Final Report:

Mapping the Distribution and Abundance of Macroalgae in the Indian River Lagoon

CONTRACT #26265

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EXECUTIVE SUMMARY

A large-scale acoustic survey was conducted between May 4 - July 1, 2010, with the objective of quantifying the abundance and distribution of seasonal drift macroalgae in the Indian River Lagoon. The survey was conducted along the same pre-planned survey lines (running east-west and spaced 200m apart) used in 2005 and 2008. Indian River was surveyed from the Sebastian Inlet to its northernmost extent in the Titusville area. Banana River was surveyed from its convergence with the Indian River northward to the Federal Manatee Zone near Cape Canaveral. River banks were surveyed to a minimum depth of approximately 1.3 m. Hydroacoustic data were collected with the same BioSonics DT-X echosounder and multi-plexed 38 and 418 kHz digital transducers used in the 2008 survey (the 2005 survey utilized a QTC system). Hydroacoustic data were processed with BioSonics Visual Bottom Typer (VBT) seabed classification software to obtain values of E0 (pre-bottom scatter), E1′ (1st part of the 1st echo waveform), E1 (2nd part of 1st echo), E2 (complete 2nd echo), and FD (fractal dimension characterizing the shape of the 1st echo). A training dataset was compiled from 180 ground-validated hydroacoustic samples collected across the extent of the study area. Following quality analysis the 38 and 418 kHz datasets were merged and submitted to a series of three discriminant analyses (DA) to refine the training samples into three pure end-member categories; BARE (bare substrate), DMA (drift macroalgae, ~5-20cm), and ShortSAV (non-DMA, ~5-10cm). The Fisher's linear discriminant functions from the third and final DA were used to classify each of the 400,000+ hydroacoustic survey records as either BARE, ShortSAV, or DMA. Percent cover of drift macroalgae was computed for blocks of ten sequential records. Drift macroalgae biomass was computed as the product of percent cover, area surveyed, and wet weight of drift macroalgae. Drift macroalgae biomass was found to be 102,162 metric tons (wet weight) within the 281.6 km^2 study area (compared to 69,859 metric tons in 2008). Average DMA cover was greater in the Indian River (19.7%) than in the Banana River (7.3%). The pattern of coverage differed between the two systems. Drift macroalgae cover was patchier within Indian River, with several large patches that had canopy heights in excess of 15 cm. Cover within Banana River was more sparse, short and equitably distributed in comparison. The overall predictive accuracy of total SAV (i.e. ShortSAV plus DMA) was 81.6% (n=359) at three levels of cover (0-33, 33-66, and 66-100%). To better understand the dynamics of drift macroalgae propagation and transport, a portion of Indian River was surveyed at the beginning, middle and end of the survey. The boundaries of drift macroalgae patches changed little, but cover thinned considerably by the third survey. The incorporation of dual-frequency digital transducers in conjunction with new post-processing techniques developed in 2008 realized the goal of establishing an accurate, efficient, and temporally consistent method for acoustically mapping drift macroalgae biomass.

INTRODUCTION

Drainage of the St. Johns River marshlands for agricultural development began in the late 19th century and rapidly accelerated in the 1940s and 1950s. By the early 1970s nearly two-thirds of the historical marshlands had been drained. During this time a number of canals were also built to divert water from the Upper St. Johns Basin into the Indian River Lagoon. These and other hydrological alterations have subjected the estuarine Indian River Lagoon to pulses of freshwater and nutrient-rich agricultural runoff. Extensive commercial and residential development over past decades has added to the list of anthropogenic disturbances to water quality. Reduced water transparency, variable salinities, and elevated nutrient levels have contributed to a shift from seagrass to macroalgae. For example, the areal coverage of seagrass in the area of the Sebastian Inlet has declined by approximately 38% between the years 1951-1984 (Goodwin & Goodwin, 1976). In an effort to restore and preserve the lagoon, the IRL Program was created in 1996 under the leadership of the St. Johns River Water Management District. The immediate goals were to improve water and sediment quality and monitor seagrass beds, with an ultimate goal of reclaiming historical seagrass ranges. A component of this initiative involved a better understanding of seasonal drift macroalgae blooms, which (1) can exceed the biomass of seagrass in some areas of the lagoon (Virnstein & Carbonara, 1985), (2) exclude seagrass by shading (den Hartog, 1994), and (3) potentially act as a nutrient sink (Davis et al., 1983). Beginning in 2002 NCRI scientists began work on methods for the acoustic remote sensing of drift macroalgae using QTC and Echo*plus* echosounders (Riegl et al., 2005). In 2005, the author conducted the first lagoon-wide survey using a QTC echosounder. While these early attempts showed promise, predictive accuracies hovered near 50%. The results presented in this chapter began with a 2007 pilot-program utilizing a BioSonics DT-X digital echosounder. It is with this system that the goal of a highly accurate and repeatable lagoon-wide survey of drift macroalgae biomass was met.

METHODS

Survey Area

The acoustic survey was completed between the dates of May 4 - July 1, 2010, during the historic peak of drift macroalgae biomass. Indian River was surveyed from its origin in the Titusville area (28.766^{o}N) to just below the Sebastian Inlet (27.826^{o}N) (Appendix A1). Banana River was surveyed from the Federal Manatee Zone near Cape Canaveral (28.433^{o}N) southward to its convergence with Indian River in the Melbourne area (28.157^{o}N). The survey vessel was navigated along the same pre-planned lines used in the 2005 and 2008 surveys, running east-west and spaced 200 m apart. The depth of the water column surveyed ranged from 1.3 to 4.3 m and averaged 2.2 m.

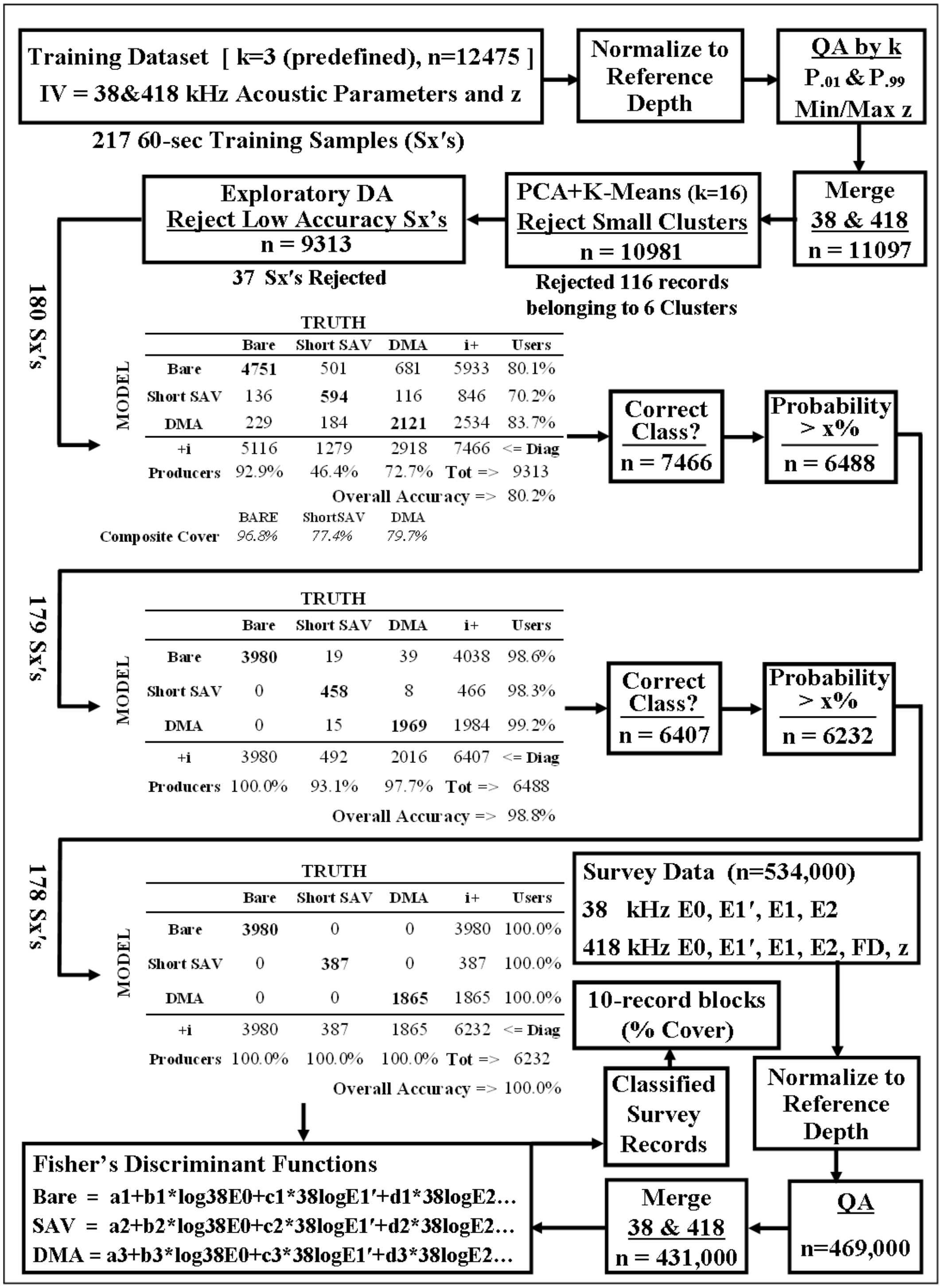
Sonar Equipment

The survey was conducted from a 7.5 m v-hull boat with a 0.5 m draft (Figure 1). Hydroacoustic data were acquired with a BioSonics DT-X echosounder and two multiplexed, single-beam digital transducers with full beamwidths of 10^{o} (38 kHz) and 6.4^{o} (418 kHz), operated at 5-Hz sampling frequency and 0.4 ms pulse duration. This was the same system used for the 2007 pilot study and the 2008 lagoon-wide survey. The two transducers were located on a swing-arm mounted to the gunwale. The GPS antenna was mounted directly above for optimal integration of acoustical and positional data strings. Global positioning data were collected with a Trimble Ag132 dGPS, differentially corrected against the WAAS signal to achieve positioning accuracies less than 0.9 m horizontal dilution of precision. The dGPS signal was interfaced with navigational software to provide real-time monitoring of vessel position with respect to the aerial images and pre-planned survey lines. To avoid turbulence-induced signal contamination, evident as a rolling oscillation on the real-time Visual Acquisition display, vessel speed was adjusted to maintain a net speed (vessel+drift) of approximately 4.5 knots.

Figure 1. Survey equipment. (left) Swing-arm in horizontal (traveling) position with 420 and 38 kHz transducers and Trimble antenna. (middle) Inside v-berth of survey vessel with BioSonics DT-X echosounder, Trimble receiver, and acquisition PC. (right) Monitor displaying gps-navigation over pre-planned lines and real-time echo returns.

Data Processing

To provide continuity with previous surveys, the same data processing workflow was followed as in 2008. Thus, results of the surveys are directly comparable. The complete workflow for the post-processing, quality assurance, and classification of hydroacoustic data is shown in Figure 2. The 38 and 418 kHz hydroacoustic data were processed with BioSonics Visual Bottom Typer (VBT) seabed classification software (v2) to obtain the following acoustic energy parameters (computed as the time integral of the squared amplitude of echo intensity); E0 (pre-bottom backscatter), E1’ (the 1^{st} part of the 1^{st} echo waveform), E1 (2^{nd} part of 1^{st} echo), and E2 (complete 2^{nd} echo). VBT also computed a value of FD (fractal dimension characterizing the shape E1). VBT allows the user to define the width of each Bottom Sampling Window in units of “samples”, i.e. the 41,667 Hz clock-speed of the DT-X internal processor. This critical setting is better understood by converting to units of meters via the speed of sound in water, shown for representative echo envelopes acquired over bare substrate and over drift macroalgae (Figure 3). The split between E1’ and E1 was set such that E1 would capture the trailing edge of the first echo. This emphasized sensitivity to the presence of SAV, as scattering from the vegetative canopy increases the proportion of signal returning to the transducer in the trailing edge of the first echo.



MODEL \ TRUTH	Bare	Short SAV	DMA	i+	Users
Bare	**4751**	501	681	5933	80.1%
Short SAV	136	**594**	116	846	70.2%
DMA	229	184	**2121**	2534	83.7%
+i	5116	1279	2918	7466	<= Diag
Producers	92.9%	46.4%	72.7%	Tot =>	9313
			Overall Accuracy =>		80.2%
	BARE	ShortSAV	DMA		
Composite Cover	*96.8%*	*77.4%*	*79.7%*		

MODEL \ TRUTH	Bare	Short SAV	DMA	i+	Users
Bare	**3980**	19	39	4038	98.6%
Short SAV	0	**458**	8	466	98.3%
DMA	0	15	**1969**	1984	99.2%
+i	3980	492	2016	6407	<= Diag
Producers	100.0%	93.1%	97.7%	Tot =>	6488
			Overall Accuracy =>		98.8%

MODEL \ TRUTH	Bare	Short SAV	DMA	i+	Users
Bare	**3980**	0	0	3980	100.0%
Short SAV	0	**387**	0	387	100.0%
DMA	0	0	**1865**	1865	100.0%
+i	3980	387	1865	6232	<= Diag
Producers	100.0%	100.0%	100.0%	Tot =>	6232
			Overall Accuracy =>		100.0%

Figure 2. Multiple discriminant analysis scheme for extracting pure end-member acoustic records from a catalog of 30-90 second hydroacoustic samples. Only those catalog records (1) classifying correctly and (2) exceeding a minimum probability for group membership pass onto the next Discriminant Analysis. The Fisher's Linear Discriminant Functions obtained from the 3rd Pass Discriminant Analysis were used to classify survey data into one of three end-member classes (BARE, ShortSAV, or DMA).

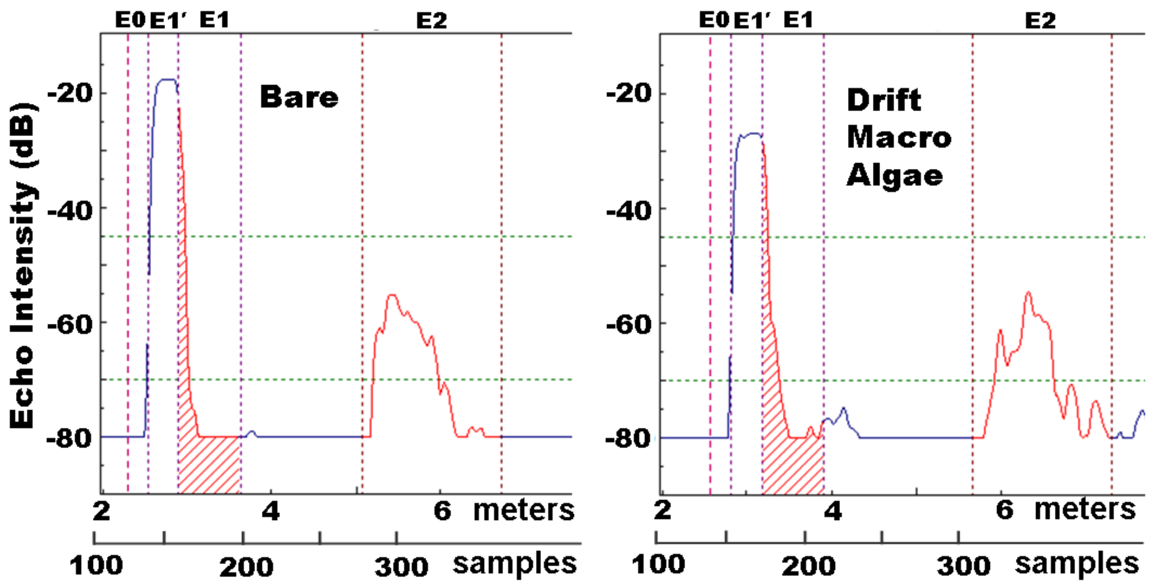


Figure 3. Representative waveforms acquired over bare substrate and drift macroalgae. The width of the E0, E1′, E1, and E2 Bottom Sampling Windows are shown in units of samples (bottom scale) and in units of meters (top scale).

