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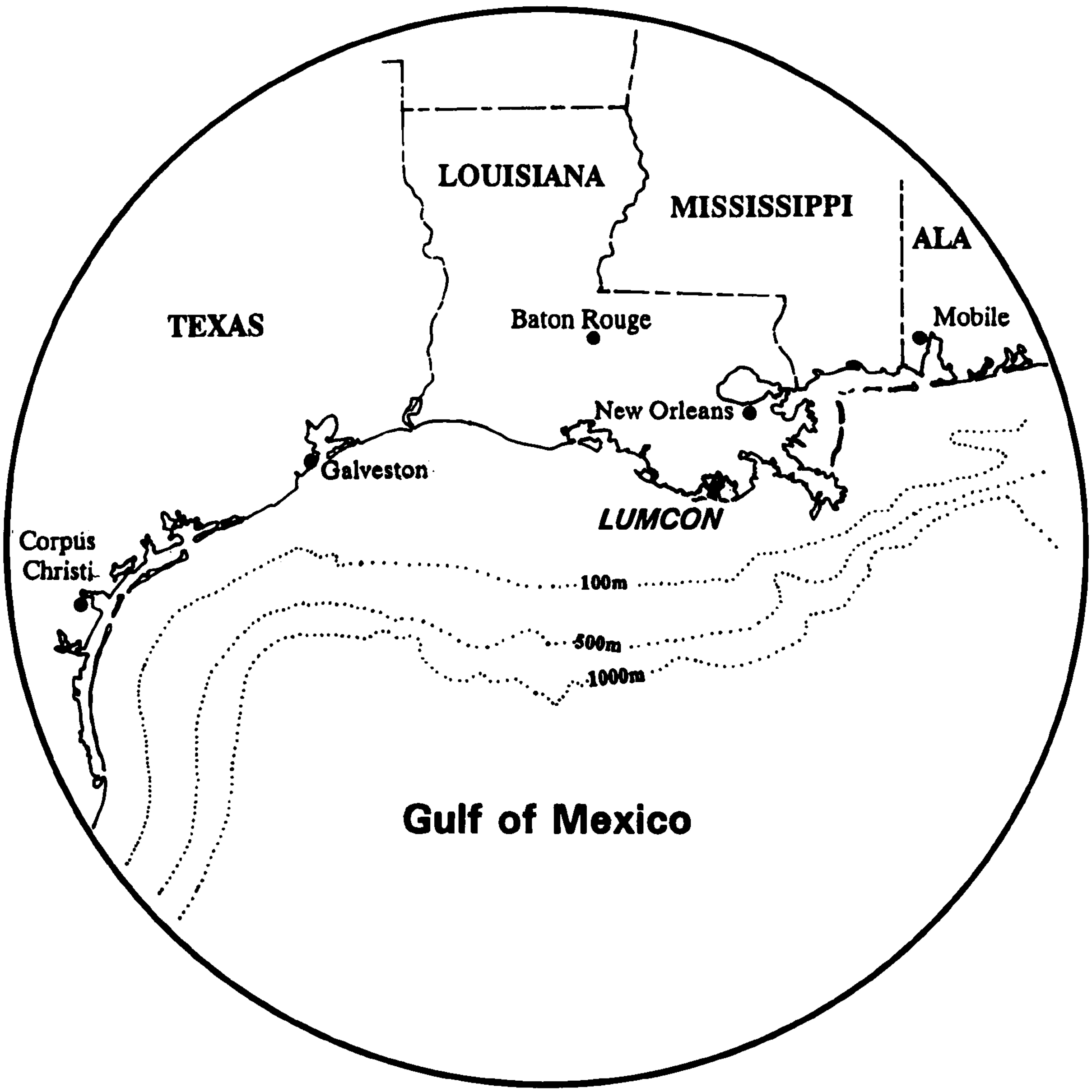
Effects of Oil Spills on Coastal Wetlands and Their Recovery: Year 4, Final Report



U.S. Department of the Interior
Minerals Management Service
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Effects of Oil Spills on Coastal Wetlands and Their Recovery: Year 4, Final Report

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September 1993

Prepared under MMS Contract
14-35-0001-30470
by
Louisiana Universities Marine Consortium
150 Riverside Mall, Room 107
Baton Rouge, Louisiana 70801

Published by

U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

Cooperative Agreement
University Research Initiative
Louisiana Universities Marine Consortium

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CITATION

Suggested citation:

Mendelssohn, I. A., M. W. Hester, and J. M. Hill. 1993. Effects of Oil Spills on Coastal Wetlands and Their Recovery. OCS Study MMS 93-0045. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, La. 46 pp.

