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Marsh canopy structure changes and the Deepwater Horizon oil spill

Elijah Ramsey III [a,*], Amina Rangoonwala [a], Cathleen E. Jones [b]

[a] U.S. Geological Survey, Wetland and Aquatic Research Center, 700 Cajundome Blvd., Lafayette, LA 70506, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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ABSTRACT

Marsh canopy structure was mapped yearly from 2009 to 2012 in the Barataria Bay, Louisiana coastal region that was impacted by the 2010 Deepwater Horizon (DWH) oil spill. Based on the previously demonstrated capability of NASA's UAVSAR polarimetric synthetic aperture radar (PolSAR) image data to map *Spartina alterniflora* marsh canopy structure, structure maps combining the leaf area index (LAI) and leaf angle distribution (LAD, orientation) were constructed for yearly intervals that were directly relatable to the 2010 LAI-LAD classification. The yearly LAI-LAD and LAI difference maps were used to investigate causes for the previously revealed dramatic change in marsh structure from prespill (2009) to postspill (2010, spill cessation), and the occurrence of structure features that exhibited abnormal spatial and temporal patterns. Water level and salinity records showed that freshwater releases used to keep the oil offshore did not cause the rapid growth from 2009 to 2010 in marsh surrounding the inner Bay. Photointerpretation of optical image data determined that interior marsh patches exhibiting rapid change were caused by burns and burn recovery, and that the pattern of 2010 to 2011 LAI decreases in backshore marsh and extending along some tidal channels into the interior marsh were not associated with burns. Instead, the majority of 2010 to 2011 shoreline features aligned with vectors displaying the severity of 2010 shoreline oiling from the DWH spill. Although the association is not conclusive of a causal oil impact, the coexistent pattern is a significant discovery. PolSAR marsh structure mapping provided a unique perspective of marsh biophysical status that enhanced detection of change and monitoring of trends important to management effectiveness.

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1. Introduction

Louisiana's coastal wetlands are experiencing the highest loss rates in the United States (Wilson and Allison, 2008). Although numerous causes account for the ongoing losses, coastal wetland marsh loss can be aggregated into two physical actions: subsidence-driven relative sea-level rise and wave erosion (Wilson and Allison, 2008). In 2010, the Deepwater Horizon (DWH) oil spill introduced another causal agent that could alter the coastal marsh viability and, thereby, its long-term stability, particularly in the oil impacted marsh in northeastern Barataria Bay, Louisiana (Ramsey et al., 2011). In response, USGS-NASA implemented a multi-year study that relied in part on Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Polarimetric SAR (PolSAR) L-band data to monitor changes in the coastal marsh in the north-central Gulf of Mexico (GOM) (Ramsey et al., 2011). The response study area encompasses most of the Mississippi River Delta (MRD) and large portions of the Louisiana coastline, but focuses on the oil impacted *Spartina alterniflora* marsh of Barataria Bay.

The analysis of PolSAR image data collected prespill in June 2009 and at the cessation of the DWH oil spill in June 2010 showed that dramatic pre-to-post spill change in dominance of the surface and volume backscatter mechanisms were associated with ground-based observations of heavily oiled shorelines in Barataria Bay (Ramsey et al., 2011). A ground survey at the time of the 2010 PolSAR data collection combined with ground and helicopter surveys through October 2010 observed that heavy oiling was contained within a narrow shoreline marsh zone about 2 to 4 m in width. The surface to volume backscatter change could extend 20 to 40 m inland of the observed heavily oiled shoreline (Ramsey et al., 2011). In addition, wide expanses of marsh further interior of the oiled shorelines also exhibited a dramatic change in backscatter mechanism primarily from surface to double bounce. Evidence supports that tides carried a surface oil film into these interior marshes; although this oil excursion into the interior marsh was not directly observed (Ramsey et al., 2011). Further, oil source fingerprinting applied to sediment samples collected a year after the oil spill cessation found DWH oil along the heavy oiled shorelines, in backshore marsh, and within interior marsh, confirming that oil reached further inland of the narrow shoreline impact zone (Ramsey et al., 2014a).

As part of the USGS-NASA effort to detect and monitor changes in the coastal marsh possibly connected to the DWH oil spill, a technique

* Corresponding author.
E-mail address: ramseye@usgs.gov (E. Ramsey).

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was developed to map marsh structure. The development entailed measurement of light attenuation over three years beginning in 2010 at four unoiled *S. alterniflora* sites and adding three sites in marsh surrounding Barataria Bay from 2011 to 2012. The light attenuation profiles were transformed to the marsh canopy structure indicators, total leaf area index (LAI) and the average orientation (Leaf Angle Distribution, LAD, 0 to 1 indicating increasing horizontal orientation) (Ramsey et al., 2015a). Empirical relationships between LAI and LAD and near concurrently collected PolSAR image data were applied to marsh surrounding Barataria Bay (Ramsey et al., 2015b). That mapping of marsh canopy structure indicated an increase in LAI from 2009 to 2010 that reverted toward prespill 2009 LAI levels after 2010 (Ramsey et al., 2015b). The fact that these marshes exhibited a change in structure from 2009 onward has implications on whether backscatter changes were a direct or indirect result of oil presence, or in part or fully a result of the atypical freshwater releases made during the DWH spill event to help prevent oil from reaching coastal wetlands. While direct oil-related causes of backscatter change in the interior marsh in 2010 are not excluded, changes after 2010 could indicate a longer term, indirect differential structural response within the core oil impact region.