Quality Assurance

Log-transformed values of E0, E1', E1, E2 and un-transformed values of FD were passed through a series of filters to identify and remove "irregular" hydroacoustic returns. The first filter checked the differential depth between successive pings against a specified maximum value, designed to remove waveforms that contacted the seabed at angles exceeding normal-incidence, typically caused by excessive vessel roll. The next filter removed records with depth-picks less than 1.3 m, the point at which the first and second echo returns are sufficiently separated for analysis. The next filter removed records with depth-picks exceeding the 99.5 percentile, usually the result of grossly misshapen waveforms. The remaining two filters protected against potentially excessive outliers by removing records for which any of the eight acoustic parameters fell beyond the 1 and 99 percentiles. Only those records for which all eight acoustic parameters passed all filters were passed onto the next stage of processing. Of the 534,000 pings recorded during the survey, approximately 20% were removed by the filters and the subsequent merging of the 38 and 418 kHz datasets.

Normalizing to Reference Depth

Depth normalization entails adjusting the width of the E1′ and E1 bottom sampling windows to maintain a consistent first echo division, as the echo predictably stretches and flattens with increasing depth. Although VBT (v2) provided a depth-normalization algorithm for E1 (but not for E1′), the depth-normalized E1 was found to vary consistently with depth. The residual depth contamination of E1 suggests other factors at work, as does the apparent contamination of E2, which should not require reference depth normalization provided an adequately wide sampling gate across the range of depths. The other factors at work likely include less-than-perfect time-varied gain compensation and depth-variant proportions of specular and backscatter returns.   To produce depth-invariant values of the acoustic energy parameters, log-transformed and filtered values of E0, E1’, E1, and E2 and un-transformed values of FD were empirically normalized to median survey depth. Depth-normalization models were constructed using 96 60-second BARE training samples, for which it could be assumed that depth was the primary factor affecting the shape of echo returns (and not varying SAV abundance). Linear and first and second order log functions were fit to plots of log(E) versus depth for each acoustic parameter (except the E0 of both frequencies and the 38 kHz E1 and FD, which did not require depth-normalization) (Figure 4). Correction factors were applied to each hydroacoustic record, calculated as the ratio of model-predicted acoustic energy at actual depth divided by the model-predicted acoustic energy at the median depth. The effectiveness of this method for treating depth-contamination is apparent as significant reduction in the slopes of the depth-normalized survey data (the complete survey dataset decimated to 20,000 records for plotting, before and after quality analysis and empirical depth normalization) (Figure 5).

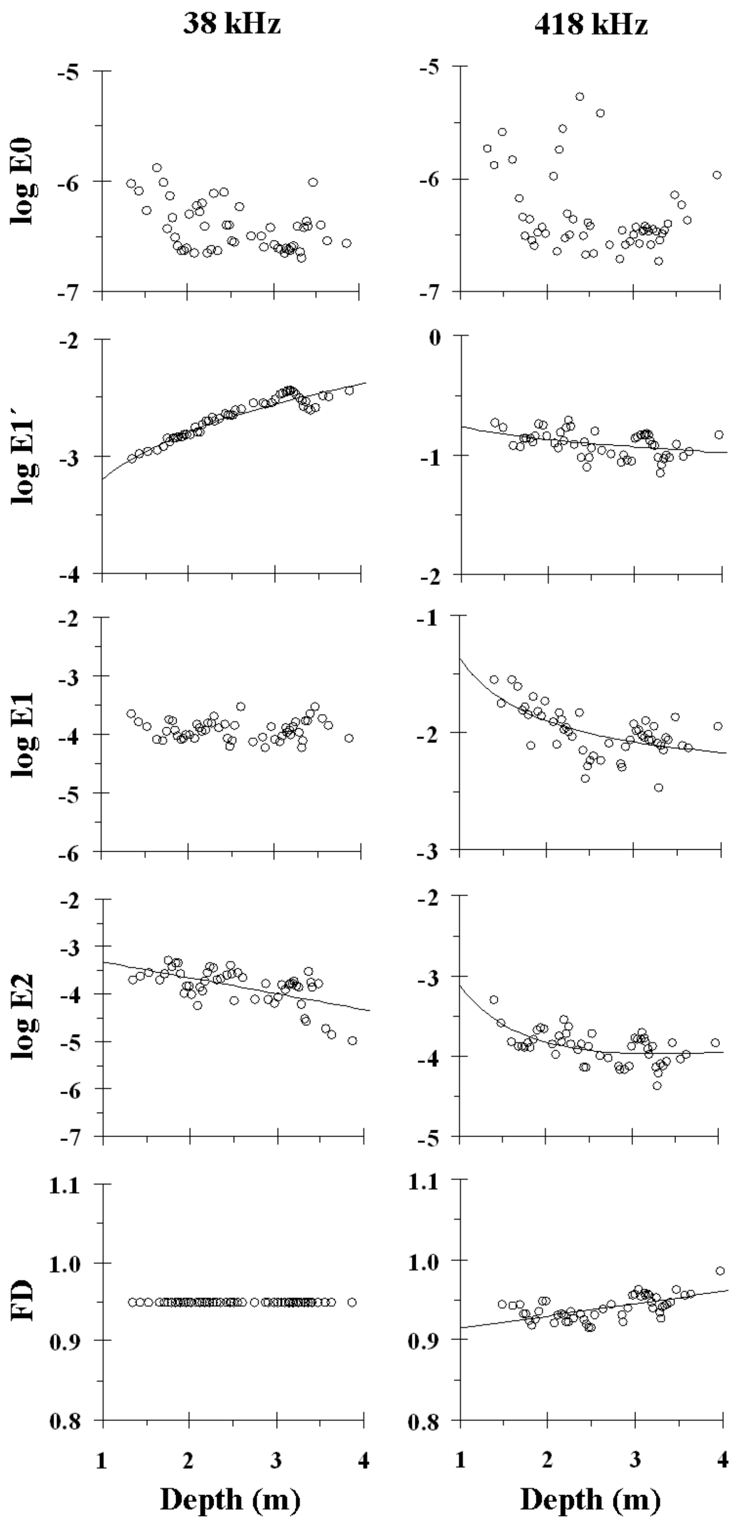


Figure 4. Empirical depth normalization using 96 BARE training samples. Depth trends of log-transformed echo returns (open circles) and fitted curves (solid lines) used for empirical depth-normalization of acoustic parameters. The 38 and 418 kHz E0's and the 38 kHz E1 and FD did not require empirical depth-normalization.

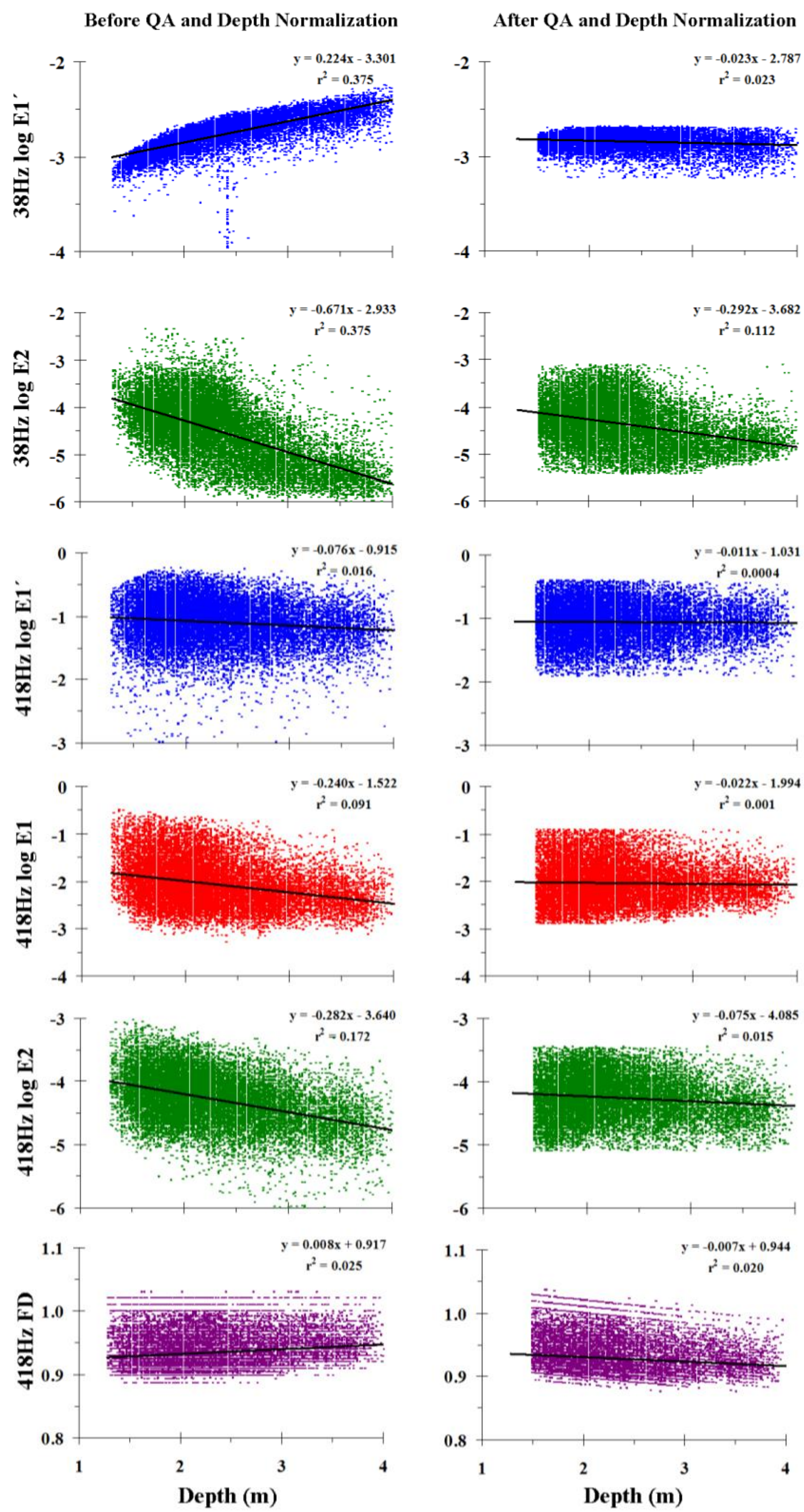


Figure 5. Complete 2010 survey dataset, decimated to 20k records, to demonstrate the effective treatment of depth contamination. Depth profiles of acoustic parameters, before (left) and after (right) quality analysis and empirical depth normalization (created from the BARE sub-set of training dataset).

Training Dataset Collection and Processing

A total of 217 training samples, all collected within the study area, were selected as potential candidates for submission to the training catalog. Each catalog sample consisted of a 30-90 second hydroacoustic file and a geo-referenced video file, acquired as the vessel drifted in idle. The training data were subjected to the same VBT post-processing, depth-normalization, and quality assurance as described previously for the survey data. Each video was reviewed post-survey and assigned a percent coverage of (1) BARE (bare substrate), (2) ShortSAV (miscellaneous vegetation, typically 5cm and up to ~10cm max), and (3) DMA (drift macroalgae, typically 5-20cm). ShortSAV was typically *Caluerpa prolifera* but also included *Halophila spp*. and miscellaneous taxa of sparse macroalgae generally less than 5 cm tall. DMA was a consortium of branched macroalgae, predominantly the rhodophyta *Gracilaria tikvahiae* and *Hypnea cervicornis*. The primary distinction between ShortSAV and DMA was based on the three-dimensional cover. If *G. tikvahiae* was present as sparse 5cm colonies it was categorized as ShortSAV, but if it was present as large stands of densely packed and unattached colonies standing 15cm high, it was categorized as DMA.

Classification Workflow

Ideally, the hydroacoustic records submitted to a supervised classification scheme should be pure end-member classes, i.e. either completely bare or contiguous SAV. The catalog should also include as many locations as possible so that all ranges of depth and sediment class are adequately represented, to prevent extraneous geophysical factors from influencing the classification process. Because of the logistical difficulties of acquiring pure end-member hydroacoustic samples, e.g. finding and double-anchoring over a small patch of contiguous SAV, a novel method was developed for extracting pure end-member records from samples acquired over heterogeneous benthos.

The 217 samples submitted to the training dataset were selected on the basis of high benthic homogeneity. Samples with <10% total SAV cover were designated as BARE. Samples with >50% short SAV cover and <10% drift macroalgae cover were designated as ShortSAV. Samples with >33% drift macroalgae cover and <10% short SAV cover were designated as DMA. After passing through quality assurance filters, the training dataset was subjected to two pre-classification 'cleaning' steps to remove (1) outlier records within individual training samples and (2) outlier training samples. First, the training data were submitted to a principle components analysis (PCA). The resulting principle components were partitioned into 16 groups using K-Means clustering. 116 records belonging to six disproportionately small K-Means clusters (<0.5% of total records) were removed from the training dataset. The training dataset was then submitted to an exploratory discriminant analysis (DA) using the three pre-defined classes (BARE, ShortSAV, DMA). 37 samples (totaling 1,668 records) with low classification accuracies were removed from the training dataset.

The remaining 180 training samples (9,313 records) were passed through a series of three discriminant analyses, using the 38 kHz E0, E1', E1, E2 and 418 kHz E0, E1', E1, E2, FD and depth as predictor variables. The 38 kHz FD was not used because it was nearly invariant (Figure 4), presumably due to a combination of the short and wide 38 kHz echo waveforms and the wide E1′ sampling window (i.e. there was insufficient 'tail' to compute the FD). Only those records that (1) correctly classed by the discriminant analysis and (2) exceeded a minimum probability of group membership were passed onto the next DA (Figure 2). This had the effect of refining the training dataset into the desired end-member classes. For example, the small target offered by *C. prolifera* resulted in frequent false negatives, i.e. misses, within the ShortSAV training dataset. It was important to remove these misses, so as to distinguish them from truly bare pings. Similarly, hydroacoustic records acquired over bare sediment would need to be removed from a catalog sample ground-validated as 50% drift macroalgae and classified as DMA.

Interpreting Discriminant Analysis Output

A discriminant function (DF) is similar in form to a multiple regression equation. The DF coefficients are computed to maximize discrimination between predefined groups. Similar to a principle component analysis, the DF's represent the lumped contribution of independent variables. When there are more than two groups, the number of DF's equals the smaller of (i) the number of groups minus 1, or (ii) the number of variables, so in this study there were two DF's. The first DF is the line through multivariate space that creates the greatest amount of between-group variance (i.e. discriminates between the most different groups), with each successive function contributing less than the preceding one.