ABSTRACT

Oil spills can have a significant short-term impact on coastal marshes, but the long term effects and perhaps eventual recovery are not well documented. The overall goal of this investigation is to document the long-term recovery rate of a Louisiana brackish marsh impacted by an oil spill on 23 April 1985, to separate the effect of the oil spill on marsh deterioration from ambient rates of marsh degradation, and to test means by which recovery can be accelerated and the damage mitigated. These goals have been accomplished through both remote sensing and ground truth assessments, ground based vegetation stress measurements, and manipulative field experiments.

A total of 68 permanent plots that were established in the oiled and control marshes at the study site in 1985 were re-surveyed for plant and soil recovery in the fall of 1989 and assessed for species composition, live and dead percentage cover, and residual oil impact. Significant vegetative recovery of the oil- impacted marsh four years after the spill was evident as indicated by significant increases in vegetative cover. However, there was also a tendency for vegetated plots that were initially highly impacted by oil to still have higher levels of total saturated hydrocarbons in the soils.

In order to assess the health of vegetation that had appeared to recover following the spill (as indicated by an increase in vegetative cover), plant photosynthetic response was measured in August 1990 in plots that were initially heavily impacted by oil, but displayed subsequent vegetative regrowth, and also in control plots that were not impacted by the spill. There were no significant differences in plant photosynthetic response between control and oiled plots for either Spartina alterniflora or Spartina patens. There were also no significant differences in interstitial water salinity, sulfide, and pH, or soil Eh between control and oiled plots, further demonstrating recovery of the oil-impacted marsh.

A field transplant experiment was established in July 1991 to determine if those areas within the oiled marsh that had not recovered could be restored through the use of vegetative plantings and to determine if the failure of these areas to revegetate was due to a residual oil effect or due to increased water depth inhibiting successful vegetative re-establishment. Spartina alterniflora transplants were planted at two elevations (ambient elevation of the dieback sediment surface, and at an increased elevation equivalent to that of the adjoining vegetated marsh surface) in association with either oil-contaminated sediment or oil-free sediment. At harvest, above- and belowground biomass, as well as numbers of living and total stems, were significantly greater in the elevated plots. Ambient elevation plots had significantly lower sediment surface redox potentials, and at one site significantly greater concentrations of interstitial water sulfides than the elevated plots, indicating that the sediment was more reduced in the ambient plots than in the elevated plots. Importantly, there were no significant differences between elevated residual oiled plots or elevated control plots for any of the variables. Therefore, failure of these areas to revegetate appears to be due to increased flooding stress.

Acreage data derived from six dates of imagery were assembled into a digital GIS (geographic information system) and land cover changes between time intervals were determined and analyzed. Wetland land loss and gain maps generated from these data sets indicated that rates of wetland land loss in the oiled marsh during an eight year period that bracketed the spill were within the historical range measured for this site and similar to the land loss rates of adjacent reference marshes. Thus, it would appear that rates of land loss in the oiled marsh were not accelerated by the initial impact of the oil to the vegetation.

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INTRODUCTION

Oil spills can have a significant short-term impact on coastal marshes, but the long-term effects and perhaps eventual recovery are not well documented. This project expands on a previous short-term 1985 oil spill study in which a pipeline break released approximately 300 barrels of Louisiana crude oil into a Louisiana brackish marsh dominated by a mixture of Spartina patens, S. alterniflora and Distichlis spicata. Existing spoil banks and booms that were deployed shortly after the spill confined the oil impact to approximately 20 ha of marsh (Figure 1). Cleanup activities consisted of spraying the vegetation and marsh sediment surface with estuarine water from adjacent water bodies and pumping the oil-ladened water to tank trucks for disposal. However, oil-saturated soil and plant material were not removed from the marsh. Marsh buggies, used during the cleanup procedure, resulted in localized mortality of the vegetation in the area of the break due to mechanical trampling.

In the initial study, both photointerpretation of aerial imagery and ground based vegetation stress measurements were used to assess the near-immediate (within the first year) impact of the oil spill on the marsh vegetation. Oil spill impact studies to date have not documented potential spill impacts on a brackish marsh and have not assessed rates of recovery beyond 1 to 3 years. The overall goal of this investigation is to (1) document the long-term recovery rate of the oil-impacted brackish marsh, (2) to separate the effect of the oil spill on marsh deterioration from ambient (background) rates of marsh degradation, and (3) to test revegetative means by which recovery can be accelerated and the damage mitigated.

The specific objectives of this project are as follows: 1) document pre-spill land loss rates using historical aerial photography and ground-truth based assessments of vegetative cover 2) document post-spill rates of marsh recovery using recent aerial photography, ground-truth based assessments of vegetative cover, and vegetation stress analyses, 3) determine the effect of the oil spill on the study area's rate of deterioration, and 4) determine growth rates and factors controlling the success of transplanted marsh grasses in impacted areas for remediation strategy considerations.