The objective of the research is to more clearly define the yearly spatial pattern of canopy structure change from 2009 to 2012 in relation to known oil impact locations, PolSAR backscatter changes and possible influences of freshwater releases. In order to reach that objective, we begin with 2009 as our prespill baseline and identify through direct comparison agents of marsh structure change and, after excluding determinable changes, the spatial alignment of change and observed oil impacts.

1.1. Study area description

Barataria Bay occupies a relic sub-delta on the western MRD within a region experiencing compaction and subsidence (Fig. 1) with soil of high organic content composed of silts and clays. Low, relatively flat, fairly uniform marsh platforms lie between natural levee ridges and encompass numerous lakes and bays (Morgan and Larimore, 1957; Bowman and Pranzini, 2008; Wilson and Allison, 2008). Marshes surrounding Barataria Bay are dominated by *S. alterniflora* (Sasser et al., 2014). Our study area is located in northeastern Barataria Bay, including Wilkinson Bay and Bay Batiste, and covers areas impacted by Deepwater Horizon oiling and areas that did not experience oiling from the spill.

In order to relate marsh DWH oiling to possible adverse response, the marsh was separated into defined zones that correlated with observed to possible oiling. “Shoreline marsh” refers to the estimated 2 m to 4 m of often heavy oiling observed by field crews in 2010 (Ramsey et al., 2011). “Backshore marsh” represents the marsh zone extending 20 to 40 m or more interior of the heavily oiled shoreline marsh where more moderate DWH oiling may have reached. The “interior marsh” extends further inland spanning some isolated islands, such as Dragon Island, or extends nearer to the boundary of the study region into “mainland marsh” as, e.g., inland of Bay Batiste (Fig. 1). The mainland marsh is also discussed in reference to Coastwide Reference Monitoring System (CRMS) hydrologic site locations used for water level and salinity records (SONRIS, 2009) (Fig. 1).

2. Materials and methods

2.1. Marsh structure mapping

Marsh structure was mapped with NASA's 5 m by 5 m ground range projected, calibrated, and multilooked complex PolSAR image data collected in 2009 to 2012 near-anniversary UAVSAR flights covering the majority of the MRD including the Barataria Bay (Table 1) (Ramsey et al., 2015b). Many of these areas were observed to have matted, heavily oiled vegetation extending about 2 m to 4 m inland at the time of the UAVSAR 2010 image acquisition (Ramsey et al., 2011; Jones et al., 2011). For that reason, the shoreline LAI and LAD values near to the land-water boundary may not represent the true marsh structure in those very restricted areas.

The individual yearly LAI and LAD maps produced with the methodology of Ramsey et al. (2015b) were combined into a single LAI-LAD classification of the study area encompassing the core region of severe oil impact. Instead of the independent classifications in Ramsey et al. (2015b), the 2010 LAI-LAD classes created with an unsupervised procedure were used to seed 2009, 2011, and 2012 classifications within a maximum likelihood classification (MLC). The outcome of the

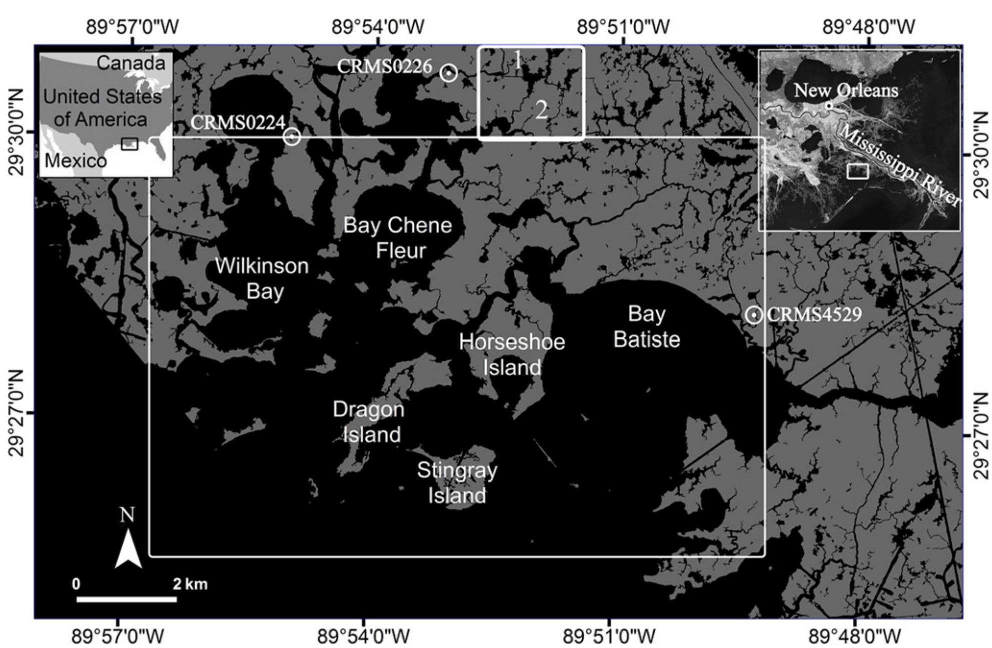

Fig. 1. The Barataria study region located on the western side of the Mississippi River Delta of Louisiana located in the north-central Gulf of Mexico. The white rectangle box locates the study region that encompasses our estimate of the core 2010 Deepwater Horizon oil spill impact area. Dragon, Horseshoe, and Stringray Islands were named by authors for ease of reference but are not official names. NASA UAVSAR data collections of Barataria Bay occurred from 2009 to 2012. CRMS hydrologic site locations are indicated. Burn site locations 1 and 2 are shown within the smaller white rectangle.

