Proposal

Submitted to

NOAA's Fisheries and the Environment (FATE) Program

Using the American Lobster Settlement Index and Environmental Indicators to Forecast Lobster Fishery Recruitment

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BACKGROUND

The American lobster is among the three most valuable single-species fisheries in the United States with US revenues in 2012 on the order of $500 million. The three stocks - Gulf of Maine (GOM), Georges Bank (GBK) and Southern New England (SNE) - are all in a state of flux. While the SNE stock is near record low abundance, the GOM and GBK stocks are at extraordinary record high levels (ASMFC 2009; American Lobster Technical Committee 2010). The causes are probably multiple and strongly linked to warmer water conditions, but fishery managers are concerned that the high abundance levels in GBK and GOM may be unsustainable and that current conservation measures will not stem the declines in SNE. The collapse of the GOM fishery would be an economic catastrophe because of the region's perilous reliance on this single fishery. The proposed research is therefore important because of the value of the lobster fishery and great uncertainty about its future in a changing environment.

The American Lobster Settlement Index (ALSI) is a key indicator of variability in lobster postlarval recruitment. It is currently used in stock assessment as an indicator of stock health (ASMFC 2009). As fishery management adapts to a changing environment, there is considerable interest in strongly integrating ALSI in stock assessment to forecast recruitment to the fishery.. Initiated in 1989, this long-term monitoring program quantifies Young-of-year (YoY) "settlers" and early juvenile abundance using diver-based and collector-based sampling in rocky coastal nursery habitats (Fig 1). Ssampling is conducted annually at the end of the late summer-early autumn postlarval settlement season (Wahle and Steneck 1991, Wahle et al. 2009b). The ALSI collaborative consists of US state and Canadian government, academic and industry participants. Sampling is now conducted across the range of lobster stocks in US waters and is the only available data on abundance of this earliest pivotal stage of the lobster benthic life. The resulting time series have been the springboard for numerous research projects, contributing to more than 30 peer reviewed publications and technical reports (see ALSI Website: Wahle 2011a). ALSI is expected to see expanded use in the next stock assessment because it provides information relevant to the root cause of recent trends in the fishery. Although it holds much potential in forecasting, to date there has been no attempt to combine ALSI with key environmental indicators to predict future catch and abundance. This research is therefore consistent with both Type I FATE proposals that "*improve stock assessments or fisheries management"* and Type II proposals that *"develop and validate ecological indicators.*"

Our proposal has benefited from constructive reviewer comments on a previous FATE proposal. Key improvements include (i) involving oceanographic expertise (Pershing), (ii) explanation of how environmental variables will be incorporated in modeling, and (iii) explicit reference to how our NOAA collaborator (Jacobson) will apply the findings and approach to US lobster stock assessment and ecosystem-based management.

The project will build statistical models that use environmental data to predict the number of settlers from the spawning stock, and in turn, the number of fishery recruits from settlers. We hypothesize that environmental data (temperature, wind, predator abundance, and shell disease prevalence) will considerably improve the predictive power of the spawner-to-settlement and the settlement-to-fishery recruit relationship, thereby improving stock assessments and management advice at the stock and regional levels. In stock assessment work, ALSI data will fill important gaps between bottom trawl survey information about spawners and fishery catch and length data (Fig. 1).

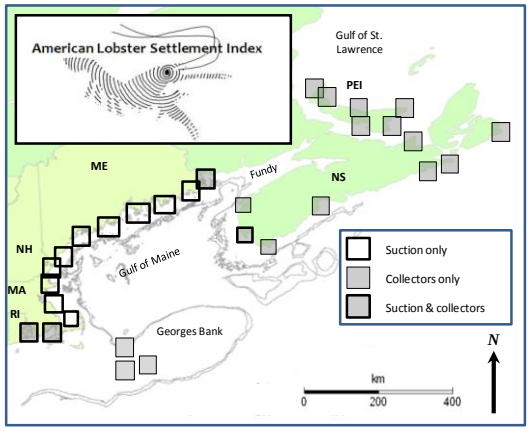


Figure 1. American Lobster Settlement Index sampling regions as of 2009. Data are collected either by suction sampling, passive collectors, or both. Multiple fixed sites are sampled annually within each region to produce the annual regional index.