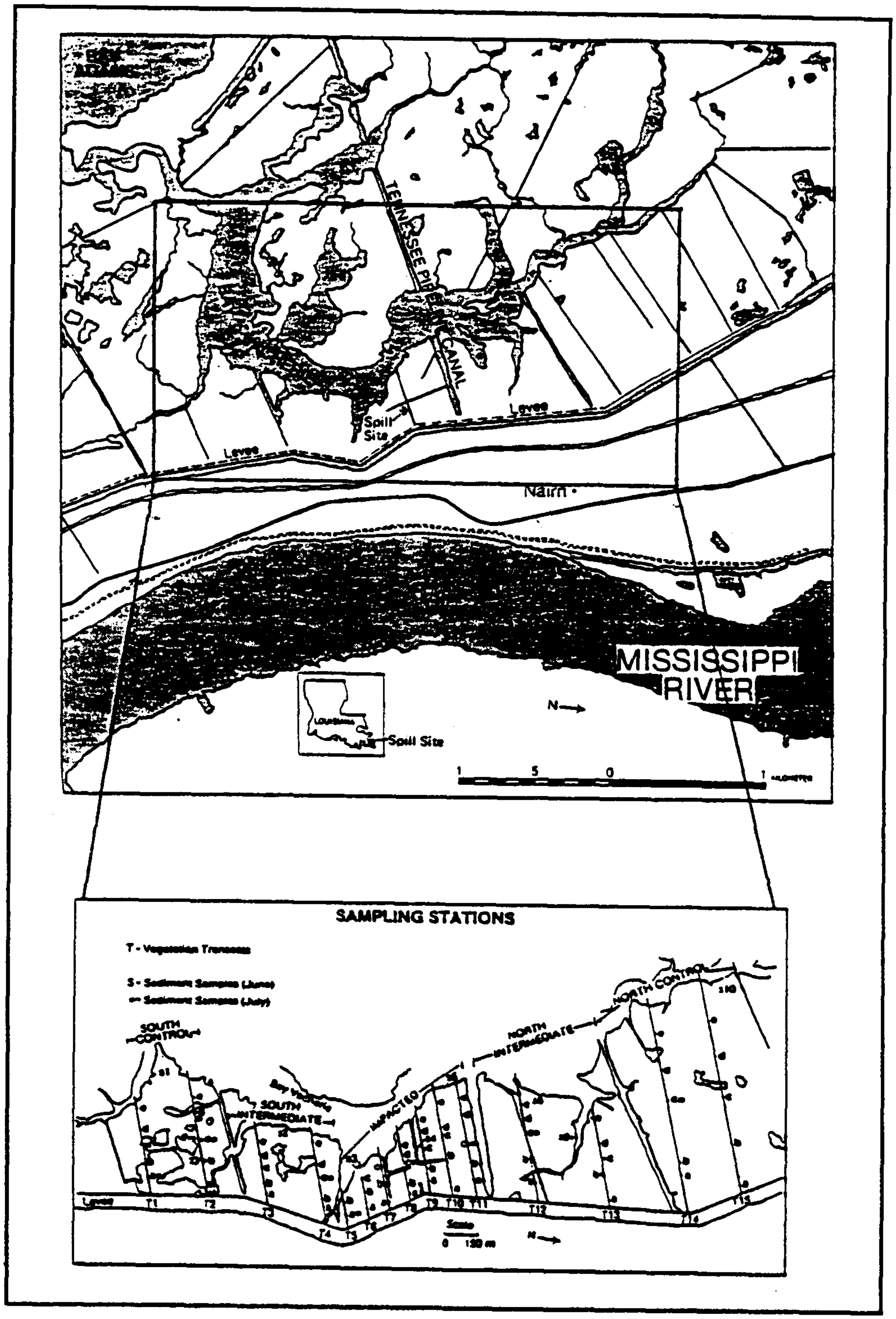

Figure 1. Study site map showing the location of the pipeline break, vegetation sampling transects and plots and sediment sample sites. Sampling plots are indicated by letters a-e.

MATERIALS AND METHODS

FIELD ACQUIRED ANALYSES

To adequately assess the recovery of the vegetation and soil from the spill we established three objectives for the field component of the research as follows: (1) assess the recovery of the vegetation and soil in permanent plots that were established in July of 1985, (2) determine the health of recolonizing vegetation by measuring plant photosynthesis (net CO_2 exchange rates) of vegetation in oil-impacted and non-impacted (control) plots and (3) determine if marsh restoration can be achieved by transplanting marsh grasses into sites where marsh recovery has been minimal (as a result of the oil spill and subsequent cleanup activities), and if a residual oil effect or increased flooding stress are important factors affecting the successful re-establishment of vegetation in these areas.