Table 1
Radar and Optical image data.

Radar		Optical			
		Burn Area1		Burn Area2	
UAVSAR	17-Jun.-09	Photography	15-Aug.-09	Photography	15-Aug.-09
	23-Jun.-10	Landsat	17-Feb.-10	Landsat	10-Dec.-10
	29-Jun.-11		29-Mar.-10		3-Jan.-11
	1-Jul.-12	Photography	9-Jul.-10		12-Feb.-11
		Landsat	10-Dec.-10		16-Mar.-11
			3-Jan.-11	Photography	1-Oct.-11
			12-Feb.-11	Landsat	5-Dec.-11
			16-Mar.-11		6-Jan.-12
					7-Feb.-12
				Photography	May-15

MLC based 2010 classification allowed direct comparability of 2009 to 2012 LAI-LAD class distributions.

An additional map product was computed focused on LAI changes. LAI differences were calculated between adjacent years; 2010–2009, 2011–2010, and 2012–2011. The mean-square-error (MSE, ± 0.44 LAI), calculated as part of the derivation of the empirical relationship used to create the LAI estimates from the PolSAR data was used to construct the LAI difference classes (Ramsey et al., 2015b). For example, the range -0.44 LAI to $<+0.44$ LAI was set as the no change class and all progressively increasing classes were set at 0.88 LAI difference increments. LAI differences <-0.44 were set to a single class so that the LAI difference maps highlighted negative differences <-0.44.

2.2. Determining the source of anomalous features

In the marsh structure classifications, distinct and at times isolated features appeared throughout the marsh. Many of these features emerged as part of the progressive changes occurring in the marsh landscape from 2009 to 2012. Others, however, materialized in one year and by the next had faded into the landscape. Similar features have been recognized in *Juncus romerianus* marsh as burn scars and successfully mapped with PolSAR image data (Ramsey et al., 1999, 2002). Even though *J. romerianus* marsh has typically narrower leaves and a more vertical orientation than the *S. alterniflora* marsh of this study (Ramsey and Rangoonwala, 2004, 2005, Ramsey et al., 2004), the feature similarity led to the conjecture that non-progressive features in the more interior marsh were fire scars. Outside of those features not tracking a progressive sequence, similar features appeared in 2011 LAI-LAD classification and LAI difference map that tended to align with heavily oiled shoreline marsh in the oil impact region.

In order to validate the cause of these ephemeral features as burn scars and differentiate them from the 2011 shoreline features, we compiled and photointerpreted a set of optical image data from 2009 to 2012. Managed and nonmanaged fires occur normally in winter to early spring and are recognizable on optical images if captured close enough to the wildfire (Ramsey et al., 1999, 2002). Table 1 lists the photographic and satellite image sources used to identify burn scars and regrowth.

2.3. Freshwater release

In an attempt to prevent the 2010 oil spill from impacting coastal marsh surrounding the MRD, freshwater discharges were increased or initiated through a number of diversions along Mississippi River (Bianchi et al., 2011, Das et al., 2012, O'Connor, 2013). The Davis Pond diversion (approx. 29°55′37″ N, 090°19′56″ W) begun on 30 April 2010 was one of the largest of these diversions with the specific intent of mitigating oil entry into Barataria Bay (Bianchi et al., 2011). By mid May 2010, a number of lesser diversions were in effect, and at least one of these, West Pointe à la Hache Outfall (approx. 29°31′46″N, 89° 48′27″ W), is located close to the upper reaches of Barataria Bay (O'Connor, 2013).

The salinity of waters inundating the marsh prior to the 2010 PolSAR data collection is most pertinent to determining whether freshwater diverted from the Mississippi River increased marsh growth compared to the same time period in 2009. In order to provide that information, above-ground surface water levels and salinities from 1 April to 15 October in 2009 and 2010 were obtained from Strategic Online Natural Resources Information System (SONRIS, 2009) containing the Coastwide Reference Monitoring System (CRMS) hydrologic database. One CRMS site was located in marsh just interior of Barataria Bay to the east while the two remaining sites were located outside the study region to the northwest (locations shown on Fig. 1). These data are complemented by observed salinities in waters located in the severe oil impact region of Barataria Bay in 2010 (Bianchi et al., 2011).

2.4. Observed shoreline oiling in 2010

In addition to mapping studies using remote sensing data that have documented shoreline and different extents of backshore oiling (Ramsey et al., 2011, Silliman et al., 2012; Kokaly et al., 2013, Ramsey et al., 2014a), Shoreline Cleanup Assessment Techniques (SCAT, 2014) observed DWH shoreline oiling occurrence and severity. The SCAT maximum oiling condition observed primarily between May and September 2010 is represented as colored vectors lining the Barataria Bay shorelines (SCAT, 2014). The light and very light categories were combined into the single light category.