Classifying Hydroacoustic Records

Discriminant analysis generates a set of Fisher's linear discriminant functions, derived from the linear combinations of predictor variables (E0, E1', E1, E2, FD, depth) that provide the greatest discrimination between the pre-defined groups (Figure 2). The Fisher's linear discriminant functions from the third-pass DA were used to classify survey records by multiplying each Fisher's coefficient by the value of the corresponding acoustic variable, summing the products, and adding the constant to get a score for each of the three groups (BARE, ShortSAV, and DMA). Each of the 400,000+ survey records passing QA were classified as the group with the largest discriminant score. The final layer of classification was to compute the percent cover of BARE, ShortSAV, and DMA (as the percentage of DA-assignments within a block of ten sequential acoustic records), yielding a total of 43,114 geo-located records of percent cover.

Partitioning by SJRWMD Segments and ICW

The 43,114 geo-located acoustic records were joined with a SJRWMD shapefile of Indian River Lagoon segments (IRL_Segments.shp) in ArcMap v 9.3. These records were further sub-divided by clipping to a SJRWMD shapefile of navigation channels (ICW.shp). The segment-average percent cover of ShortSAV and DMA were calculated as the simple average of acoustic records falling within a particular segment, either within or outside of navigation channels. The area surveyed within each segment was obtained by clipping the segment shapefile to the actual survey extent.

SAV Coverage Maps

Ordinary point kriging, a geostatistical method based on the spatial autocorrelation inherent in landscape patterns, was used to produce spatially continuous maps of ShortSAV and DMA percent cover. Each kriged contour feature was subsequently clipped to the perimeter of the area traversed within each survey tile, i.e. the boundaries of the contour maps do not extend beyond the area of acoustic sampling.

Accuracy Assessment

A total of 374 external accuracy assessment samples were collected in-line with the 2010 survey by intermittently slowing to idle speed, deploying a weighted video camera overboard, and continuing to record hydroacoustic data while simultaneously collecting video for a period of 30-60 seconds. The Trimble dGPS latitude and longitude and UTC time were burned onto the recorded video for post-survey synchronization with hydroacoustic data. The accuracy assessment videos were reviewed post-survey and assigned a visually-estimated percent coverage of (1) bare substrate, (2) short SAV, and (3) drift macroalgae. The ground-truth data were subjected to the same VBT post-processing, depth-normalization, and quality assurance as described previously for the survey data. Of the 374 samples collected, 359 remained for accuracy assessment following QA, totaling 18,000+ hydroacoustic records. Each hydroacoustic record was classified as either BARE, ShortSAV, or DMA using the same Fisher’s linear discriminant functions used to classify the survey data. The acoustically-predicted cover of BARE, ShortSAV and DMA was then calculated for each accuracy assessment sample as the simple average of the ~60 classified records per sample.

The accuracy assessment was performed directly on the hydroacoustic records, not on the kriged contour plots of percent cover, because (i) biomass was calculated directly from individual hydroacoustic records, and (ii) the heterogeneous nature of the benthos would introduce uncertainty if the area sampled was not within the acoustic footprint. A confusion matrix was constructed as a square array of numbers arranged in rows (discriminant analysis classification) and columns (ground-truth). An accuracy assessment could not easily be conducted on the individual percent cover of drift macroalgae and short SAV, since many ground-truthing samples were a mixture of both. The accuracy assessment was instead conducted on total SAV (ShortSAV plus DMA) grouped into three abundance categories; 0-33, 33-66, and 66-100% cover. The overall accuracy (Po) was calculated as the sum of the major diagonal, i.e. correct classifications, divided by the total number of ground-truth samples. Each diagonal element was divided by the column total to yield a producer's accuracy and by the row total to yield a user's accuracy. The producer's and user's accuracies provide different perspectives on classification accuracy. The producer's accuracy (omission/exclusion error) indicates how well the mapper classified a particular category, i.e. the percentage of times that substrate known to be sparsely covered was correctly interpreted sparse cover. The user's accuracy (commission/inclusion error) indicates how often map categories were classified correctly, i.e. the percentage of times that a sample classified as sparse cover was actually sparse and not abundant or contiguous.

The Tau coefficient is a measure of the improvement of classification accuracy over a random assignment of map units to map categories. The form of Tau based on equal *a priori* probability of group membership (T_e) was used for this study. In this case, the probability of random agreement simplifies to the reciprocal of the number of categories ($1/r$), and T_e is simply an adjustment of P_o by the number of map categories. As the number of categories increases, the probability of random agreement diminishes, and T_e approaches P_o. Values of T_e were calculated as follows:

Tau coefficient for equal probability of group membership = $T_e = (P_o – 1/ r) / (1 – 1/ r)$

RESULTS

Verifying Temporal and Spatial Consistency

Supervised classification requires temporal and spatial consistency of predictor variables over the course of acquiring catalog and survey data. Otherwise, classification accuracy would diminish as the relationship between acoustic parameters and SAV abundance shifted, due to instrument drift (temporal inconsistency) or intrusion of extraneous geophysical factors into the acoustic signature (spatial inconsistency). Temporal and spatial consistency was assessed using the 180 hydroacoustic samples constituting the training dataset. These samples were collected throughout Indian and Banana Rivers, from Mims in the north to Wabasso in the south (~120 km distant). 71 training samples were collected in 2007, 44 in 2008, and 65 in 2010. Temporal consistency was assessed from scatter plots of canonical variable scores of the first two (of two) discriminant functions generated from the first, second, and third-pass discriminant analyses (Figure 6). The center-points (mean class value) and boundaries (1 standard deviation) are essentially identical for the 2007, 2008 and 2010 training samples of all three classes (BARE, ShortSAV, DMA), clearly demonstrating the temporal consistency of the acoustic interpretation of bottom classes. Spatial consistency was similarly assessed from scatter plots of the canonical variable scores from the third pass discriminant analysis (Figure 7). The BARE sub-set of the training dataset, consisting of 94 60-second samples, was sorted by IRL Segments and the mean and standard deviation of canonical variable scores were computed for four regions of the Indian River (Mims to Wabasso North) and two regions of Banana River (Cape Canaveral South to Satellite Beach).

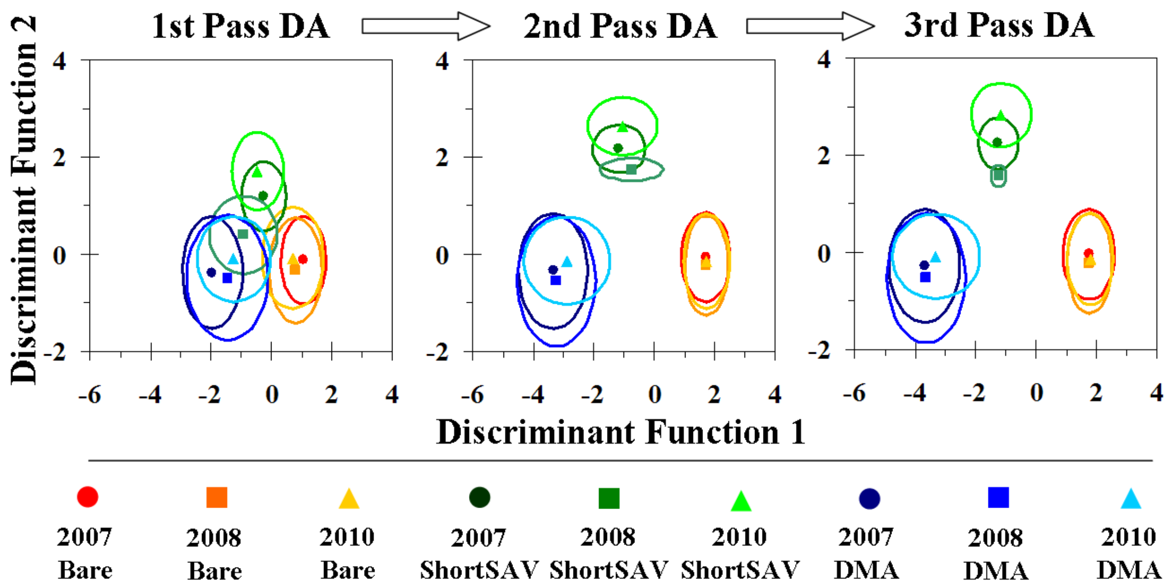


Figure 6. Temporal consistency of training dataset (60-sec samples; 94 BARE, 24 ShortSAV, 62 DMA). Scatter plots of canonical variable scores of the first two discriminant functions from the 1st-3rd DA's. Centerpoints denote group means, ellipses are dispersion (1 standard deviation) about x and y, calculated individually for samples acquired in 2007 (n=71), 2008 (n=44), and 2010 (n=65). The refinement of the training dataset with successive DA passes is also evident as greater separation between groups.

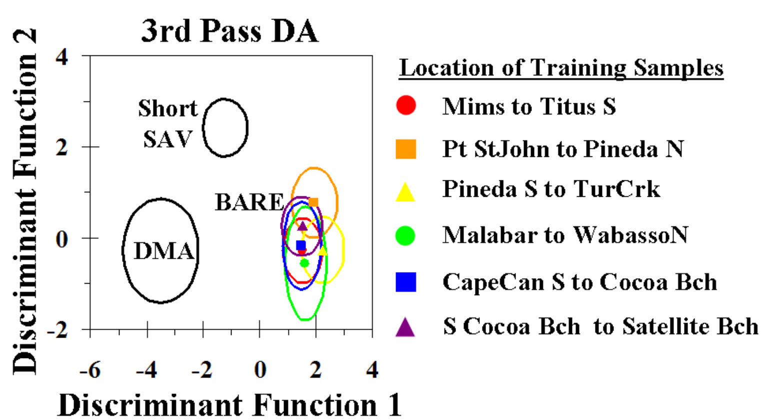


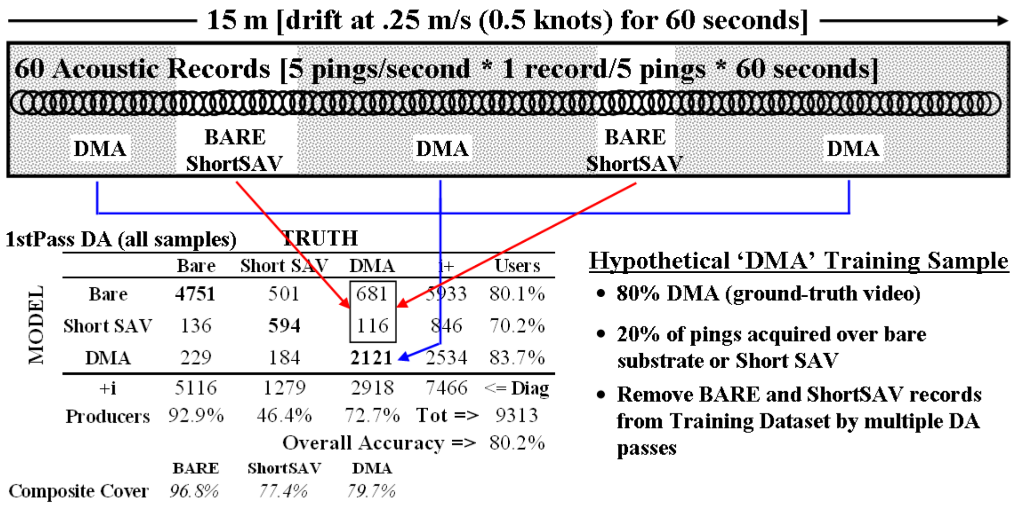
Figure 7. Spatial consistency of training dataset (60-sec samples; 94 BARE, 24 ShortSAV, 62 DMA). Scatter plots of canonical variable scores of the first two discriminant functions of the 3rdPass DA. Centerpoints denote group means, ellipses are dispersion (1 standard deviation) about x and y. BARE variable scores calculated for six regions within the Indian and Banana Rivers.

The acoustic interpretation of bare substrate was very similar for all six regions of Indian and Banana Rivers. Comparing Figures 6 and 7, while both temporal and spatial consistency were high, temporal consistency was slightly better than the spatial consistency, which is not surprising given the large variations in bottom types along the length of the rivers.

Interpreting the Classification of the Training Dataset

Recall that while training samples were selected on the basis of high benthic heterogeneity, issues of practicality required some compromise. Samples with <10% total SAV cover were designated as BARE. Samples with >50% short SAV cover and <10% drift macroalgae cover were designated as ShortSAV. Samples with >33% drift macroalgae cover and <10% short SAV cover were designated as DMA. The composite ground-validated cover of each category was computed as the average percent cover of the various training samples (post-survey review of spatially-coincident video), weighted by the number of acoustic records per sample. The 94 BARE training samples submitted to the 1stPass DA averaged 96.8% bare substrate, the 24 ShortSAV training samples averaged 77.4% short SAV, and the 62 DMA training samples averaged 79.7% drift macroalgae (Figure 2). Therefore, the Producer's accuracies of the 1stPassDA should not equal 100%, but should instead (ideally) equal the ground-validated values. The proper interpretation of the Producer's accuracy is explained below, using the DMA group as an example.

It was known *a priori* that the 2918 acoustic records submitted to the 1stPass DA as DMA were not all acquired directly over drift macroalgae, as the composite ground-validated cover was only 79.7% (i.e. the DMA group contained 20.3% 'impurities'). The purpose of the multi-pass DA scheme was to remove these 'impurities', leaving behind only pure end-member records in the training datasets. This was made possible by the combination of narrow beamwidths and shallow depths, which produced acoustic footprints so small (~1 foot diameter) that it could be reasonably assumed that each ping insonified a 'pure' bottom class, e.g. all bare substrate or all drift macroalgae (Figure 8). Thus, only 2325 (2918*0.797) of the 2918 DMA records would have actually insonified drift macroalgae and the remainder would have insonified bare substrate or short SAV. Therefore, the 1stPassDA Producer's accuracy of 72.7% was even more accurate than it might at first seem. Ground-validation found that 79.7% of the cover was drift-macroalgae and the acoustic classification predicted 72.7%. The internal accuracy for detecting drift macroalgae in a heterogeneous benthos is therefore 91% (=72.7/79.7).



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	BARE	ShortSAV	DMA		
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Figure 8. Hypothetical drift macroalgae training sample. 60 seconds of acoustics and spatially-coincident video collected with the survey vessel drifting approximately 15m, translating into 60 acoustic records (~0.31m diameter footprint, with considerable overlap). To achieve pure end-member classification, the acoustic records acquired over bare substrate and short SAV were removed by multiple passes through discriminant analysis, retaining only those records that classified correctly and exceeded a minimum probability of group membership.

Assessing the Training Dataset (Internal Accuracy Assessment)

The effect of successive discriminant analyses (DA) can be seen as an increasing separation of data clouds in the scatter plots of canonical variable scores (Figure 6), as a result of refining the variably heterogeneous training samples into pure end-member elements. Continuing from the previous section, refinement was predominantly in the form of rejecting pings acquired over the minor constituents within a given training sample, e.g. rejecting the pings acquired over bare substrate within the DMA category. In this multi-pass DA classification scheme, it was assumed that the acoustic records within the DMA training dataset that ‘mis-classified’ as BARE and ShortSAV actually belonged to pings acquired over bare substrate and short SAV (and were thus not mis-classes after all, but rather correct classifications of a heterogeneous benthos). These records were removed from the training dataset by two additional DA passes (Figure 2). Achieving pure end-member categories required only a modest reduction in the total number of acoustic records (from 9313 to 6232, or 33%), a strong indicator of a robust classification scheme.