Sampling Design

Aerial reconnaissance of the oil spill site on 19 June 1985 resulted in the designation of three geographical areas in the vicinity of the spill : (1) A heavily oil-affected area (in which the oil was contained with booms) of ca. 20 ha immediately surrounding the pipeline break, was designated the Impacted Marsh, which extended from the Tennessee Pipeline Canal 0.7 km to the south (Figure 1); (2) Adjacent marshes north and south of the Impacted Marsh that could have potentially received oil, but which showed no obvious signs of oil coverage of the vegetation were designated the North Intermediate and South Intermediate Marshes (Figure 1); (3) Marshes north and south of the Intermediate Marshes that were selected as controls and designated the North Control and South Control Marshes (Figure 1).

A sampling design of 15 parallel transects oriented approximately perpendicular to the west levee of the Mississippi River were established (Figure 1). Transects 1 and 2 were located in the South Control Marsh, transects 3 and 4 in the South Intermediate Marsh, transects 5 through 11 in the Impacted Marsh, transects 12 and 13 in the North Intermediate Marsh, and transects 14 and 15 in the North Control Marsh (Figure 1). Each transect was divided into 100 m sections and within each section a permanent sampling plot ($1.0\ m^2$) was located using random numbers between 1 and 99 to designate the position of the plot on that 100 m section. This procedure allowed us to select sampling plots randomly, but also insured that each transect was thoroughly sampled. All transects, except 5, 6, and 7, were roughly 500 m in length and therefore contained 5 permanent plots each (see Figure 1).

Vegetation and Soil Assessment

Sampling was conducted by helicopter in July 1985, three months after the pipeline break, and again in November 1989. Sixty-eight sampling plots, were located from the air by using a color infrared photomosaic on which the transects and plots were delineated. During the 1985 sampling, each randomly selected 1.0 m^2 sampling plot was established on the marsh with a quadrat and marked with white PVC pipe. The following data was collected from each of the 68 plots in 1985 and again in 1989: 1) Total (live plus dead) percentage vegetative cover; 2) Live percentage vegetative cover by species; 3) Dead percentage vegetative cover (not differentiated by species); and 4) Oil impact to the vegetation. Oil impact was determined by the following scale:

(a) 0 (No Impact) - Vegetation having a natural appearance; stem and leaf chlorosis not exceeding a slight mottling or occasional yellowing; no oil evident in plot.

(b) 0.5 (Trace Impact) - Vegetation having an intense speckled chlorosis; no oil evident in plot.

(c) 1.0 (Light Impact) - Vegetation green but with considerable chlorosis (50% or less of the plant chlorotic); oil present on plant stems but occurrence on ground variable.

(d) 2.0 (Medium Impact) - Vegetation having more than 50% yellowing of leaves and stems; oil present on plant stems and ground.

(e) 3.0 (Heavy Impact) - Vegetation dead; oil present on plant stems and ground.

(f) 3.0G - Same as 3.0 but with subsequent new growth which occurred since the oil spill.

Percentage vegetative cover (the percentage of the area of ground covered by vegetation) was determined visually by the Braun-Blanquet (1932) method with 5% cover intervals. Two other parameters were mathematically derived from the field collected data: (1) Adjusted live percentage cover = live percentage cover x (100% cover ÷ % total cover) and (2) Adjusted dead percentage cover = dead percentage cover x (100% cover ÷ % total cover). These parameters normalized the live percentage cover and the dead percentage cover to values based on 100% total cover of the plot. This adjustment was necessary in order to make valid comparisons of the live or dead percentage covers of plots having unequal total percent covers. The assumption was made that the proportion of live to dead percentage cover of a plot was relatively constant regardless of the absolute total percentage cover.

In addition to the vegetation analysis, soil samples of the surface 10 cm were collected for petroleum hydrocarbon analyses from all plots in 1989. A subsample of five of these soil samples, ranging in initial oil impact from heavily oiled to control, were analyzed by Dr. Jay Means of the Department of Environmental Sciences, LSU.

Photosynthetic Response of Recolonizing Vegetation

In August 1990 plant photosynthetic response was measured in 24 selected permanent plots in order to determine if any subtle effect of the oil was still present. The criteria for plot selection was that both Spartina patens and Spartina alterniflora be present, and that percentage cover by these two species be at least 10% for Spartina patens and 5% for Spartina alterniflora. Pairs of oiled and control plots were then established such that percentage covers were similar within a pair. From this set, 12 pairs of oiled (ten plots with initial oil impact rating of 3 and two plots with an initial rating of 2) and control plots (all with initial oil impact rating of 0) were randomly selected. Plant photosynthetic response (net CO_2 exchange rate) was measured on leaves of Spartina patens and Spartina alterniflora in each plot using a portable infrared gas analyzer (Analytical Development Company, Herts, England; model LCA-2). Sampling of control and oiled plots was alternated every two plots to reduce the possibility of any diurnal fluctuations in photosynthesis from interfering with treatment responses. Soil cores were also collected at each plot and preserved under an anaerobic atmosphere (N_2 gas) for sulfide, pH, and salinity analysis. Redox potential (Eh) was measured at the marsh surface and at 15cm depth using brightened platinum electrodes and adjusted for the potential of the calomel reference electrode. Vegetative cover by species was also measured as described above.