3. Results

3.1. Marsh structure

Combined LAI and LAD classified maps and class dominances showed a dramatic change in marsh structure from prespill (2009) to 2010 near the time of the oil spill cessation (Table 2, Fig. 2a and b). The dominant LAI-LAD class in 2009 had an LAI mean of 2.6 and a LAD mean of 0.67. By 2010, much of the dominant 2009 LAI-LAD class had shifted to a denser (LAI = 4.0) and slightly more horizontal (LAD = 0.72) marsh. A lesser portion of the 2009 dominant LAI-LAD class had moved to classes exhibiting even higher LAI and more vertical orientations, particularly those comprising class 5 (LAI = 5.3, LAD = 0.62) and class 4 (LAI = 6.6, LAD = 0.5). Class 4 coverage, mostly within mainland marsh to the north and northwest, increased nearly 14 times over its 2009 presence primarily by extending into the 2009 class 7 (LAI = 4.0, LAD = 0.72). The three remaining 2010 classes, barely noticeable in 2009, largely were located progressively more interior of the 2010 class 4 marsh. In 2010, Class 3 (LAI = 7.92, LAD = 0.43) ordinarily occupied the boundary between class 4 and classes 2 and 1 (LAI = 9.23 and 11.0, LAD = 0.40) marsh. We note a localized change from class 6 (LAI = 2.59, LAD = 0.67) to class 7 along the heavily oiled shores of Dragon and Stingray Islands in 2010.

The primary changes from 2010 to 2011 in marsh structure were the loss of marsh class 1 defining the highest LAI and lowest LAD, and although class 7 retained its dominance in extent, class 6 had increased primarily at the expense of class 7 (Table 2, Fig. 2b and c). Also noticeable was the concentration of class 6 along shorelines and adjacent backshore marsh that had observed highly oiled shorelines in 2010.

The 2012 marsh structure map exhibited a dramatic decrease of classes 2 through 4 encompassing the highest LAI and lowest LAD exhibited by the most inner marsh (Table 2, Fig. 2d). Classes 5 and 6 continued to increase and class 7 returned to 2010 levels. Marsh within a number of islands occupying the study region had fully returned to 2009 structure. Broadly, the marsh structure was trending toward LAI-LAD classes of lower LAI and more horizontal orientation, and the marsh structure was reverting to the more uniform coverage existent in 2009.

Table 2
LAI and average LAD per class and the observations (pixels) in each LAI-LAD class in 2009, 2010, 2011 and 2012. The class color coding is used in Fig. 2a–d.

	Observations				Mean LAD	Std LAD	Mean LAI	Std LAI
Class #	2009	2010	2011	2012				
1	397	13,280	5273	434	0.40	0.19	11.00	0.94
2	353	33,362	26,428	1426	0.40	0.20	9.23	0.36
3	2204	109,761	112,256	13,390	0.43	0.22	7.92	0.38
4	20,102	275,644	333,414	129,288	0.50	0.25	6.63	0.36
5	146,468	787,565	827,264	847,290	0.62	0.27	5.29	0.38
6	2,857,874	867,038	1,044,424	1,077,591	0.67	0.31	2.59	0.56
7	676,958	1,596,081	1,344,342	1,586,640	0.72	0.29	3.99	0.40

The class color coding is used in Fig. 2a–d
LAI = leaf area index (bulk density), LAD = leaf angle distribution (average orientation), std = standard deviation.

3.2. Freshwater release

Data collected at the three hydrograph locations (Fig. 1) confirmed that the salinity of tidal flood waters leading up to July differed little in 2009 and 2010 (Fig. 3). Although the recording sites are located within marsh not far from Bay waters, the agreement in the 2009 and 2010 salinity comparison confirms that freshwater releases had not substantially altered the northern Bay waters before the 2010 UAVSAR collection.

This finding agrees with results of sampling within northern Bay waters (Bianchi et al., 2011) and suggests that change in the structure of marsh surrounding the inner Bay did not result from an atypical decrease in the 2010 Bay water salinity. Although eliminating a sudden drop in salinity as a cause of the increased LAI in backshore marsh, the results are not necessarily extendable to the mainland marsh where the highest LAI increases were mapped. However, the lack of water salinity recordings within much of the mainland marsh prevents full accounting of salinity conditions there.

3.3. LAI difference maps

The LAI-LAD yearly classifications revealed isolated changes that exhibited contrast within the general progression of the yearly classifications (Fig. 2a–d). While in many cases these features were noticeable on the classifications, the LAI difference maps accentuated their contrast within the year-to-year marsh landscape changes (Fig. 4a–c). The accentuated contrast provided higher spatial pattern definition, and as well, increased recognition of similar features not clearly identified in the classification maps.

3.3.1. Fire scars and burn recovery

The LAI difference maps accentuated features within the interior marsh that manifest as relatively low LAI in one year followed by a relatively high increase the next year. In order to identify these presumed burn features, we isolated them and compared LAI expression of the burn and its recovery to that observable with optical data (Fig. 5).

To provide a comparable optical progression, we choose two features located just north of the study area (locations shown on Fig. 1). The suite of optical image data verified that the features were burn scars and subsequent marsh regrowth. The optical and LAI comparison identified these interior marsh features as the result of marsh burning and described the LAI expression of a burn progression. Although too limited to evaluate burn detection and recovery mapping performance, the LAI mapping demonstrated the ability to quantitatively track burn recovery.

3.3.2. Oil occurrence and marsh structure

As in the mapping of marsh burns, spatial patterns in the 2009 to 2012 LAI-LAD classified maps showed evidence of changes in some locations that might have a common causal source (Fig. 2a–d). In contrast to the fire scars and subsequent recovery patterns, these changes tended to be concentrated within backshore marsh and to be aligned with observed severe shoreline oiling (Fig. 4b). In addition, change in the backshore marsh was particularly evident in 2011, which is consistent with 2010 oiling causality.