The duel-frequency acoustic dataset significantly improved discrimination between the three groups, as can be seen in the confusion matrices of the 1stPass DA of the training dataset at duel and single frequencies (Table 1). The smaller-wavelength 418 kHz signal was more capable of detecting the low canopy and relatively sparse areal cover of ShortSAV, but there was a clear synergy when combined with the 38 kHz signal. The 38 kHz signal was not as effective at discriminating bare substrate because it frequently confused bare silt/mud as drift macroalgae, due to signal reverberation into the loose sediment (which appeared similar to backscatter from the drift macroalgae canopy), but the combination of the 38 and 418 kHz signals improved the overall classification.

Table 1. Confusion matrices for 1st-Pass discriminant analysis of training dataset utilizing (a) 38 and 418 kHz data, (b) 418 kHz only, and (c) 38 kHz only.

a. 38 & 41kHz & Depth

		TRUTH		
		BARE	**ShortSAV**	**DMA**
MODEL	**BARE**	**4751**	501	681
MODEL	**ShortSAV**	136	**594**	116
MODEL	**DMA**	229	184	**2121**
	Producer's	92.9%	46.4%	72.7%
	Overall Accuracy (P_o)			80.2%
	Adjusted to Equal Sample Size			70.7%

b. 41kHz E0 E1′ E1 E2 FD & Depth

		TRUTH		
		BARE	**ShortSAV**	**DMA**
MODEL	**BARE**	**4773**	597	702
MODEL	**ShortSAV**	91	**280**	141
MODEL	**DMA**	252	402	**2075**
	Producer's	93.3%	21.9%	71.1%
	Overall Accuracy (P_o)			76.5%
	Adjusted to Equal Sample Size			62.1%

c. 38kHz E0 E1′ E1 E2 & Depth

		TRUTH		
		BARE	**ShortSAV**	**DMA**
MODEL	**BARE**	**4111**	1002	1250
MODEL	**ShortSAV**	45	**21**	57
MODEL	**DMA**	960	256	**1611**
	Producer's	80.4%	1.6%	55.2%
	Overall Accuracy (P_o)			61.7%
	Adjusted to Equal Sample Size			45.7%

The multi-pass DA classification was further checked for internal consistency by classifying the unrefined training dataset (the same data that was submitted to the 1stPass DA), using the Fisher's linear discriminant functions from the 3rdPass DA (Figure 9). Predictions of bare substrate were in very close agreement with the ground-truthed values; the 94 BARE training samples classified as 92.2% bare substrate, compared to a visually-estimated bare cover of 96.8%. The DA model consistently under-predicted short SAV abundance, particularly at the highest level of SAV cover. The DA-predicted versus visually-estimated short SAV cover at the two levels of cover were 47.6% vs. 63.7% (21% under-prediction) and 43.7% vs. 94.8% (54% under-prediction). The DA model performed well across the full range of drift macroalgae cover, under-predicting only slightly at the highest levels of cover. The DA-predicted versus visually-estimated drift macroalgae cover was 45.6% vs. 40.5% (13% over-prediction), 72.4% vs 69.0% (5% over-prediction), and 80.8% vs. 95.2% (15.1% under-prediction).

Table 2. Fisher's Linear Discriminant Functions from 3rdPass DA, used to classify hydroacoustic survey records.

Variable	BARE	ShortSAV	DMA
Depth 418kHz	19.8	14.7	13.2
E0 38kHz	-77.2	-77.0	-74.9
E1' 38kHz	-271.0	-271.4	-271.5
E1 38kHz	-38.0	-38.7	-40.9
E2 38kHz	38.5	36.1	40.7
E0 418kHz	-64.6	-62.8	-65.4
E1' 418kHz	48.6	45.9	40.4
E1 418kHz	-94.8	-86.1	-78.6
E2 418kHz	-18.3	-16.4	-23.1
FD 418kHz	2517.0	2592.7	2593.6
Constant	-2158.0	-2200.1	-2212.1

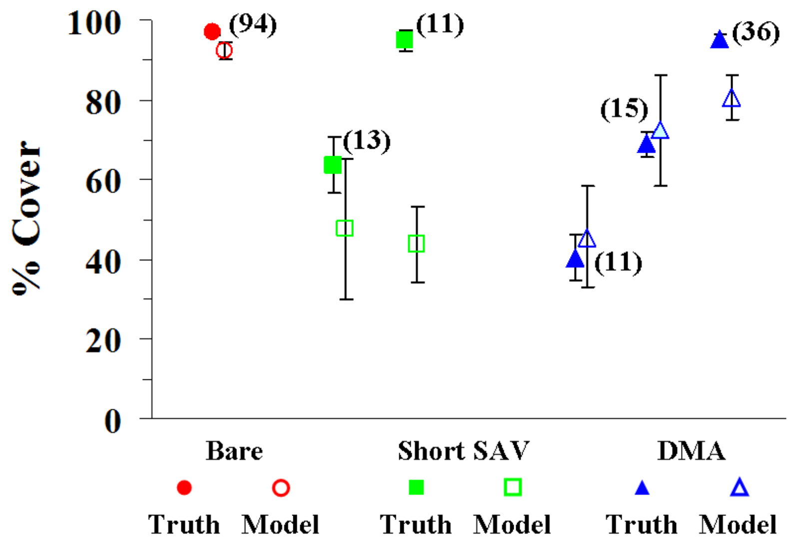

Figure 9. Internal accuracy assessment of multi-pass DA classification. Comparison of ground-truthed (closed symbols) and acoustically-predicted (open symbols) for classification of the un-refined training dataset. Short SAV was binned into two levels of abundance. DMA was binned into three levels. Error bars are 95% CI. Numbers in parenthesis denote the number of individual 60-second training samples.

Classifying Survey Data

The Fisher's linear discriminant functions (Table 2) resulting from the third-pass DA were used to classify each of the 400,000+ survey records as either bare substrate (BARE), short SAV (ShortSAV), or drift macroalgae (DMA). This was done by multiplying each coefficient by the value of the corresponding acoustic parameter, summing the products, and adding the constant to get a score for each of the three categories. Survey records were assigned to the category with the largest discriminant function score. The final layer of classification was created by tallying the assignments for a range of ten consecutive records and computing the proportion of BARE, ShortSAV, and DMA assignments for each group of ten records.

SAV Coverage Maps

Ordinary point kriging, a geostatistical method based on the spatial autocorrelation inherent in landscape patterns, was used to produce spatially continuous maps of ShortSAV and DMA percent cover. Each kriged contour feature was subsequently clipped to the perimeter of the area traversed within each survey tile, i.e. the boundaries of the contour maps do not extend beyond the area of acoustic sampling (Appendix A2-A9).

External Accuracy Assessment

A confusion matrix could not easily be produced for the individual categories of drift macroalgae and short SAV, since many ground-truthing samples were a mixture of both. Instead, the percent cover of drift macroalgae and short SAV were summed and grouped into three abundance categories; 0-33, 33-66, and 66-100% cover. The important distinction is that the confusion matrix was based on the classified hydroacoustic records, not on the kriged contour plots of percent cover. Performing accuracy assessment directly on the classified hydroacoustic records was deemed most appropriate, since biomass was calculated directly from individual hydroacoustic records. The overall predictive accuracy for the 359 external accuracy assessment samples was 81.6% for the three coverage categories of total SAV cover. The Tau coefficient for equal probability of group membership (T_e) was 0.724 ± 0.061 (α=0.05), i.e. the rate of misclassifications was 72.4% less than would be expected from random assignment of hydroacoustic records to SAV cover (Table 3).

To assess the accuracy of the individual predictions of drift macroalgae, the relationship between acoustically-predicted percent cover and the visually-estimated percent cover was also examined by simple linear regression. Figure 10 displays the acoustically-predicted percent cover drift macroalgae versus the visually-estimated cover for each of the 359 external accuracy assessment samples. To better illustrate the overall trends, the average predicted values were also calculated for ground-validated values in the range of 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100% cover.

Table 3. Confusion matrix of 359 external accuracy assessment samples comparing acoustically-predicted versus visually-estimated for three abundance ranges of Total SAV (ShortSAV plus DMA).

		TRUTH (% Cover)				
	Total SAV	**0 to 33**	**33 to 66**	**66 to 100**	**i+**	**Users**
MODEL (% Cover)	**0 to 33**	**229**	17	4	250	91.6%
	33 to 66	17	**23**	22	62	37.1%
	66 to 100	1	5	**41**	47	87.2%
	+i	247	45	67	293	**<= Diag**
	Producers	92.7%	51.1%	61.2%	**n =>**	359
				Overall Accuracy (P_o)		81.6%
				Tau (T_e) = 0.724 ± 0.061		

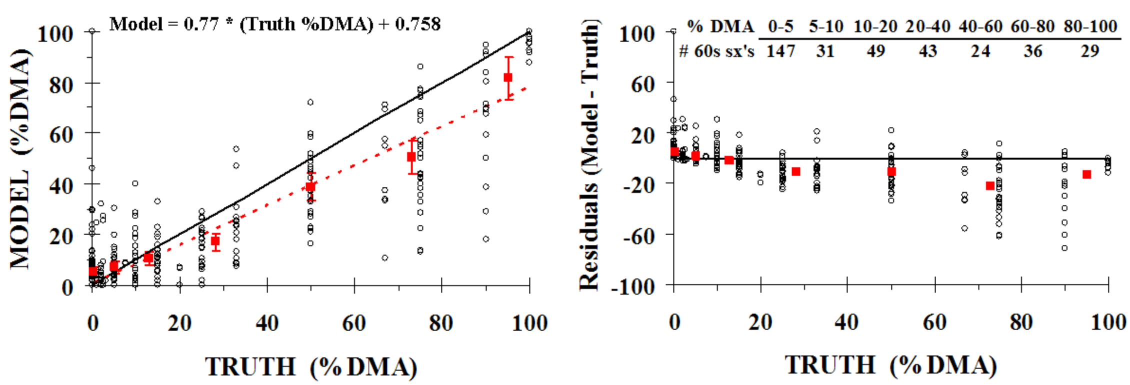

Figure 10. External accuracy assessment of predictive cover models. Acoustically-predicted values (right) and model residuals (left) of drift macroalgae for the 359 external accuracy assessment samples. Displayed as individual ground-truth samples (open circle) and as the average of samples falling within bins of ground-truthed cover (solid triangle). Linear regression (---) was performed on individual samples. Error bars are 95% CI.

Accuracy of Drift Macroalgae Predictions

As seen previously in the internal accuracy assessment of training data, acoustic classification of survey data performed well across the full range of drift macroalgae cover, as judged by both the scatter plot of predicted versus ground-truthed cover and the model residuals (predicted minus ground-truthed percent cover). Cover was slightly under-predicted as ground-validated cover increased beyond 20% (as seen in the 2008 survey). For the 29 accuracy assessment samples in the 80-100% bin (average = 95.2%), 81.3% of the pings were acoustically classified as DMA (Figure 10).

Drift Macroalgae Biomass

The average percent cover of ShortSAV and DMA was calculated individually for the SJRWMD segments shown in Appendix A1, using the ten-record averages of classified hydroacoustic records (Table 4, Figure 11). The lagoon-wide percent cover of ShortSAV and DMA were found to be 6.5% and 17.9%, respectively (compared to 24.1% and 11.2% in 2008).

Table 4. Drift macroalgae biomass and proportions (0-1) of short SAV (~5-10cm<) and drift macroalgae cover, partitioned by SJRWMD segments and by proximity to navigation channels.

Survey Area		Inside Navigation Channel						Outside Navigation Channel						DMA wet wt metric tons
			Mean Depth	Acoustic Cover			Survey Area		Mean Depth	Acoustic Cover			Survey Area	
Name	Segment	n	(m)	Short SAV	Drift MA	Total SAV	(km^2)	n	(m)	Short SAV	Drift MA	Total SAV	(km^2)	
Mims	IR2	4	2.40	0.000	0.000	0.000	0.36	3124	1.72	0.033	0.326	0.359	33.60	21907
TitusvillA North	IR3	11	2.88	0.018	0.073	0.091	0.28	696	1.72	0.067	0.184	0.251	7.31	2727
TitusvillB North	IR4	46	3.61	0.017	0.011	0.028	0.36	741	1.99	0.059	0.143	0.202	5.12	1474
Titusville South	IR5	64	3.10	0.014	0.056	0.070	0.98	5256	2.16	0.014	0.280	0.293	46.33	26041
Port St. John	IR6	200	2.84	0.029	0.078	0.108	1.40	6886	2.08	0.060	0.119	0.179	31.97	7847
Cocoa	IR7	73	3.59	0.022	0.015	0.037	0.37	1217	2.45	0.124	0.146	0.270	5.85	1715
Rocklege	IR8	106	3.53	0.018	0.022	0.040	0.80	1820	2.77	0.069	0.081	0.150	10.03	1661
Pineda North	IR9	105	3.85	0.003	0.019	0.022	0.76	1440	2.92	0.047	0.071	0.119	9.56	1395
Pineda South	IR10	107	3.77	0.007	0.011	0.019	0.69	2900	3.04	0.033	0.099	0.133	16.98	3389
Eau Gallie	IR11	16	3.60	0.000	0.038	0.038	0.31	1345	2.58	0.102	0.252	0.354	11.80	5958
Crane Creek Seg	IR12A	20	3.27	0.045	0.080	0.125	0.30	883	2.32	0.111	0.182	0.293	6.55	2427
Turkey Creek	IR12B	89	3.15	0.029	0.106	0.135	0.38	1674	2.35	0.065	0.180	0.245	8.90	3285
Malabar	IR13A	58	2.79	0.024	0.110	0.134	0.40	2680	2.10	0.041	0.235	0.276	11.76	5622
Grant	IR13B	117	3.48	0.018	0.049	0.067	0.57	822	1.87	0.078	0.178	0.256	4.91	1802
Sebastian Br C	IR14BRE	95	2.95	0.079	0.107	0.186	0.65	1595	1.75	0.088	0.150	0.238	9.51	2994
Sebastian IR C	IR14IND	17	2.10	0.218	0.082	0.300	0.55	1679	1.80	0.068	0.190	0.257	11.68	4519
Wabasso North	IR15													
Cape Canaveral S	BR2	55	2.89	0.036	0.267	0.304	0.43	705	2.01	0.153	0.093	0.246	4.25	1016
Port Canaveral	BR3	22	2.79	0.055	0.027	0.082	0.12	1607	1.93	0.119	0.083	0.202	11.90	1990
Cocoa Beach	BR4							250	1.81	0.022	0.001	0.023	3.68	6
S. Cocoa Beach	BR5							4183	2.30	0.139	0.070	0.209	26.54	3695
Satellite Beach	BR7							422	2.24	0.201	0.102	0.303	3.38	692
	Total =>						9.7						281.6	102162
Weighted Lagoon Average =>			3.16	0.034	0.063	0.098			2.18	0.065	0.179	0.245		

The biomass of drift macroalgae within each SJRWMD segment was calculated as the product of the average percent cover of DMA, the area surveyed within a segment, and the wet weight of drift macroalgae (2000 metric tons per km^2, as reported in the 2004 pilot study). At the time of the survey (May 4 – July 1, 2010) the drift macroalgae biomass was found to be 102,162 metric tons (wet weight) within the 281.6 km^2 study area (compared to 69,859 metric tons in 2008). Drift macroalgae cover was patchier within Indian River, with several large patches that had canopy heights in excess of 15 cm. Cover within Banana River was more sparse, short and equitably distributed in comparison. The effect of depth on drift macroalgae zonation varied regionally. In the northern Mims and Titusville South segments, the largest drift macroalgae accumulations were near the center of the river (Appendix A2, A4), whereas the Eau Gallie to Malabar accumulations were mostly on the eastern bank, between the spoil islands west of the ICW, and near causeways (Appendix A6, A8). These differences were reflected in the depth profiles of drift macroalgae. In the Mims and Titusville South segments, the depth profile of drift macroalgae was only marginally shallower than the depth profile of the survey area, whereas in the Eau Gallie to Malabar segments, the depth profile of drift macroalgae was considerably shallower than the depth profile of the survey area (Figure 12). This can be seen in the side-by-side track-plots of DMA and 418 kHz depth for the Eau Gallie and Crane Creek segments, where the DMA is almost exclusively sited near the west bank, the scalloped margins of the east bank, and near causeways.