Transplant Study

In July 1991, 30 experimental transplant plots of Spartina alterniflora were established in two dieback areas of the oil impacted marsh to determine if the failure of certain areas to revegetate was due to a residual oil effect, or due to increased water depth inhibiting successful seedling establishment. One of these sites (site 1) had experienced marsh dieback from the oil spill, but was not mechanically impacted by the cleanup effort. The other site (site 2) was within 50 m of the pipeline break, and as a result was subjected to heavy mechanical impact from marsh buggies during the cleanup effort in addition to being impacted by the oil. This site was essentially devoid of vegetation immediately following the spill and cleanup.

At each site elevation differences between the bare mud surface and the adjacent vegetated marsh surface were determined. At site 1 the unvegetated mud surface averaged 10 cm lower than the vegetated marsh surface. At site 2 this elevation difference was 15 cm. Plastic collars (29 cm diameter) were constructed for each site such that when inserted into the sediment to a depth of 5 cm, the height of the top of the collar was equal to the elevation of the adjacent vegetated marsh surface. Control collars were also constructed that were 5 cm in height, so as to be at the ambient elevation of the unvegetated marsh surface once inserted into the sediment. All collars had 1 cm diameter drainage/water exchange holes drilled in the side walls at 15 cm spacings within rows, and at 3.8 cm spacings between rows.

Five replicates of the following three treatment combinations were randomly established at each site: Elevated Control - elevated collar filled with sediment from a non-oiled, control marsh; Elevated Oiled - elevated collar filled with sediment from the oil impacted site; Ambient Oiled - ambient elevation collar filled with sediment from the oil impacted site. Each plot (collar) was planted with three Spartina alterniflora transplants that were obtained from a Louisiana supplier.

The transplant experiment was established in July 1991, checked in September 1991 to ensure that we had good survival in the elevated control plots, and harvested in December 1992. Prior to harvesting the biomass, soil cores were collected from each plot and preserved under an anaerobic atmosphere (N_2 gas) for sulfide, pH, and salinity analysis. Redox potential (Eh) was measured at the marsh surface (2 cm) and at 15 cm depth as described above. Biomass was harvested by excavating around each collar and then carefully lifting the intact experimental units (intact sods with shoots and attached roots) from the marsh and placing them in large plastic bags for transport back to the laboratory where they were refrigerated until processed. Each sod was rinsed with tap water over a mesh screen to remove soil from the roots and to rinse the shoots. Sods were then separated into belowground and aboveground (live and dead) components and the number of live and dead stems recorded. Biomass was oven-dried at 65° C for three days until constant weight was achieved and weighed.

Statistical Analyses

All data were analyzed with SAS (Statistical Analysis System Institute, Inc. 1982) analysis of variance (ANOVA) procedure. Significant differences are reported at the 0.05 probability level unless otherwise stated.

The permanent plot data was analyzed as a split plot design with marsh area (i.e., oil-impacted, intermediate, or control marsh) serving as the main plots. Marsh main plot effects were tested with the transect within marsh mean square for the error term. The sub plot effect of year, as well as the interaction of marsh x year were tested with the residual mean square. Duncan's multiple range tests were used to aid in showing where significant differences occurred. Specific single-degree-of-freedom contrasts were also used to give higher resolution of specific transect and marsh effects. The error terms used in these specific comparisons and contrasts were the same as in the respective ANOVA's.

The ANOVA of the photosynthetic response data was performed both as a two by two factorial (oiled or control plots and Spartina patens or Spartina alterniflora) and also as a completely randomized design of two treatments (oiled or control plots) analyzed for each species separately.

Analysis of the transplant study data used ANOVA of a randomized block design of three treatments. The two marsh sites that failed to revegetate served as blocks (to remove variation between sites) and each contained five randomly established replicates of the three treatments (elevated control, elevated oiled, and ambient oiled).

PHOTOINTERPRETIVE ANALYSES

A national search of available historical imagery of the study area was conducted by Aero-Data Corporation (ADC), Baton Rouge, Louisiana. Twenty-nine (29) individual dates of historic and recent (new) imagery were located. Table 1 describes the summary of accessible and useful imagery (i.e., dates, scale, source, etc.). The initial goal was to acquire imagery of the study area that could be mapped for 8 -10 year intervals. Unique events, such as very rapid rates of land loss, could then be singled out and added to the digital map data base. Upon acquisition and visual assessment of the available imagery, eight (8) dates were selected for mapping and analysis (Table 1). However, not all dates of historical imagery listed were accessible from the U.S. Army Corps of Engineers photographic archives in New Orleans, Louisiana and additional dates were located within NOAA/NOS.