Our recent analysis of ALSI data suggests that recruitment patterns and their environmental determinants are coherent over regional spatial scales (Pershing et al. 2012). Therefore techniques that combine local and regional predictions are needed to

forecast lobster recruitment over the wide spatial scale of entire stocks.

ALSI aids our understanding of how the environment impacts lobster populations. A recently developed coupled bio-physical model of lobster larval transport connects the distribution of egg bearing females to ALSI-validated settlement patterns along the coast (Xue et al. 2008, Incze et al. 2010). Interannual variability in settlement has since been explained by atmospheric processes that influence larval transport (Pershing et al. 2012). Regionally, ALSI has also proved to be a useful predictor of spatial (Steneck and Wilson 2001) and temporal (Wahle et al. 2009a) patterns in New England's lobster harvest.

We are currently working with the Atlantic Coastal Cooperative Statistics Program (ACCSP; http://www.accsp.org/) to create a Web portal to centralize the ALSI database, automate data submission and reporting and maximize the use of ALSI for scientific and fishery management. This process implements data submission and quality assurance protocols, access rules, and a dedicated Website for the Index. This proposal aims to capitalize on these efforts.

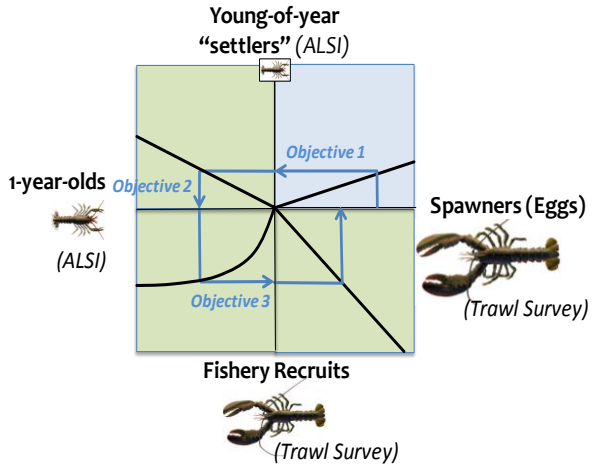


Figure 2. Lobsters have a complex, multi-stage life cycle. They spend 1-2 months in the plankton (blue sector), settle to the bottom, and then require several years to mature and recruit to the fishery (green sectors). Radiating lines and curves in the figure illustrate hypothesized functional relationships among successive stages to be tested for the three objectives of this proposal. Trawl surveys estimate the number of fishery recruits and spawners. Environmental factors have been implicated in two portions of the life cycle. Nearshore summer weather conditions strongly influence the number of settlers, while temperature, predator abundance, and disease influence growth and mortality in the years after settlement.

APPROACH

We propose to evaluate four objectives related to the predictive links between parallel time series generated by ALSI and state/federal trawl surveys, and additional environmental indicators. We will: (1) Evaluate spawner-to-settler relationships; (2) Evaluate cohort fate over first years of benthic life; (3) Forecast fishery recruitment, and (4) Make stock level data available for use in the stock assessment model. Work to modify models to use the index will take place independently. In effect, the two-year project closes the lobster life cycle by evaluating the spawner-to-fishery-recruit relationship at stock-wide and sub-stock spatial scales. ALSI data will improve forecasting capability because the fishery is recruitment driven and there is currently no available information about the strength of recruitment.

Table 1. Timetable of proposed activities. Dark gray cells indicate activities for proposed NOAA-FATE program support. Light gray cells are activities currently under way with other sources of support.