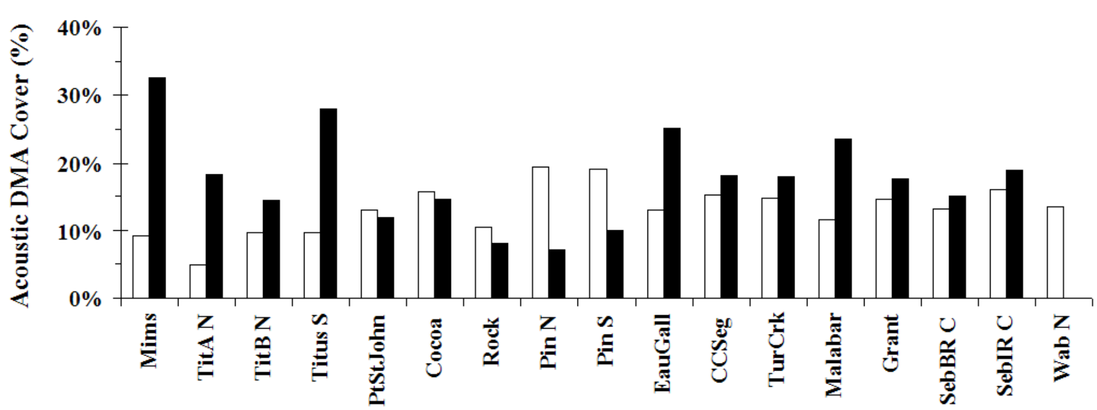

Figure 11. Acoustically-predicted drift macroalgae cover by segment. (white) 2008 survey. (black) 2010 survey.

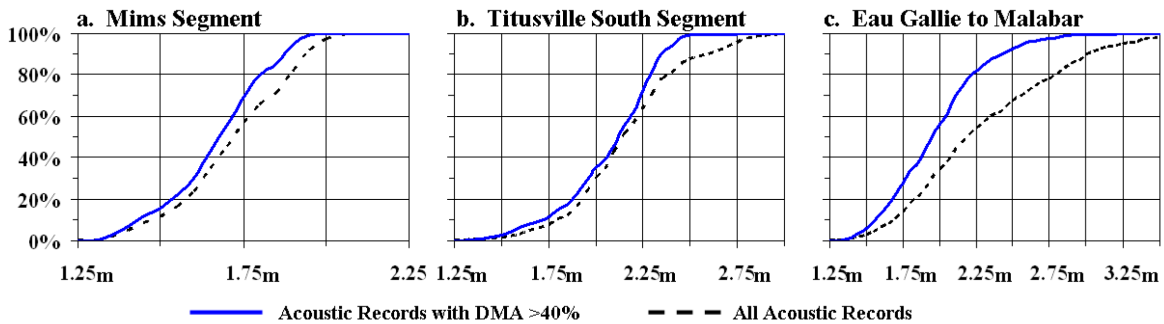

Figure 12. Depth profile of acoustically-predicted drift macroalgae in the (a) Mims and (b) Titusville South segments of Indian River. (solid blue) Cumulative frequency of depth for acoustic survey records with drift macroalgae cover greater than or equal to 40% (average of 10-record blocks). (dashed line) Cumulative frequency of depth for all acoustic survey records.

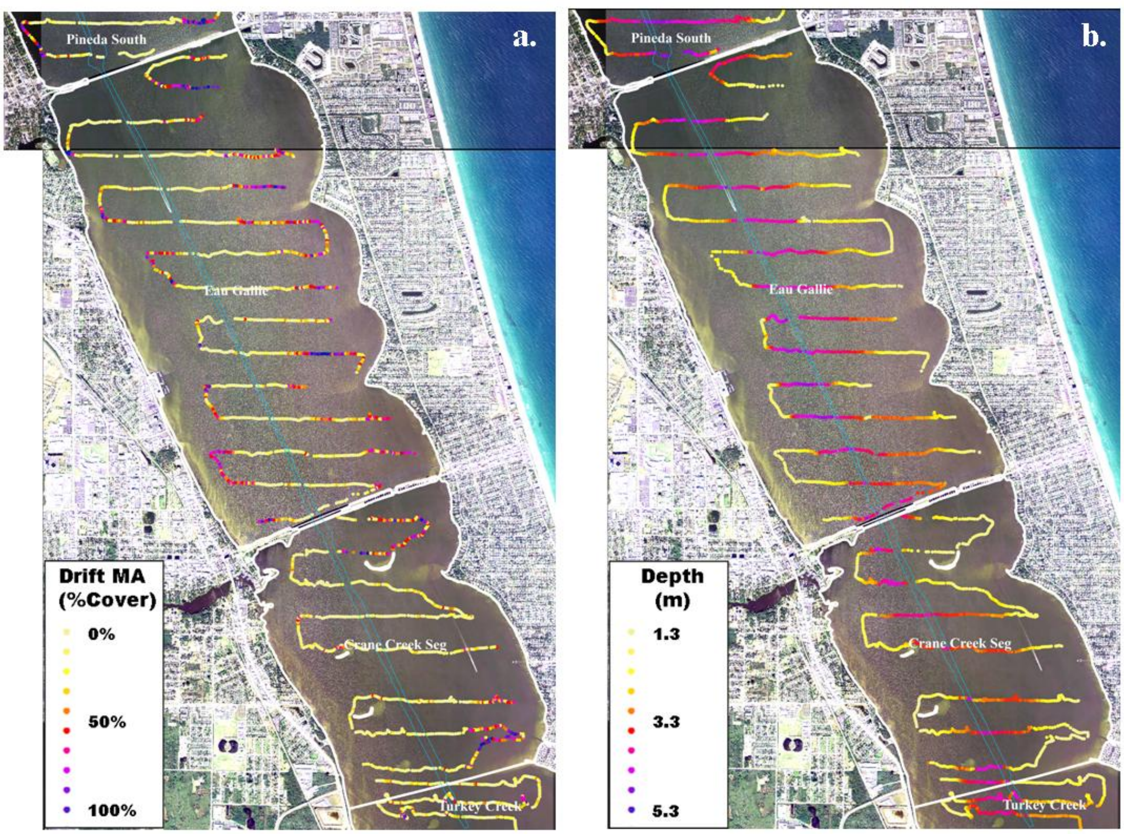

Figure 13. Track-plot of the (a) acoustically-derived percent cover of drift macroalgae and (b) 418 kHz depth for Eau Gallie and Crane Creek segments of Indian River. In the lower segments (Pineda South to Sebastian), the drift macroalgae tended to occupy the shallower depths, particularly near the scalloped margins of the east bank and spoil islands of the west bank, and near causeways.

Time Series

To better understand the dynamics of drift macroalgae propagation and transport, a portion of Indian River (Pineda South, Eau Gallie, and Crane Creek segments) was surveyed as a time series (TS). These segments were surveyed on three separate occasions; just prior to commencing the lagoon-wide survey (TS1, May 4-7), midway through the survey (TS2, May 29 - June 4), and at the end of the survey (TS3, June 28 - July 1). The elapsed time between surveys was 26.5 days (TS1-2) and 29 days (TS2-3). Track-plots of acoustically-predicted drift macroalgae and short SAV are displayed in Figure 14. The segment-by-segment proportions of acoustically-predicted drift macroalgae cover are listed in Table 5 and plotted in Figure 15. The drift macroalgae cover was computed as the percentage of acoustic records that classified as DMA in a 10-record block (e.g. if five classified as BARE, three as ShortSAV, and two as DMA, the ten-record block would be classified as 20% DMA).

Track-plots of acoustically-predicted drift macroalgae show that the boundaries and percent cover of individual patches changed very little between TS1 and TS2 (Figure 14a-b). By the time of TS3 the predicted drift macroalgae cover had decreased significantly, but could be observed to occupy the same general locations as seen in TS1-2. Simple averaging of acoustic records revealed that DMA cover was steady at 15-16% for TS1&2, followed by a drop to 6.3% at TS3 (Table 5, Figure 15a-c). The three individual segments all underwent a similar decline in DMA cover, although in absolute numbers the starting DMA cover of Crane Creek and Eau Gallie was roughly twice that of Pineda South. The frequency distributions of acoustically-predicted cover (i.e. 11 bins spanning 0-100% cover) revealed a near-complete loss of high-cover records (DMA > 50%) at TS3 (Figure 15c), i.e. the decline in acoustically-predicted DMA cover at TS3 was disproportionately driven by the decline of high-cover records. The acoustic predictions of (i) consistent patch boundaries and (ii) decreasing number of high-cover records suggest the observed decline in DMA cover was due to a breakdown of dense drift macroalgae patches, not due to large-scale movement of the patches themselves. This idea is reinforced by the track-plots of ShortSAV (Figure 14). In several locations where DMA had disappeared or appreciably declined during TS3, ShortSAV cover increased in the same location at the time of TS3. For example, the area on the east bank just south of the Melbourne causeway changed from 45.4% DMA and 14.6% ShortSAV in TS1 to 12.3% DMA and 46.8% ShortSAV in TS3 (see inset, Figure 14c&f). Recalling that ShortSAV was effectively a catch-all class of short and sparse SAV, it is presumed that thick mats of 10cm+ drift macroalgae classified as DMA in TS1-2, but classified as ShortSAV in TS3, after the mats had reduced in height and areal cover, suggesting the drift macroalgae patches broke-down *in situ*. The idea that the canopies of DMA patches thinned between TS2 and TS3 is reinforced by trackplots of the 38 kHz depth-pick minus the 418 kHz depth-pick, for the area in Crane Creek just south of the Melbourne causeway (Figure 16, area indicated in Figure 14). The 418 kHz signal tends to bounce off the top of tall and densely-packed DMA patches, whereas the 38 kHz signal tends to penetrate any thickness or density of DMA to provide a true measure of bottom depth. While not a reliable stand-alone indicator of DMA, the general trend of delta(38-418kHz depth) supports the idea of "thinning" DMA patches. As the DMA canopy decreased in height and density between TS2 and TS3, the acoustic predictions shifted from DMA to Short SAV and the delta(38-418kHz depth) simultaneously indicated a decrease in canopy height (Figure 16). This trend of decreasing canopy height can be clearly seen in the frequency distributions of records from this area that classified as either ShortSAV or BARE (Figure 17). It could be speculated in this particular case that a significant portion of the DMA that later washed ashore came from relatively stationary patches. At some critical canopy height, continued DMA production is exported by wind-shear. As conditions driving the bloom subside, DMA patches reduce in both height and density, but generally do not relocate within the lagoon.

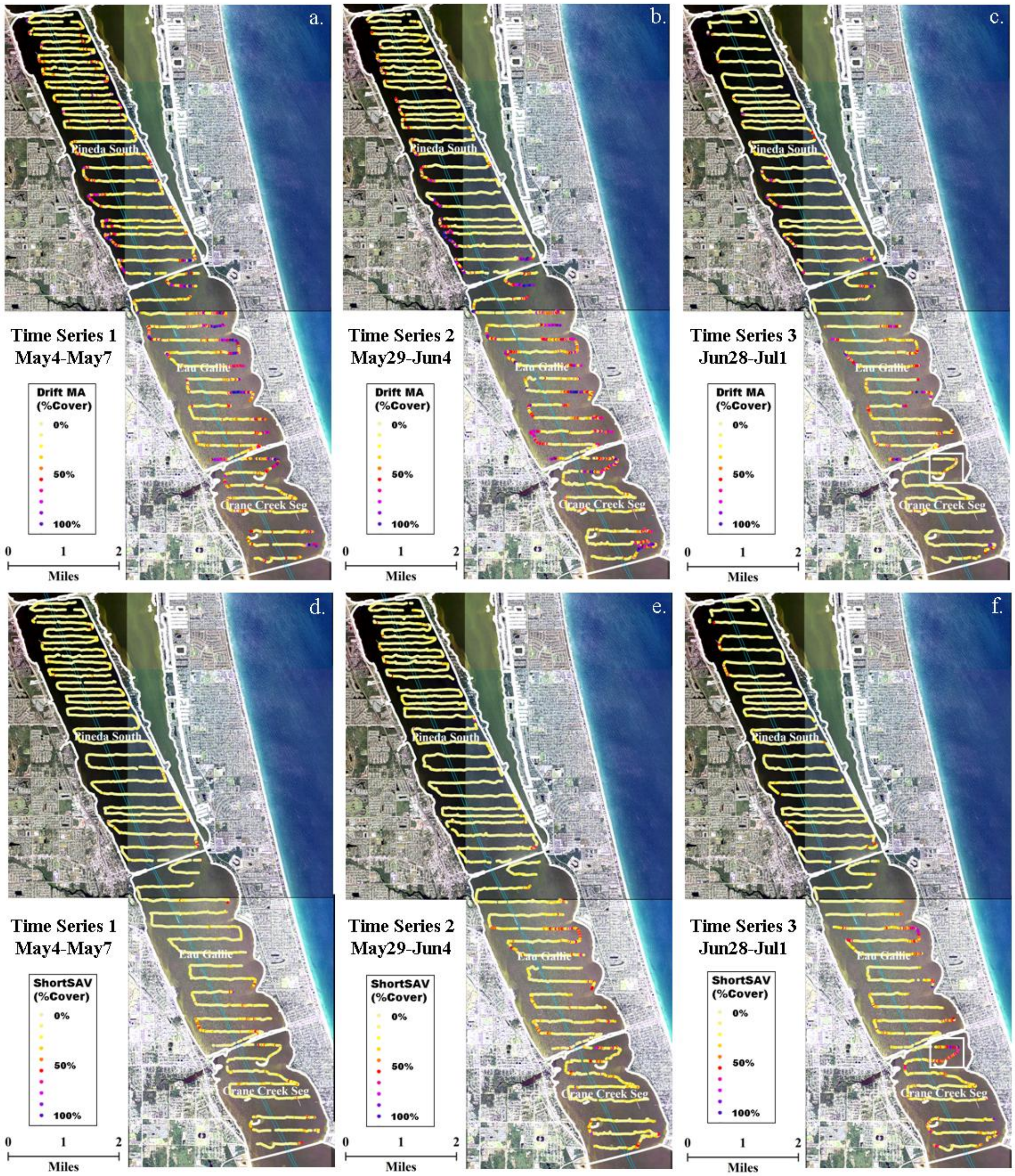

Figure 14. Time series study (top DMA, bottom ShortSAV). Track-plot of acoustically-derived percent cover of drift macroalgae for the same stretch of Indian River (Pineda South, Eau Gallie, and Crane Creek segments), conducted; just prior to the start of the survey (left), midway through the survey (middle), and at the conclusion of the survey (right). Data within the boxes just south of the Melbourne causeway are addressed in subsequent figures.