In order to clarify possible causes of the backshore patterns evident in the 2011 LAI-LAD map, we used the same optical image interpretation and LAI change analyses that identified anomalous features as burns within more interior marsh. In contrast to providing evidence of burns, interpretation of the suite of optical images showed no clear

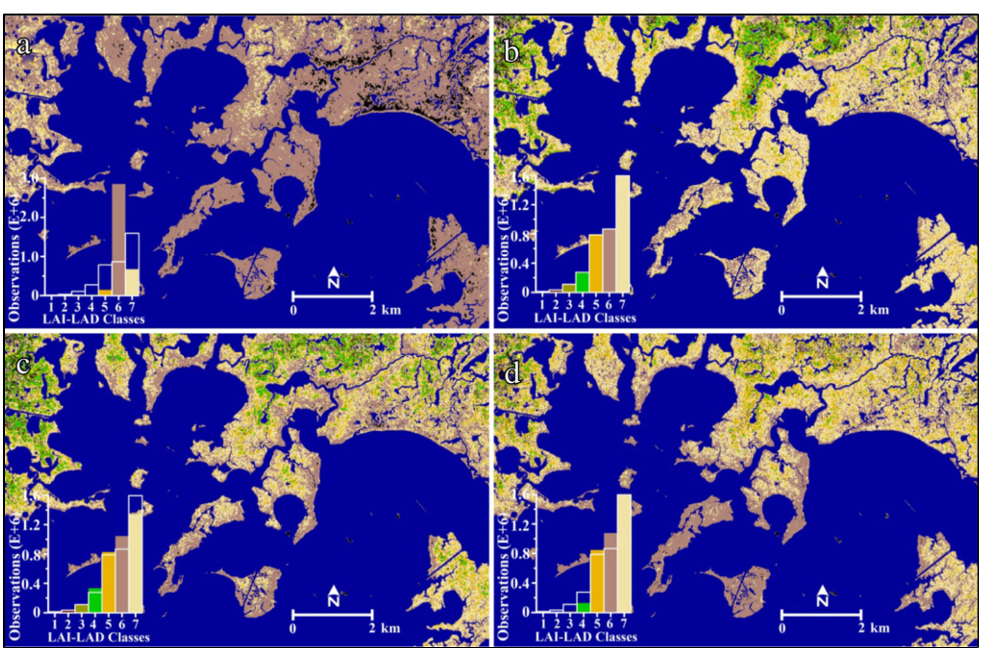

Fig. 2. LAI-LAD (a) 2009, (b) 2010, (c) 2011, and (d) 2012 classified maps. See Table 2 for LAI-LAD color legend and individual class LAI and LAD mean statistics. The 2009, 2011, and 2012 LAI-LAD classifications were seeded with 2010 classes making all classifications directly comparable (as shown in Table 2). The bar charts shown in the lower left of each map represents the observations per class listed in Table 2 (note 2009 to 2010 scale change). The colored bars represent the class frequency distribution of the map year and the white outline bars the 2010 class frequency distribution. Black areas indicate regions with non-physical LAD classification values.

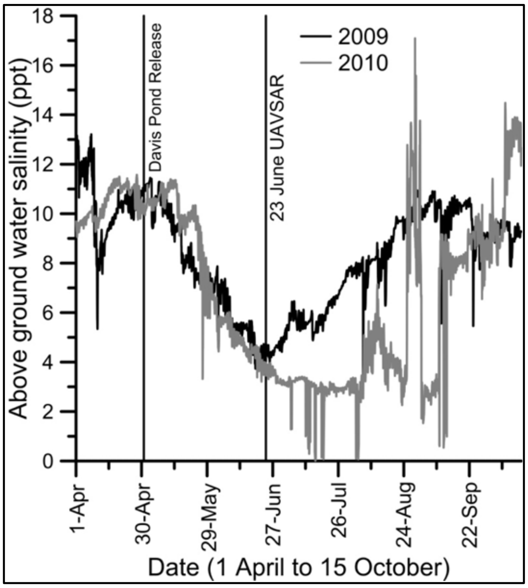

Fig. 3. Salinity of above-ground water from the CRMS 4529 station located within the interior of Barataria Bay (See Fig. 1 for location). The vertical lines locate the start of the 2010 freshwater release to help forestall the Deepwater Horizon oil from impacting coastal marsh and the 2010 UAVSAR data collection. The timing of the resultant abrupt change in salinity shows that the freshwater releases did not influence backshore marsh until after the UAVSAR collection.

sign of burn occurrence in these backshore marshes. Changes in the tone and texture occurred over the four year period, but these did not have the appearance of a burn and burn recovery.

The LAI 2010–2009 difference image did exhibit some deviation in the study region from the overall 2009 to 2010 LAI increase. This is shown on Dragon and Stringray Islands where the backshore marsh exhibited the nearly ubiquitous 2009 to 2010 LAI increase, while the interior marsh exhibited relatively less increase (Fig. 4a). Overall changes from 2010 to 2011 were more subtle than from 2009 to 2010. Although more subtle, LAI difference often revealed a pattern of heightened decrease in backshore marsh lying behind shorelines that experienced heavy oiling in 2010 (Fig. 4b). By 2012, backshore marsh exhibiting a 2010 to 2011 LAI decrease showed recovery while others remained near 2011 levels (Fig. 4c). As revealed in the 2012 LAI-LAD classification (Fig. 2d), in some interior marsh LAI had simply decreased to the 2011 backshore level. In others, as shown in Horseshoe Island and marsh nearer the Bay entrance to the south of Bay Batiste, LAI in the interior and backshore marshes differed. A complication in identifying possible causes in the 2012–2011 LAI changes was the occurrence of tropical storm Lee in October 2011 well after the 2011 PolSAR image collection. In some areas, Lee deposited a substantial amount of dead marsh (wrack) along shorelines and within backshore marsh that may have contributed to 2012 LAI-LAD patterns and 2012–2011 LAI changes.