	2013	2014	2015
Database & Web portal construction for ALSI collaborative with ACCSP			
Objective 1: Spawner to settler relationships			
Objective 2: Early cohort fate analysis			
Objective 3: Settler to fishery recruit relationships			
Objective 4: Make stock level data available for assessment model			

Objective 1 – Evaluate spawner-to-settler relationship (Year 1): Spawner-to-settler relationships in large crustacean have been most successfully quantified when environmental drivers are included in the analysis. Recently, Pershing et al. (2012) found strong correlations between the ALSI time series and atmospheric indicators, in particular, temperature, geopotential height, and wind strength and curl (Fig. 3). The strong dependence on summer weather conditions explains the large-scale coherence in settlement. However, when the models were used to make out-of-sample predictions for the years 2005-2009, the accuracy of the predictions varied along the coast: Models for northern MA and mid-coast ME performed well, whereas the model over-predicted settlement for RI, and under-predicted it for Beaver Harbour, NB. Adult lobster abundance has changed dramatically in both regions, declining in RI due to shell disease

and increasing in New Brunswick. We hypothesize that including spawning stock biomass will improve predictions of settlement. In a preliminary analysis using data collected in Rhode Island, for example, Gibson (2008) found that the abundance of mature females in the RI nearshore trawl survey explained a significant amount of the annual variability in settlement the same year, and that the North Atlantic Oscillation (NAO) Index added further explanatory power. These relationships therefore warrant further investigation.

We aim to examine the spawner-settler relationship more comprehensively using data collected along the coast from RI to eastern ME where trawl survey and suction sampling data time series are sufficiently long. The relationship will be examined at local and regional scales (a single stock-wide relationship does not exist, ASMFC 2009). Sites will be aggregated into spatially coherent regions according to a recent correlation analysis among the time series (Pershing et al. 2012). We will expand the set of environmental indicators to include the NAO Index, weather buoy data, and observed or modeled surface and bottom temperature data (Locarnini 2011; Xue et al. 2008) for the years in question. We expect that bottom temperatures may be especially important in recent years, where warmer waters have led to earlier inshore migration and molting (Mills et al. 2013). This will involve parametric spawner-recruit models or potentially nonlinear and nonparametric Generalized Additive Models with spawning biomass and environmental data as predictors. Here and in what follows, environmental predictor variables will be tested for statistical significance and predictive power while localities and years may be represented as random effects.

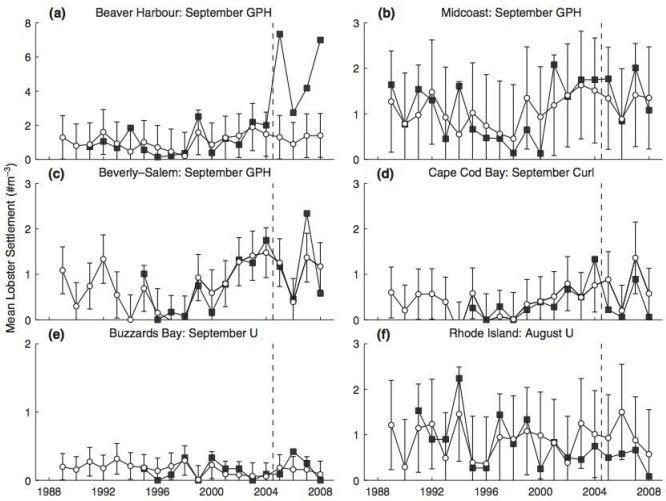
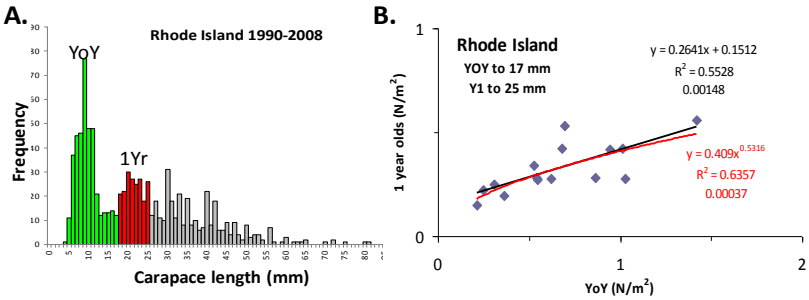