Table 5. 2010 time series study. Frequency distributions of acoustic classifications for three Indian River segments (Pineda South, Eau Gallie, and Crane Creek segments) surveyed in a time series. The same tracklines were followed three times; just prior to the start of the survey (TS1), midway through the survey (TS2), and at the conclusion of the survey (TS3). For example, 1.06% of 10-record blocks acquired within Crane Creek during TS1 had all ten records classify as DMA. The contribution of each level of DMA cover to the overall decline of DMA cover between TS2 and TS3 is shown under the heading 'TS2-3 (del% DMA)'. For example, the decline in 10-record blocks classifying as 100% DMA accounted for 18.73% of the 13.3% decline of acoustically-predicted DMA cover between TS2 and TS3 in the Crane Creek segment.

	TS1 Frequency			TS2 Frequency			TS3 Frequency			TS2-3 (del %DMA)		
%DMA	PS	EG	CC	PS	EG	CC	PS	EG	CC	PS	EG	CC
0	47.03	33.16	36.25	65.01	35.03	41.49	81.12	64.35	73.32			
10	24.05	19.55	23.87	17.43	16.11	21.63	8.97	12.06	14.84	16.66	2.80	5.13
20	13.18	13.03	13.90	5.89	9.86	11.35	3.99	6.88	6.13	7.47	4.12	7.87
30	6.02	8.76	8.31	2.93	8.24	6.97	2.18	5.41	2.57	4.41	5.87	9.97
40	2.99	6.95	5.89	1.76	7.21	4.49	1.11	3.79	1.85	5.14	9.47	7.96
50	2.92	4.63	4.38	1.63	7.21	3.90	0.90	3.25	0.43	7.14	13.71	13.10
60	1.35	3.91	3.17	1.23	5.08	2.96	0.41	1.08	0.57	9.68	16.59	10.79
70	1.03	3.26	1.36	0.83	4.05	1.89	0.53	1.62	0.00	4.09	11.74	9.99
80	0.82	2.24	1.21	1.23	2.35	1.42	0.33	0.77	0.29	14.21	8.75	6.84
90	0.29	2.10	0.60	0.67	2.43	1.42	0.41	0.54	0.00	4.50	11.75	9.63
100	0.32	2.39	1.06	1.40	2.43	2.48	0.04	0.23	0.00	26.71	15.20	18.73
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMA Cover	12.3%	23.0%	17.6%	9.6%	24.9%	18.3%	4.5%	10.5%	5.0%	-5.1%	-14.5%	-13.3%
	Avg DMA = 16.1%			Avg DMA = 15.0%			Avg DMA = 6.3%					

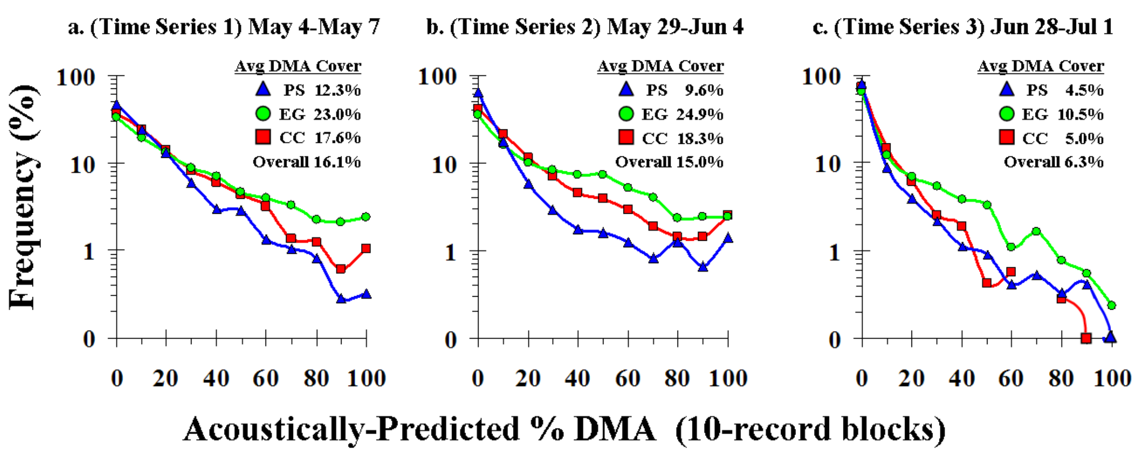

Figure 15. 2010 time series study. Plots of frequency distributions from Table 5. Note the near-total loss of high-cover 10-record blocks at the time of the third time series.

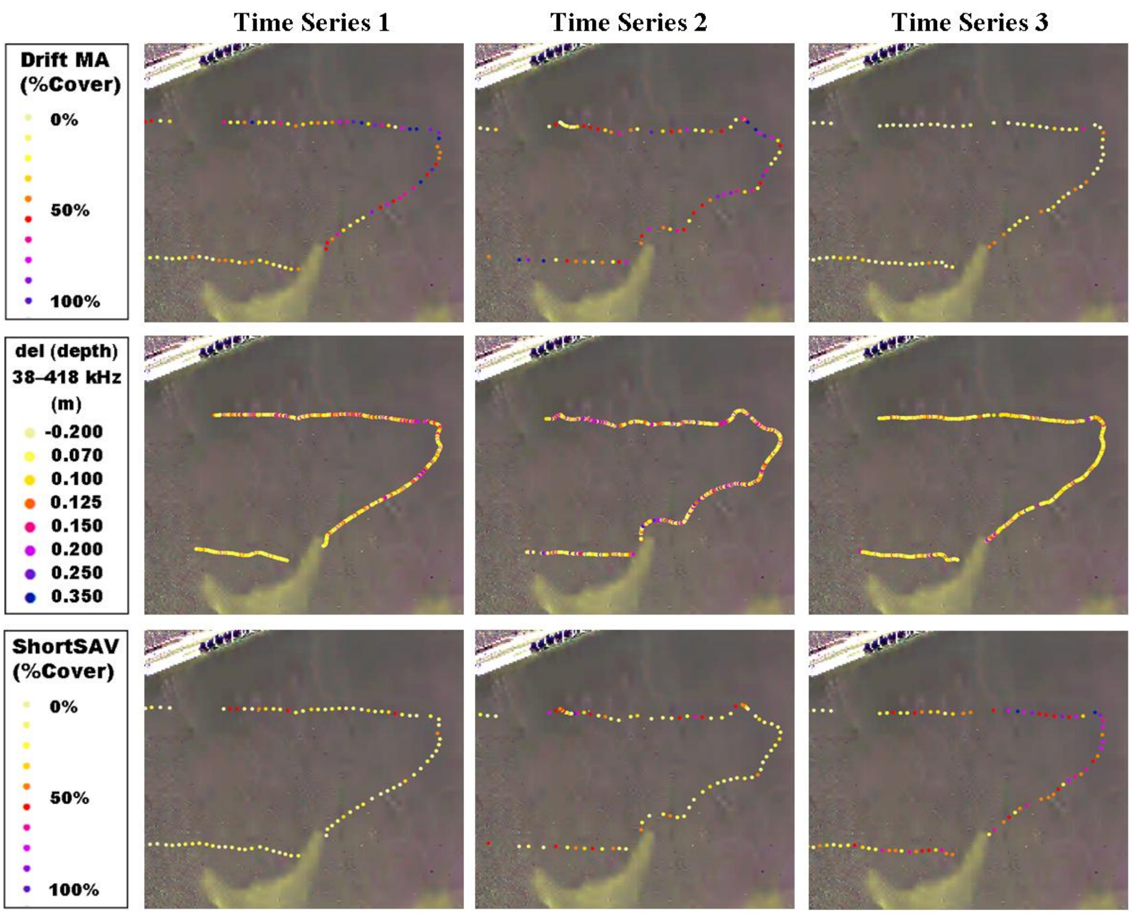

Figure 16. 2010 time series study. Crane Creek segment, just south of Melbourne causeway (area indicated in Figure 14). Many records that had classified as DMA in TS1 and TS2 can be seen to change to ShortSAV in TS3, suggesting a "thinning" of the DMA canopy. This is supported by the diminished value of delta(38-418kHz depth); the 38 kHz signal penetrates tall DMA canopies, whereas the higher frequency tends to reflect off tall DMA canopies).

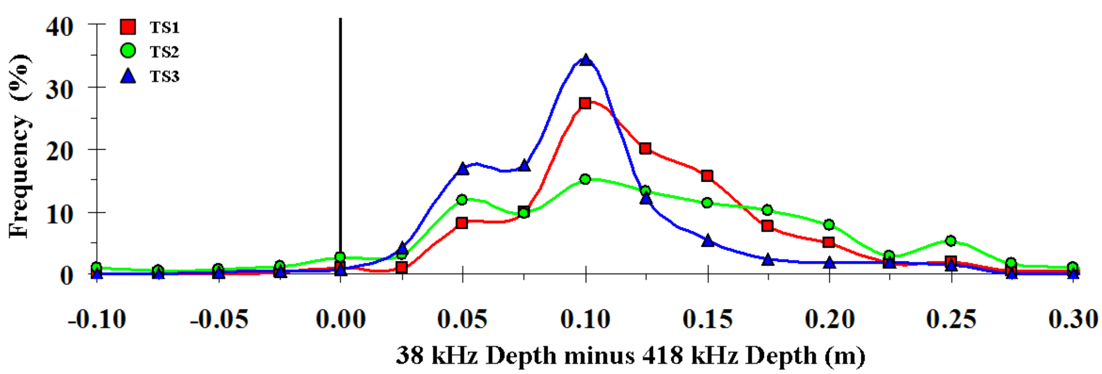

Figure 17. 2010 time series study. DMA patch in Crane Creek segment, just south of Melbourne causeway. Frequency distribution of 38 kHz depth minus 418 kHz depth for records that classified as either ShortSAV or DMA. The differential depth is proposed as a proxy for canopy height, which shows a clear decline at TS3.