4. Discussion

LAI and LAD marsh structure maps created from PolSAR image data collected from 2009 to 2012 on near anniversary dates at full canopy development provided a unique and highly informative assessment of pre-to-post changes within DWH oil impacted marsh. The combined LAI-LAD classifications standardized to 2010 LAI-LAD classes revealed LAI had increased throughout the Barataria Bay marsh from 2009 to 2010 with the exception of a couple island marshes within the study region. The increase in LAI was separated into two groups. Most marsh extending from shoreline into the interior had become slightly more horizontal, while further inland mainland marsh exhibiting the highest LAI overall was associated with an increased vertical orientation.

There was a nearly ubiquitous increase in marsh LAI from 2009 to 2010; however, the possibility that increase within marsh surrounding the inner Bay resulted from increased freshwater input was disproven. Moreover, the abnormal decrease in salinity from July to September after the 2010 PolSAR image collection did not change the overall LAI decrease from 2010 to 2011 (Table 2). This was particularly noticeable in backshore marsh lying just inland of the oil-impacted shoreline marshes (Fig. 4b).

Although in marsh closer to the Bay the 2010 LAI increases were not a consequence of freshwater diversions that cause could not be discounted for mainland marsh LAI increases. The sudden LAI increase and subsequent decrease is similar to the 2010 to 2012 sudden dieback and recovery of *S. alterniflora* marsh to the west and inland of Barataria Bay (Ramsey et al., 2014b). Although the cause was not determined for the higher biomass in 2010 or the subsequent dieback in that previous study, the combined measurement of biomass, LAI, and LAD helps elucidate their relationship. That study documented that the 2010 to 2011 dieback was associated with marsh containing relatively higher live biomass, reflecting higher total biomass in these marshes than in the similar surrounding marsh (Ramsey et al., 2015b). Marsh at both validation sites had similar and high biomass weights and LAI values in 2010, but one was highly horizontal (LAD = 1.04) and the other was more vertical (LAD = 0.6). The more vertical marsh collapsed in 2011 while the more horizontal marsh recovered by 2012. Even though the LAI magnitudes of marsh prior to dieback did not reach those represented in the top three classes of this study (Table 2), that comparison shows LAI does not necessarily monotonically track average orientation. In addition it shows new growth can increase overall canopy LAI while exhibiting a decidedly more vertical orientation than a more full growth *S. alterniflora* marsh (Ramsey et al., 2015a). This suggests that the highest increases in LAI and vertical orientation within mainland marsh in 2010 could indicate new *S. alterniflora* growth. It is possible that one of the smaller releases may have directly impacted the mainland marsh of Barataria Bay promoting rapid new growth before the 2010 PolSAR collection; however, that causal connection could not be resolved with the available data.

Inspection of the optical image suite used in the burn corroboration determined that backshore marsh features exhibiting a 2010 to 2011 LAI decrease were not associated with burns. Instead, the spatial alignment of these features with observed heavily oiled shoreline marsh in 2010 suggests a possible causal connection. Since Ramsey et al. (2011) suggested the possible increased inshore extent of oil impact without initial marsh structural damage, Silliman et al. (2012), Kokaly et al. (2013), and Peterson et al. (2015) have reported that marsh oil exposure can extend beyond the heavily oiled shoreline into the adjacent backshore marsh. A more recent study found above-ground biomass of heavily oiled marsh in Barataria Bay had not recovered three and a half years after the DWH spill, while moderately oiled marsh took up to two and a half years to fully recover (Lin et al., 2016). We suggest that their heavily oiled category represents the narrow 2 to 4 m heavily oiled and often structurally damaged shoreline marsh and their moderately oil category provides an example of our defined non-damaged and oiled backshore marsh.

Widespread exposure of the marsh to oil, particularly backshore and interior marsh, most likely was during a week of prolonged high tides that occurred two weeks before the 2010 PolSAR image collection (Ramsey et al., 2011). The shortness in time since exposure makes it unlikely that the moderately oiled backshore marsh would have exhibited a measureable LAI change at the time of the 2010 collection. On the other hand, the timing of the 2011 anniversary collection near the mid-point of biomass loss to full recovery was most likely to capture a discernable decrease in LAI if existent.

PolSAR mapping did capture a pattern of accentuated decrease localized within backshore marsh that occurred widely throughout the study area. Multiple studies showing that DWH oil to some extent contaminated the backshore marsh and that biomass decreased in