Figure 3. Observed (closed circles) and predicted (open circles) YoY settlement using environmental predictors. Model developed using ALSI data through 2004. Model predictions for subsequent years through 2008 (to right of vertical dashed line) fit well for regions b, c, d, e, but under- and over-estimate it for regions a and f, respectively, locations where spawner abundance has dramatically changed. We hypothesize that including spawner abundance will substantially improve these forecasts (from Pershing et al. 2012).

Objective 2 – Evaluate cohort fate over first years (Year 1): This objective looks within the ALSI data base to characterize the functional relationship between YoY settlement and recruitment to subsequent early juvenile stages (1- and 2-yr olds) still residing within the nursery habitat. One of the benefits of the settlement time series is the ability to evaluate the fate of cohorts over their first few years of life before they emerge from nursery habitats. Because crustaceans have no morphological age indicators, it is necessary to understand how the age-size relationship varies regionally with differences in the environment. Size range definitions of 0-, 1- and 2-yr age groups are reasonably well established for some regions, but not all. Refining these size-definitions is a necessary step before evaluating the fate of cohorts. For each region we will evaluate the functional relationship between 0-year and subsequent ages with the appropriate time lag and with and without environmental correlates, possibly using localities as random effects. For the proposed research, we will carry out a comprehensive analysis of all 13+ regions with sufficiently long time series.

An example of this analysis using existing MatLab code is illustrated in Fig. 4. This analysis can yield valuable new insights on early post-settlement processes, such as survival, the strength of density-dependent controls and environmental effects. For example, the relationship for RI illustrated in Fig. 4b suggests weak, if any, density-dependence operating over the first year of life. The slope of the linear regression in this example suggests on the order of 25% survival, on average, over the first year of life.



C.

YoY upper size limit (mm)

1 Yr upper size limit	9	10	11	12	13	14	15	16	17	18	19	20
14	0.0150	0.0029	0.0011	0.0020	0.0267							
15	0.0000	0.0056	0.0335	0.0398	0.0605	0.2194						
16	0.0007	0.0095	0.0499	0.0525	0.0653	0.1577	0.0140					
17	0.0012	0.0076	0.0286	0.0181	0.0180	0.0389	0.0062	0.0484				
18	0.0238	0.0574	0.1502	0.1352	0.1350	0.1877	0.1067	0.1530	0.4147			
19	0.0325	0.0699	0.1793	0.1956	0.2208	0.2996	0.2383	0.2829	0.4275	0.0856		
20	0.0615	0.1044	0.2137	0.2166	0.2287	0.2838	0.2363	0.2569	0.3786	0.1754	0.0762	
21	0.0927	0.1420	0.2465	0.2441	0.2631	0.3001	0.2578	0.2825	0.3979	0.2376	0.1780	0.1685
22	0.0699	0.1075	0.2093	0.2170	0.2386	0.2908	0.2495	0.2762	0.4112	0.2456	0.1629	0.174
23	0.1156	0.1516	0.2560	0.2801	0.3105	0.3613	0.3414	0.3799	0.4768	0.3610	0.3133	0.3599
24	0.1210	0.1622	0.2709	0.2987	0.3258	0.3803	0.3753	0.4322	0.5106	0.4062	0.3714	0.3608
25	0.1340	0.1827	0.3068	0.3628	0.3980	0.4560	0.472	0.4983	$\boxed{0.5528}$	0.4648	0.4329	0.4069
26	0.0998	0.1365	0.2288	0.2520	0.2735	0.3209	0.3138	0.3327	0.4016	0.2966	0.2653	0.2423
27	0.1199	0.1551	0.2340	0.2483	0.2592	0.2933	0.2821	0.2959	0.3615	0.2697	0.2248	0.2002
28	0.1025	0.1339	0.2081	0.2249	0.2420	0.2768	0.2626	0.2762	0.3438	0.2444	0.2182	0.1870