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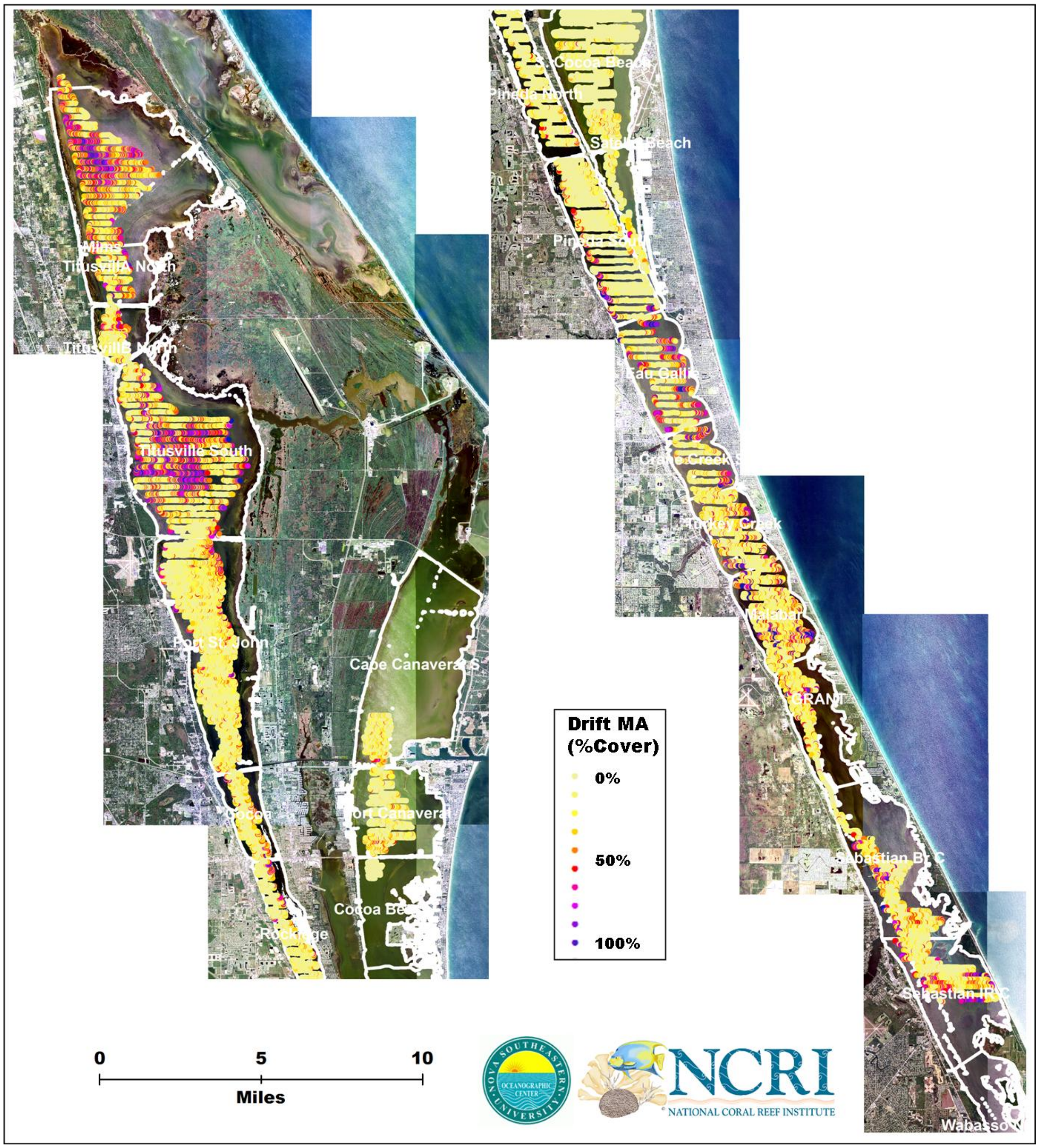
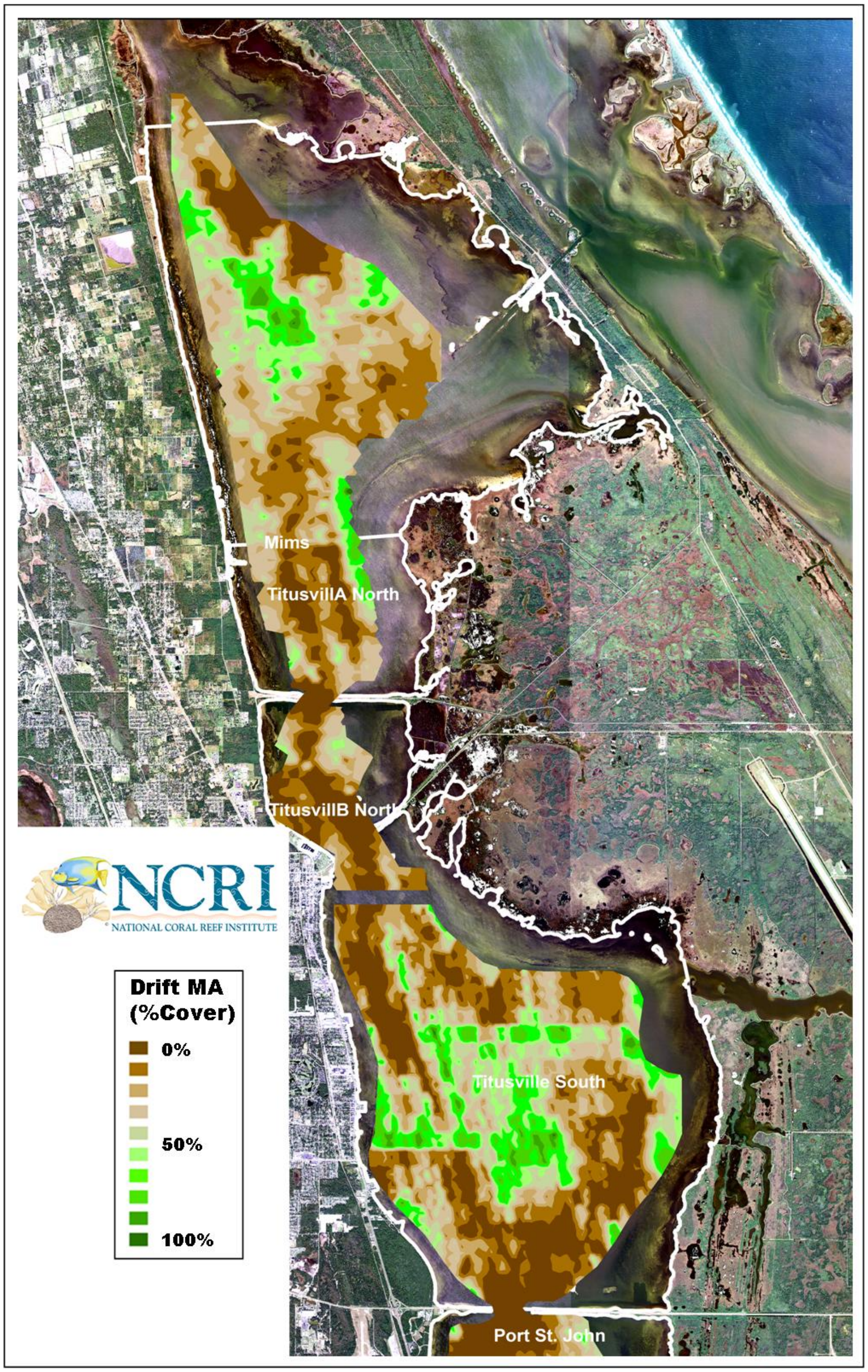
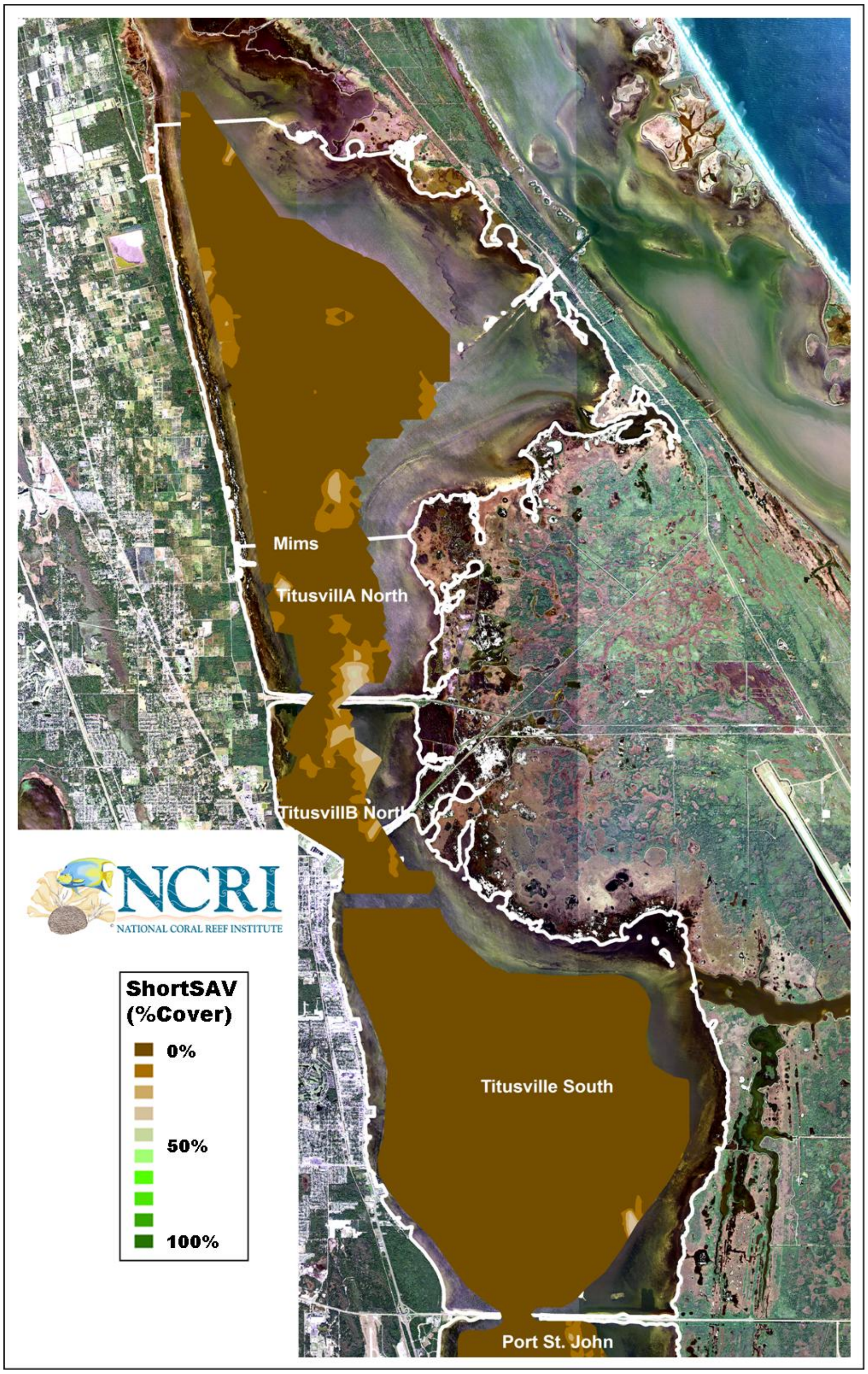
APPENDICES



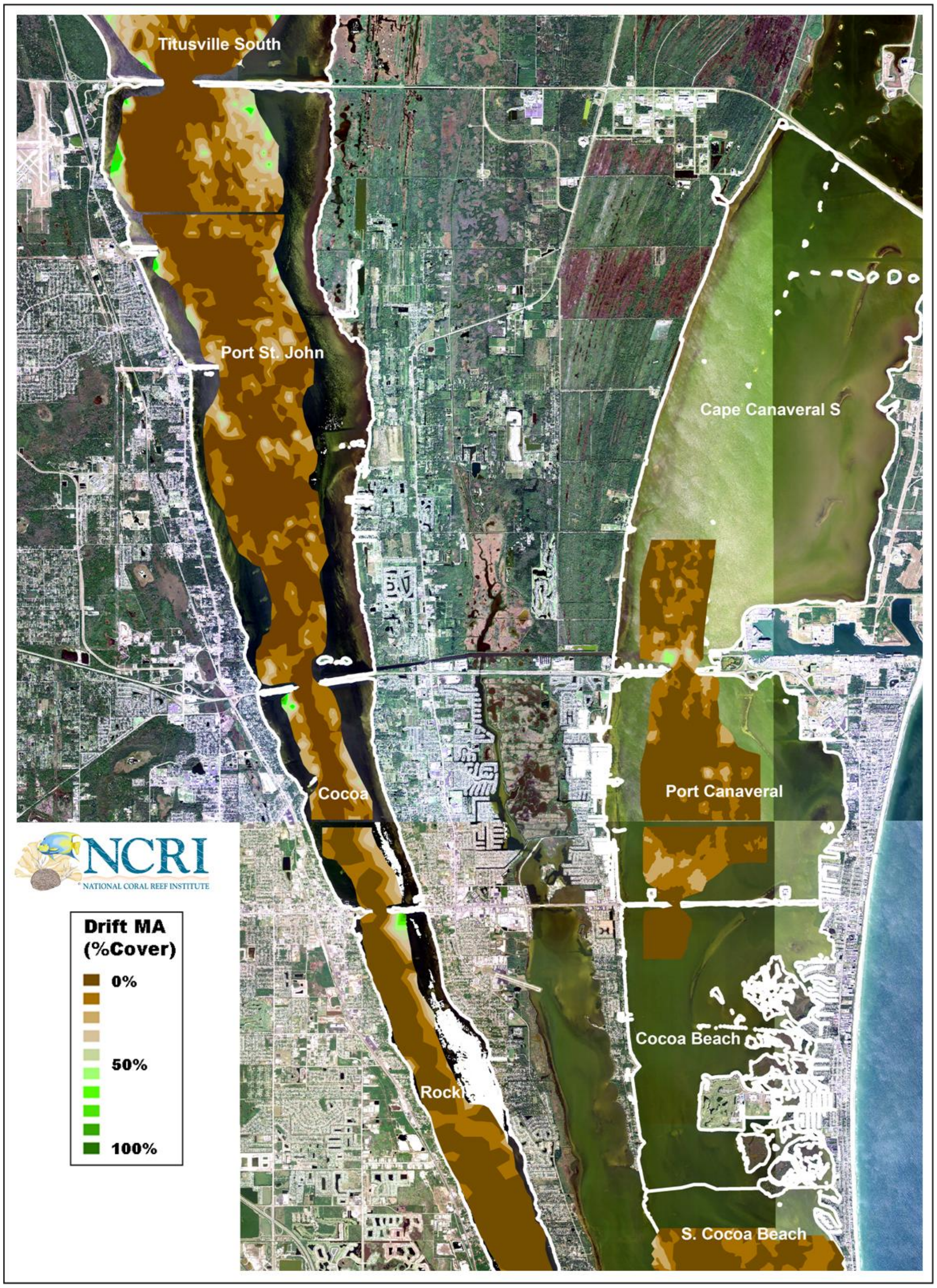
Appendix A1. Extent of the 2010 acoustic survey, displaying the track-plot of the acoustically-derived percent cover of drift macroalgae. The boundaries of SJRWMD segments are displayed for reference.



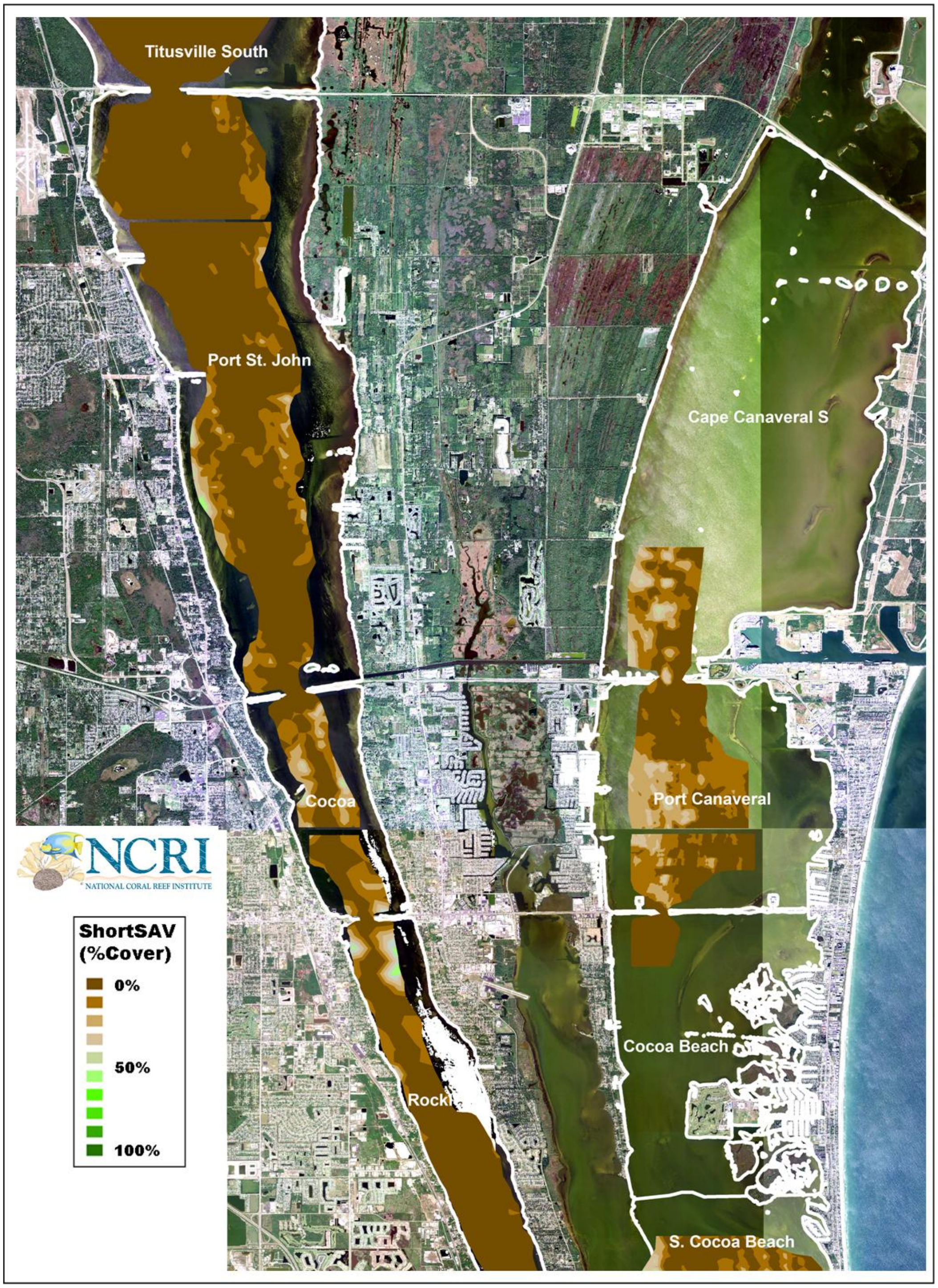
Appendix A2. 2010 Acoustic Survey (Mims to Titusville South). Kriged contour plot of acoustically-predicted percent cover of drift macroalgae. The boundaries of SJRWMD segments are displayed for reference.