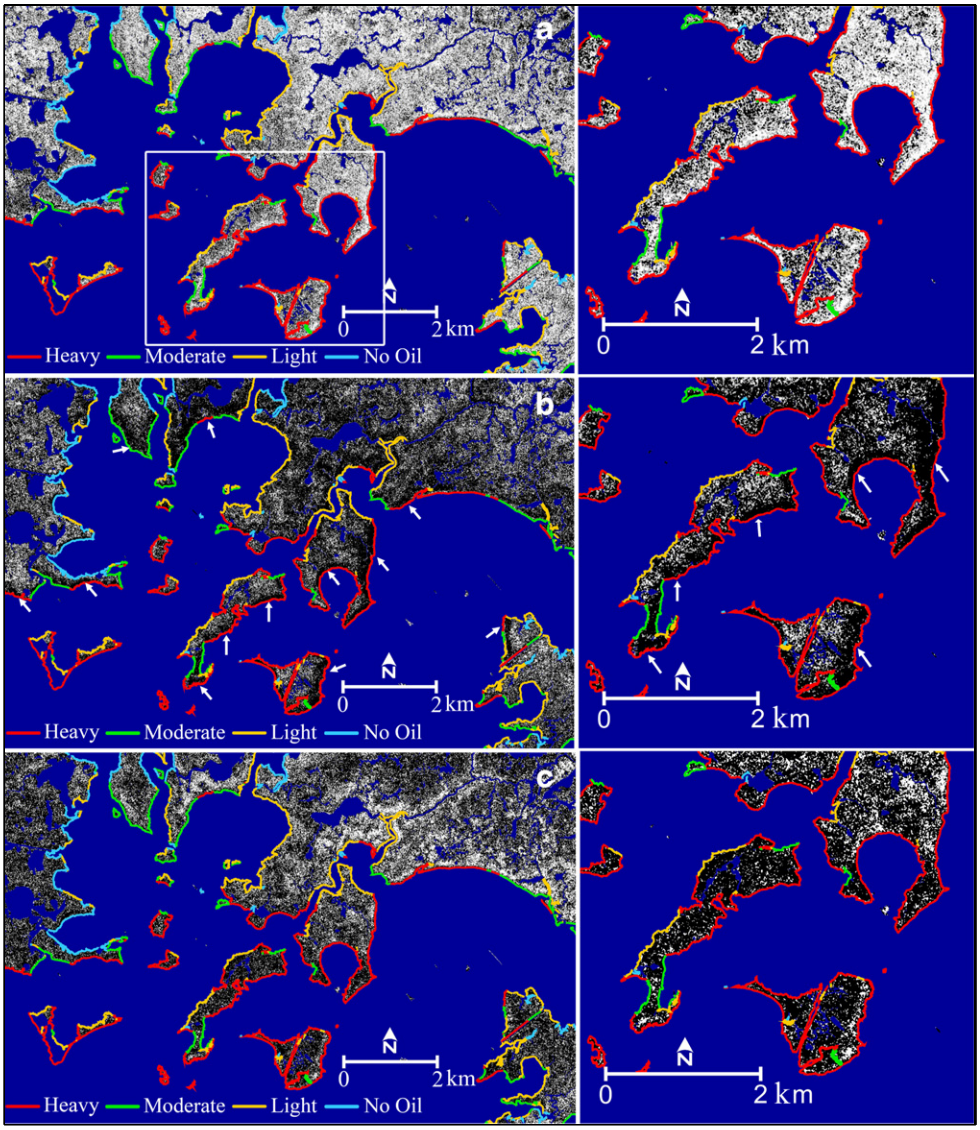

Fig. 4. The LAI differences (a) 2010–2009, (b) 2011–2010, and (c) 2012–2011. Progressively brighter grey tones partitioned as discrete 0.88 LAI classes represent increasing differences from zero (−0.44 to +0.44). Black represents all differences <−0.44 LAI. Colored vectors depict SCAT shoreline oil-spill categories (see legends). Arrows placed on the 2010–2011 overview (4b on left) locate features similar to those identified on the close up to the right that accentuate the 2011 LAI decrease in backshore marsh often associated with heavily oiled shorelines.

marsh moderately contaminated by DWH oil, indicate backshore marsh could have exhibited a LAI decrease by 2011. Those results combined with the spatial alignment in many areas between the backshore LAI decrease and heavy to moderate shoreline oiling support a causal relationship. Although the inferential nature of that association and the inability to discount unknown factors preclude a conclusive result, the differential decrease in backshore LAI uncovered by the PolSAR mapping and its often alignment with heavily oiled shorelines is a compelling and significant finding of this study. This relationship should be further explored through experiment and case studies.

Separate from the possibility of elevated freshwater intrusions and oil impact, fire was confirmed as the cause of localized and abrupt changes of LAI-LAD and LAI difference features in the mainland marsh. The validation of the cause of the ephemeral features as burn scars also enabled comparison of PolSAR and optical burn recovery mapping. Although results do not confirm a preference in PolSAR or optical performance in burn scar detection, they demonstrate that the canopy structure metrics, LAI and LAD and especially LAI difference, derived from PolSAR produce easily identifiable burn scar features. These PolSAR-based metrics also provide trackable and quantifiable burn recovery progression.

After 2010 and apart from the fire and possible oil-related irregularities, the marsh tended to discard the highest and most vertically oriented classes found in the marsh interior, progressing to a more uniform moderate LAI (ca. 2.6 < LAI < 6.8) and horizontal orientation. By 2012 the backshore features that showed lower LAI in 2011 possibly related to oiling, now showed greater variability, with different locations showing recovery, little change, or further loss of canopy LAI.