Table 1. Available, appropriate historical and recent aerial photography acquired for this project.

	Photo Date	Photo Scale	Photo Type	Photo Source	Selected[1]
1)	12/7/50	20,000	B&W	COE	Yes
2)	3/22/60	20,000	B&W	COE	Yes
3)	10/18/69	20,000	B&W	COE	No
4)	11/30/70	40,000	B&W	NOS	Yes
5)	3/17/72	121,031	CIR	NASAJS	No
6)	10/17/74	118,000	CIR	NASAJS	No
7)	10/15/78	64,375	CIR	EROS	Yes
8)	1/24/82	36,000	Color	NOS	Yes
9)	6/13/85	12,000	CIR	Aero-Data	Yes
10)	12/6/85	64,500	CIR	EROS	No
11)	10/15/86	12,000	CIR	Aero-Data	Yes
12)	1/17/89	65,000	CIR	EROS	No
13)	6/24/90	12,000	Color	Aero-Data	Yes
14)	10/20/90	12,000	CIR	Aero-Data	No

[1] Aerial photography has been photointerpreted, maps constructed, and area measurements determined for the dates indicated with a 'yes'.

The photographic mapping procedure was as follows:

The first step was to produce scaled and cropped 16" x 20" stereo graphic pairs for each selected date. A suitable scale was selected which enabled the full study area to be covered by a single 16" x 20" print. No attempt was made to round this off to an even number scale, as this would have caused the print to cover a larger area than necessary and would have reduced the scale of the prints and mapping accuracy.

A standard work print was produced from the 12/6/85 high altitude CIR photography, as this date was found to be the most distortion-free photograph of those in the date sequence. This date, thereby, was used as the baseline data set to register and map all other data sets. In the darkroom, the prints for all other dates were scaled, cropped, and leveled to produce the best possible match with the work print. All stereo pairs were produced in this manner.

Mapping began by generating a baseline control map from the 12/6/85 photography. A clear overlay was placed over one of the stereo pairs and using a stereoscope, each polygon was interpreted and traced using a colored Pilot permanent SC-UF pen. Particular attention was given to the shoreline details. Appropriate control points and a coordinate system were next added to the overlay by transferring to the overlay photoidentifiable points from the USGS quadrangle sheet (scale = 1:24,000) of the area.

The overlay was next placed on a digitizing tablet where registration points were entered into the AutoCad map file. The overlay information was digitized and a clear plot was generated on 5 mil mylar film. The overlay was then placed back on the print and edited. The final edited 1985 overlay was then used as the control overlay for all other dates as they were interpreted. In this way, the interpretations for all dates were kept within an accurate geographic registration system. As a result of this control system, later change detection calculations will reflect actual spatial changes taking place within the study area rather than changes caused by miss-registration of small polygons.

The first comparative date to be interpreted and mapped in detail was the Aero-Data flight of 6/13/85. The 1985 baseline overlay with its features was registered to the much higher resolution CIR print showing the site two weeks after the spill. Each mapped polygon was then traced on the overlay with the aid of a stereoscope.

The overlay was then placed on a digitizing tablet and digitally registered. Each polygon was then digitized and color coded to show the the type of mapping category. Each mapping category was assigned a separate data layer and color for each date. The coordinate grid and title block was common for all dates interpreted.

The mapping categories utilized are as follows:

Mapping Category	Color	Description
Baywater	blue	Open water connected to the bay
Canwater	blue/hatched	Water from canal dredging or associated erosion
Intwater	brown	Interior water bodies in the marsh
Veg	green	Marsh with 50% or greater vegetation cover
Spoilbank	red/hatched	Areas where spoil was placed
Levee	red	Areas where the levee was located

If a canal widened into an interior water body, the interior water remained classified as interior water.

The information digitized was next plotted at the same scale as the photograph, placed on the photograph, and edited. After all corrections were made, the plot was produced once again, this time at the precise scale of the next date in the photointerpretation sequence.

The detailed and edited 6/13/85 interpretation overlay had many details that precisely matched the features seen in the next date further in the past (1/24/82). This allowed for accurate registration of the control overlay (1985) to the 1982 stereo prints. Interpreters could then identify and reinterpret the polygons that had changed, appeared or disappeared between the two dates. Once interpretation was completed for a specific date, the information was digitized, plotted, and edited. In editing, both dates were reviewed to assure that mapping was consistent through all dates and that depicted changes were supported by the photography. Close attention was also placed in the association of visible changes with logical sequences of marsh processes.

In the same manner described above, all dates were interpreted, mapped, and registered to one another both prior to and after the starting date of 6/13/85. This was accomplished by using the previously interpreted and plotted overlay for each date as control. It was necessary to reinterpret and digitize the dates previously studied in the original or initial oil spill study, because earlier interpretations did not match the mapping accuracy obtainable with these methods.