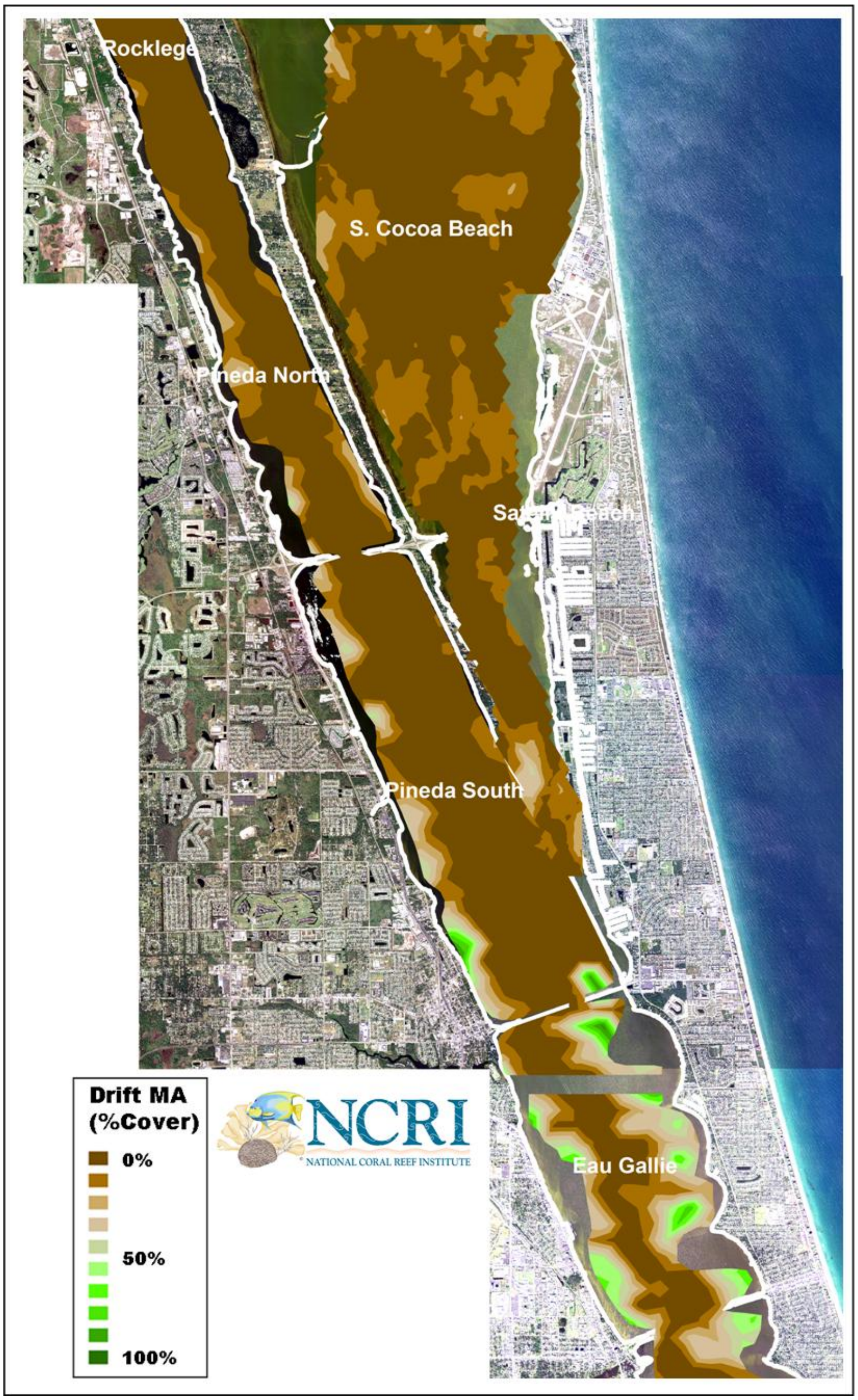
Appendix A3. 2010 Acoustic Survey (Mims to Titusville South). Kriged contour plot of acoustically-predicted percent cover of short SAV. The boundaries of SJRWMD segments are displayed for reference.



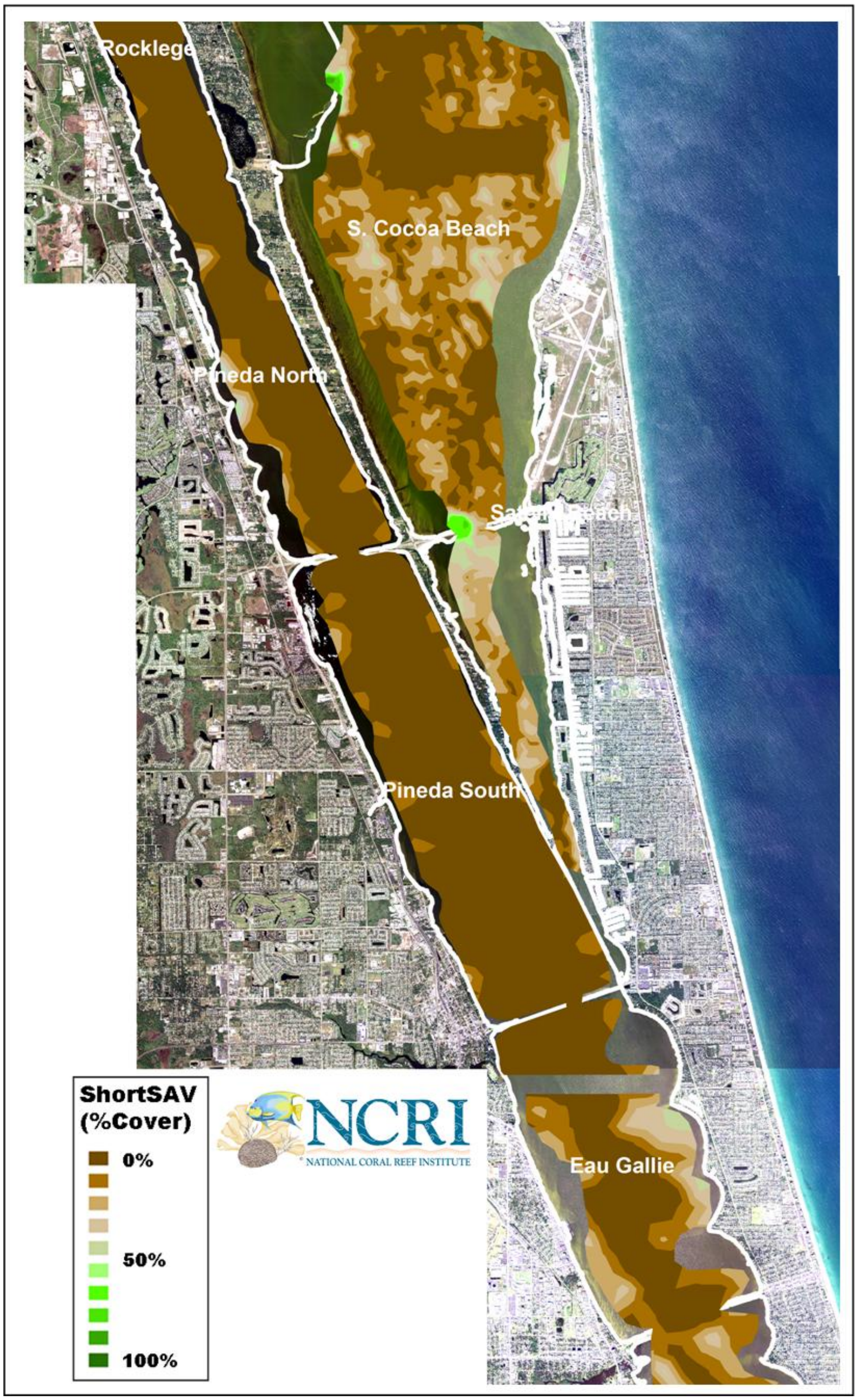
Appendix A4. 2010 Acoustic Survey (Port StJohn to Rockledge). Kriged contour plot of acoustically-predicted percent cover of drift macroalgae. The boundaries of SJRWMD segments are displayed for reference.



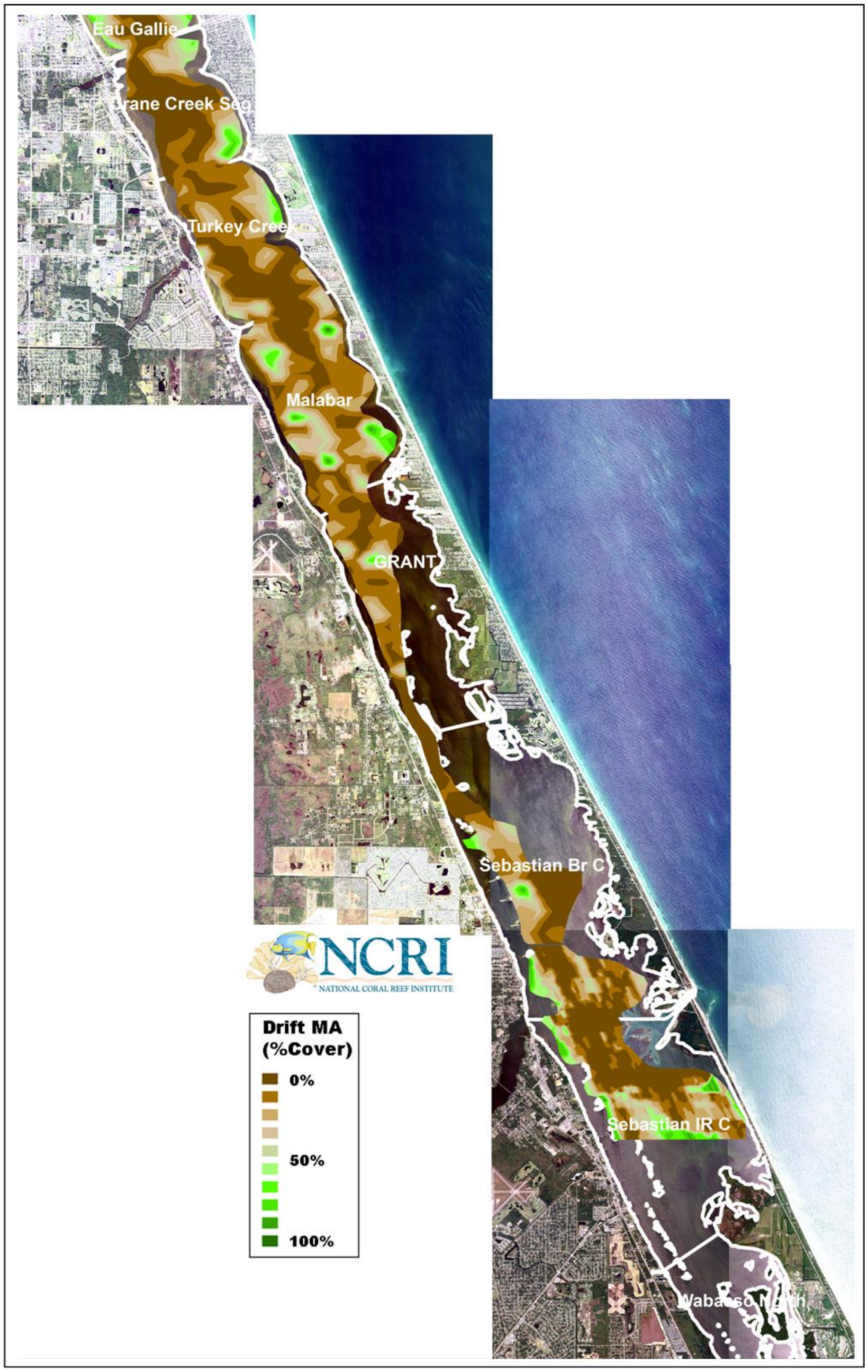
Appendix A5. 2010 Acoustic Survey (Port StJohn to Rockledge). Kriged contour plot of acoustically-predicted percent cover of short SAV. The boundaries of SJRWMD segments are displayed for reference.



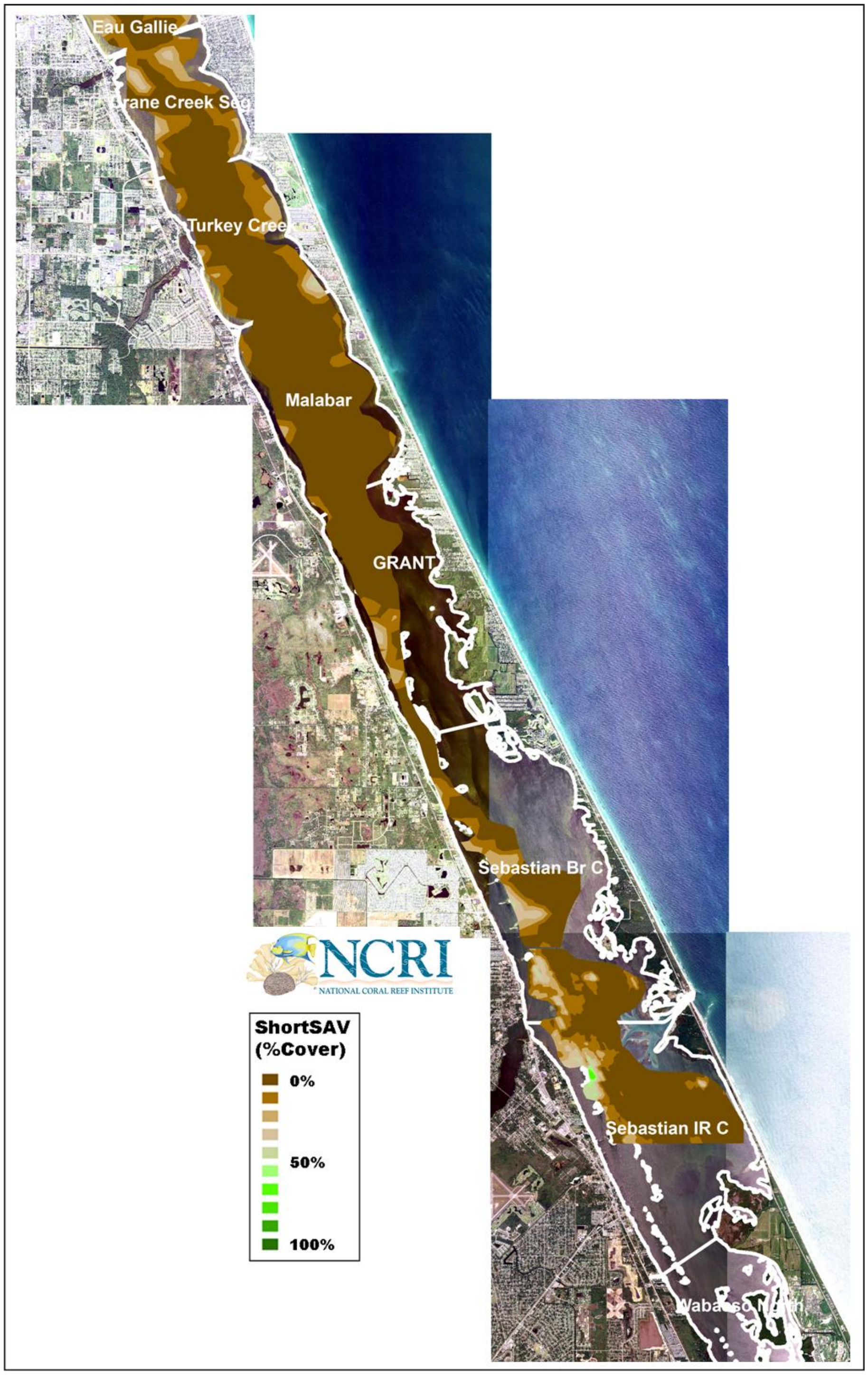
Appendix A6. 2010 Acoustic Survey (Rockledge to EauGallie). Kriged contour plot of acoustically-predicted percent cover of drift macroalgae. The boundaries of SJRWMD segments are displayed for reference.



Appendix A7. 2010 Acoustic Survey (Rockledge to EauGallie). Kriged contour plot of acoustically-predicted percent cover of short SAV. The boundaries of SJRWMD segments are displayed for reference.



Appendix A8. 2010 Acoustic Survey (Crane Creek to Sebastian). Kriged contour plot of acoustically-predicted percent cover of drift macroalgae. The boundaries of SJRWMD segments are displayed for reference.



Appendix A9. 2010 Acoustic Survey (Crane Creek to Sebastian). Kriged contour plot of acoustically-predicted percent cover of short SAV. The boundaries of SJRWMD segments are displayed for reference.