5. Conclusion

Structural changes of coastal *S. alterniflora* marsh surrounding the 2010 oil impact region of Barataria Bay were successfully mapped with NASA's UAVSAR polarimetric (PolSAR) image data on near-anniversary summer dates from 2009 to 2012. Standardizing the combined leaf area index (LAI) and leaf angle distribution (LAD) classification to 2010 LAI-LAD classes allowed a direct comparison of marsh structural changes from pre-to-post Deepwater Horizon oil spill. The classified

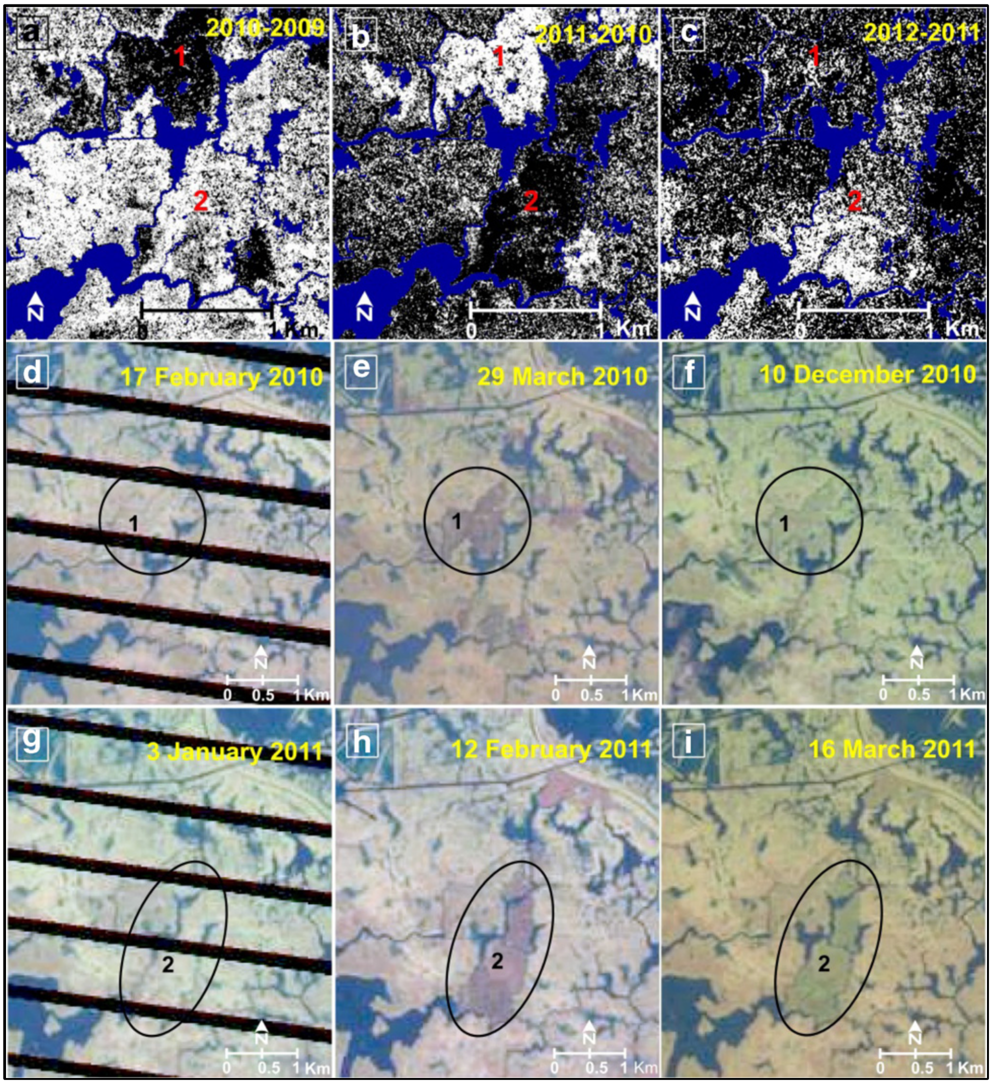

Fig. 5. (a–c) Burn-1 and burn-2 LAI difference maps 2010–2009, 2011–2010, and 2012–2011 located on Fig. 1. (d–f) A partial set of available natural color optical images covering burn-1 and (g–i) burn-2, showing the optical expression of preburn, burn scar and burnt marsh recovery. (See Table 1 for complete photography image set).

sequence and spatial pattern of marsh structure maps from 2009 to 2012 revealed a structurally dynamic marsh landscape. Although dynamic, change patterns documented in the independent classifications were reasonable, offering a compelling history of progression from year to year. That history documented an overall change in marsh structure from 2009 to 2010 (spill cessation) that was broadly divided into (1) moderate LAI and horizontal orientation increases in island marsh and marsh surrounding the Bay, and (2) high increases of LAI and vertical orientation in the mainland marsh. Results confirmed that freshwater releases to mitigate coastal oil impacts were not a contributing factor to structural changes of marsh closer to the Bay; however, the lack of available data prevented similar documentation in much of the mainland marsh. As a result of the PolSAR marsh structure mapping integrity, irregular patterns of marsh structure change were uncovered. One pattern depicted as ephemeral features in the LAI and LAD (orientation) and LAI difference mapping tracked the recovery of the burnt marsh. Once the fire related features were accounted, the irregularity in the 2010 to 2011 pattern of backshore LAI changes was shown to align with the 2010 heavily oiled shorelines. The 2011 LAI decrease exhibited by these features fit nearly midway between the reported two plus year recovery period measured for moderately oiled marsh.

This study demonstrates the unique perspective on marsh biophysical change offered by PolSAR marsh structure mapping. As shown by the LAI and LAD yearly mapping and the appearance one year after the spill event of irregular marsh LAI and LAD structure patterns largely aligning with observed severe oil impacts, marsh structure mapping is critically important in understanding changes in marsh condition and should become an integral component of the monitoring of coastal resources.

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