For each selected date (see Table 1), the photointerpreted maps were divided into three sections: (1) the south control marsh, (2) the oiled marsh and (3) the north control marsh (note that the marsh areas designated as 'control marshes' for the historical land loss analyses are equivalent to the marsh areas designated as 'intermediate marshes' used for the ground truth measurements of recovery). For each of these sections, we calculated the (1) total area for each category of landcover classification (bay water, canal water, interior water, levees, spoil banks and vegetated marsh), (2) areas of marsh gain from each category of landcover and (3) areas of marsh loss to each category of landcover. Marsh gain calculations indicate the type of classification that the marsh replaced. Marsh loss calculations indicate the type of category that replaced the marsh. With total areas, gain and loss for the eight dates of photography, this resulted in 22 possible measurements by 3 sections for a total of 66 calculations of area and change. Based on visual inspection of the vector data, a raster cell resolution of 3 meters on a cell side was determined optimum for analysis. Vector data was converted to raster format and then translated for input into the geographic information system (GIS) for conducting the analysis. Slight irregularities in vector data resulted in errors in the resulting raster data. However, the errors were evenly distributed and occurred in less than 0.5% of the data, so they are not considered to significantly bias the results.

RESULTS

FIELD ACQUIRED ANALYSES

Vegetation and Soil Assessment

Data for the 1985 and 1989 plant cover categories and oil impact index are summarized in Table 2 by marsh area. Significant year differences ($P<.05$) were detected for total plant cover (live plus dead percentage cover), adjusted live percentage cover, adjusted dead percentage cover, and oil impact index (Table 2). In general, these significant year effects can be attributed to increases in total and adjusted live percentage cover (Figures 2 and 3) and decreases in adjusted dead percentage cover and oil impact index from 1985 to 1989 (Figures 4 and 5; Table 2). It is important to note that in 1989 there were no longer any significant main effects due to marsh area, whereas the 1985 data consistently showed an oil effect and reduction in plant cover in the impacted area compared to the intermediate and control areas (Table 2; Figures 3 and 5). In 1989 there were no longer any visual signs of oil on the vegetation or the marsh surface (Figure 5).

Although the impacted area doubled in total percentage cover from 1985 to 1989, the other areas also showed an increase in total percentage cover (Table 2; Figure 2). This increase in total percentage cover in the intermediate and control areas may be a seasonal effect, since the 1985 data were collected earlier in the growing season (July) than the 1989 data, which were collected at the end of the growing season (November) when total cover would be expected to be near the yearly maximum.

Despite the lack of a significant main effect due to marsh area in the 1989 data, a priori single-degree-of-freedom contrasts that compared the impacted area to the intermediate and control areas still showed a significant reduction in total and live percentage cover, but not adjusted live percentage cover in the impacted area. This is interpreted to mean that although the impacted area had not attained as high a percentage of total plant cover as the other areas, the proportion of live healthy vegetation in the impacted area was comparable to the other areas, and is indicative of recovery. The recovery of the vegetation in the impacted area is more clearly evident from the increase in adjusted live percentage cover (Figure 3) and decrease in adjusted dead percentage cover in the impacted

Table 2. Total percentage cover (TPC), adjusted live percentage cover (ALPC), adjusted dead percentage cover (ADPC), and oil impact index (OII) by marsh area for 1985 and 1989.

		Variable							
		TPC		ALPC		ADPC		OII	
Marsh Area	n	1985	1989	1985	1989	1985	1989	1985	1989
North Control	10	53 ab[1]	82 a	63 a	84 a	37 b	16 a	0.00 b	0.00 a
North Intermediate	10	53 ab	90 a	83 a	85 a	17 b	15 a	0.00 b	0.00 a
Impacted	28	32 c	64 a	28 b	80 a	72 a	16 a	2.27 a	0.00 a
South Intermediate	10	61 a	84 a	77 a	83 a	23 b	17 a	0.05 b	0.00 a
South Control	10	40 bc	76 a	88 a	85 a	12 b	15 a	0.10 b	0.00 a

[1] Column means followed by the same letter are not significantly different (P>0.05) based on a Duncan's Multiple Range Test.