Figure 4. Following the fate of cohorts through time starts with refining size definitions for early juvenile age groups. Using the Rhode Island settlement time series as an example, knife edge size definitions for age 0 (YoY) and 1-year old lobsters are initially approximated based on the location of size modes in the size distribution of lobsters residing in cobble nurseries (a). Regression analysis (b) evaluates the relationship between YoY and resultant 1-year olds a year later; both linear (black) and non-linear (red) fits are shown for the size definitions giving the highest coefficient of determination (r^2). The matrix of r^2 results from the iterative series of linear regressions for reasonable non-overlapping size definitions (c). Highlighted are the statistically significant relationships (light orange: $p < 0.05$; dark: $p < 0.01$) with the maximum r^2 enclosed in box. Size definitions giving the maximum r^2 illustrated in (a) and (b).

The very existence of a positive relationship between successive ages over these first years gives a promising sign, but no guarantee, that the predictive relationship may carry through to mature ages. On the other hand, early decoupling of the relationship will reduce expectations of seeing a predictive relationship in later stages under Objective 3. Lobster growth rates are strongly temperature dependent. Therefore, we expect that including temperature as a covariate will allow for improved estimates of lobster recruitment from ALSI.

Objective 3 - Forecasting fishery recruitment (Year 2): One of the long-standing goals of the ALSI collaborative has been to evaluate whether the settlement index is a useful predictor of future fishery recruitment at regional and whole-stock levels (Fig. 1). We will address this question by examining relationships between the settlement index and subsequent fishery recruitment as measured by state inshore and federal offshore trawl surveys and including environmental variables. Lobsters recruit to the fishery at about age 5-8 year, so early recruitment forecasts could give managers considerable advance warning prior to major recruitment effects on the fishery. As under Objective 2, relationships between YoY and subsequent ages will be evaluated statistically with the appropriate time lags, and with and without environmental correlates, possibly using localities as a random effect. Regional recruitment forecasts will be combined and weighted based on recruit numbers or density to develop and test whole-stock forecasts.

Our first success story in this type of analysis was for RI where the joint effects of settlement and shell-disease explain a considerable proportion of the variability in pre-recruit abundance 3-yr later (Wahle et al. 2009a). Since shell disease is still mostly limited to southern New England, it is clear that a one-size-fits-all model of fishery forecasting is not appropriate for the American lobster. Tailored regional forecasts will likely be necessary. For most of the lobster domain in the US, the ALSI time series is now long enough to make such an evaluation. We therefore propose to conduct a comprehensive statistical analysis on a region-by-region basis to evaluate how well projections based on ALSI correlate with a fishery independent index of fishery recruitment from state inshore trawl surveys and environmental variables. We will project fishery recruitment from the settlement index in two ways. First, we will simply assume the recruiting group is composed of a single age class (e.g., 7-yr-olds). The second more realistic and more complex approach models the mix of ages that comprise recruits to the fishery in any given year. The latter method, first presented in Wahle et al. (2004), distributes the time lag to produce a mixture of ages at the time of fishery recruitment, assuming a constant natural mortality rate (Fig. 5). Realistic size distributions at age will be provided by a recently developed probabilistic stepwise growth model that incorporates temperature (Bergeron et al. 2011).

We will test three components of the environment that are likely to influence the post-settlement fate of a lobster cohort up to the time it recruits to the fishery. First, temperature will be included as it influences growth. Then, two biotic environmental factors, shell disease and predatory fish abundance, can have a profound effect on lobster recruitment. Both are measured in the same trawl surveys used to assess lobster abundance. The incidence of shell disease has

previously been included in our lobster model for RI (Wahle et al. 2009a), but predator abundance has not.

