Atlantic sturgeon.

Dynamic management and/or stakeholder decision-making is quickly becoming a useful method to reduce interactions while minimizing burdens (Brodie et al. 2017, Hazen et al. 2018, Welch et al. 2018). This study takes a species distribution model, created on dynamic environmental data, and creates a framework to automatically gap fill missing data, partition the study area by depth and geographic region, assess encounter risk, and deliver an easily interpretable forecast product to stakeholders who are interested in avoiding an endangered species while minimizing economic losses. Relying on data products that have fine-scale global coverage makes this framework readily transferable to many SDMs where better estimation of encounter risk would benefit conservation efforts.

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SUPPORTING INFORMATION

Additional supporting information may be found online at: <http://onlinelibrary.wiley.com/doi/10.1002/eap.2358/full>

OPEN RESEARCH

The environmental data utilized in this study is available from the NOAA ERDDAP archive at http://basin.ceoe.udel.edu/erddap/griddap/viirs_sturgeon_model.html and http://basin.ceoe.udel.edu/erddap/griddap/Aqua_gapfilled_1day.html. For the Atlantic Sturgeon Occurrence Model and associated data, please see Breece et al. 2018. The R code and all supplemental files needed to reproduce the three aspects (Interactive Application, Sturgeon Model Predictions, and Forecast Production and Messaging) of this study are permanently archived (Breece et al. 2021) in Dryad: <https://doi.org/10.5061/dryad.jsxksn08b>.