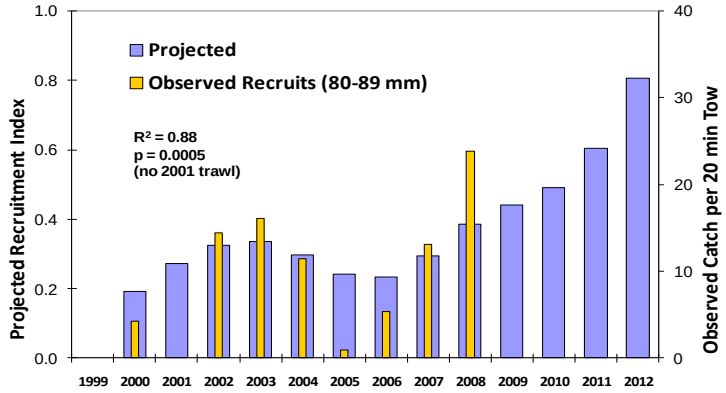


Figure 5. Projected time trend in relative abundance of American lobsters recruiting to the eastern Maine (Zone A) lobster fishery through 2012 (blue bars), compared to time trend of recruits observed in nearshore trawl survey in the same region through 2008 (orange bars). Projected fishery recruits are based on the settlement index and empirically derived growth trajectories using the method of Wahle et al. (2004). By this method fishery recruits for this region are estimated to range in age from 7 to 12 y with a median of 9 y. Coefficient of determination (r^2) and significance given for linear regression between observed and projected recruitment (No trawl survey in 2001).

Objective 4 – Make stock level data available for use in the stock assessment model (Year 2+)

The current lobster stock assessment model is a state-of-the-art length-based approach that incorporates modern statistical methods such as maximum likelihood and prior distributions for Bayesian estimation (ASMFC 2009). It represents collaborative programming work by staff at UMaine, NMFS and ASMFC. Our NOAA co-investigator (Jacobson) is an active member of the ASMFC Lobster Assessment Model Development Team and its Lobster Stock Assessment Team. He has been very active in coding and testing the model to accommodate new data and approaches. He, his staff and the rest of the Model Development Team will be in an ideal position to modify and test the assessment model so that it accommodates the new recruitment index in fitting the model and projections.

BENEFITS

With a landed value of ~$500 million, the American lobster fishery is the most valuable single-species fishery in the US Northeast, but just as the Gulf of Maine stock is at historic highs, southern New England's fishery has been devastated by disease and episodes of mass mortality. Environmental change surely plays a role of in these diverging trajectories. This research is consistent with both Type I FATE proposals that *"aim to improve stock assessments for fisheries management through the inclusion of environmental or oceanographic information,"* and with Type II proposals that *"synthesize existing data sets and result in the development and validation of ecological indicators.*" ALSI indices and associated environmental indicators would improve lobster management because they are the only data available for forecasting future recruitment in stock assessments. Potential benefits for improving recruitment forecasts are high because of the very high value of this recruitment-driven fishery, and because climate change and human impacts are increasing uncertainty about the fishery's future.

DELIVERABLES

Our NOAA co-investigator (Jacobson) and his staff are members of the ASMFC Lobster Technical Committee, Lobster Stock Assessment Modeling Committee and the stock assessment process. ALSI indices will be used in the UMaine Lobster Stock Assessment Model currently used by fishery managers (ASMFC 2009). Necessary modifications to the model will be made by Jacobson with the ASMFC Lobster Model Development Committee.

The principle deliverables are: (1) Recruitment indices for immediate use in stock assessments and to forecast abundance and catch, (2) Models of the <u>spawner-to-settler relationship</u>, linking data on spawner abundance from trawl surveys and environmental conditions to the abundance of juveniles; (2) Models of the <u>fate of early benthic cohorts</u> during their first years that evaluate early post-settlement survival, density-dependent and temperature effects; and (3) F<u>orecast models of lobster fishery recruitment</u> using the ALSI data base and key physical and biotic environmental variables.

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