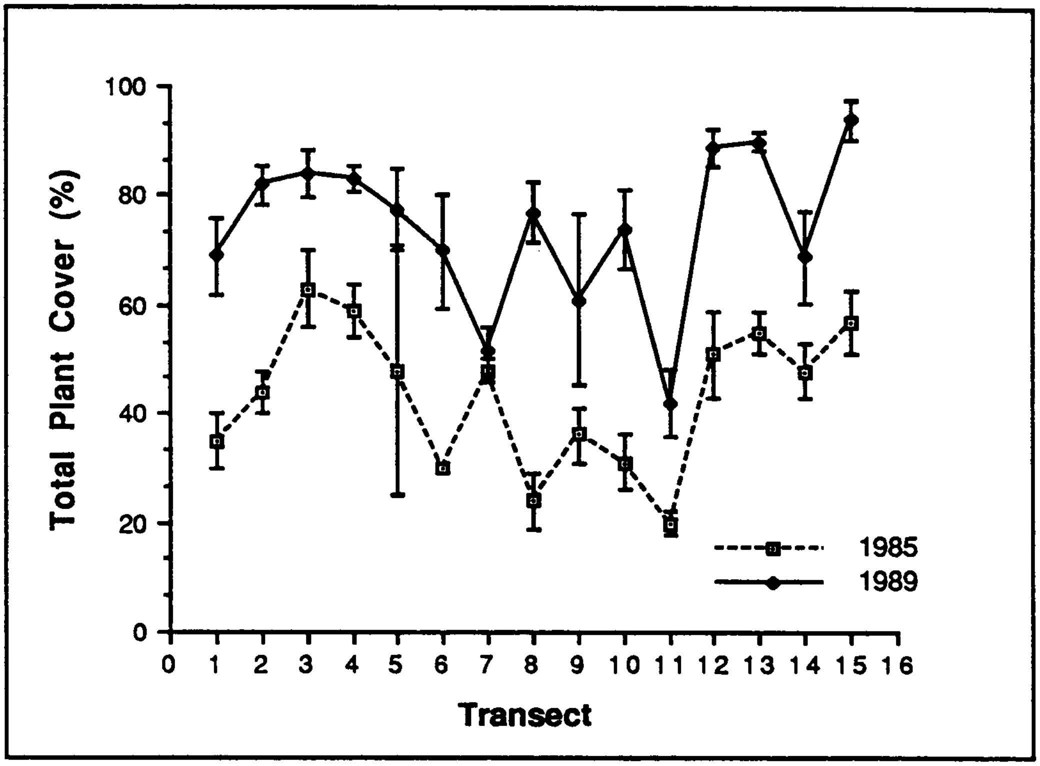

Figure 2. Total plant cover (live cover plus dead cover) by transect for the 1985 and 1989 sampling dates.

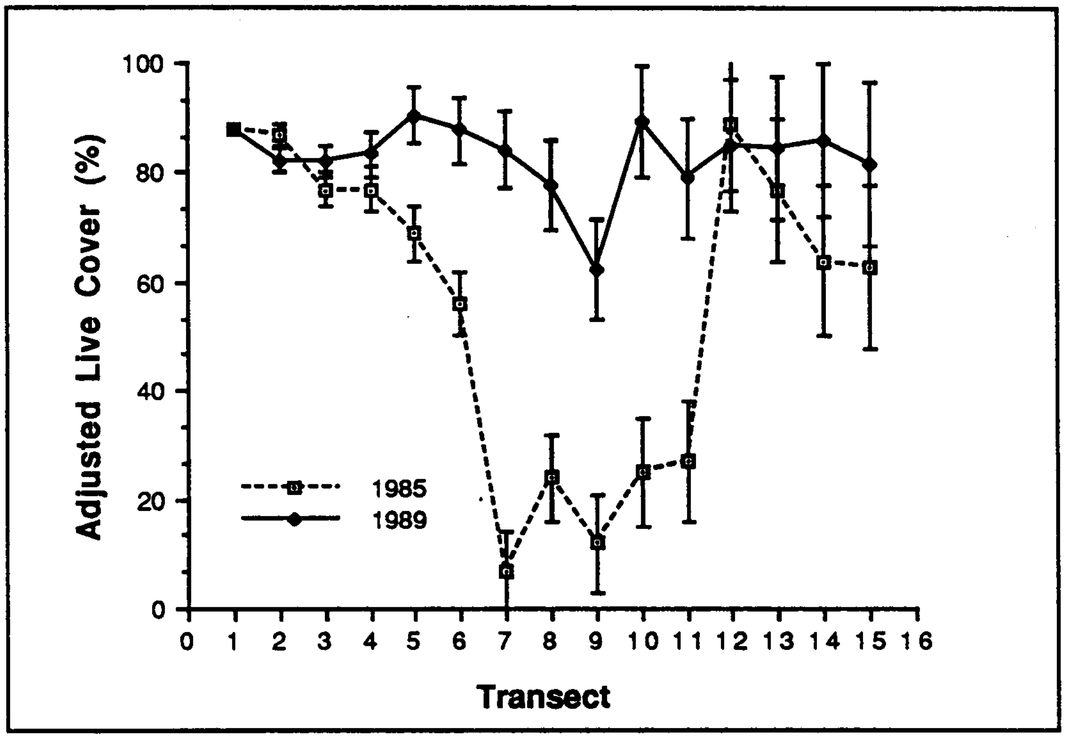

Figure 3. Adjusted live plant cover (100% x live cover/total cover) by transect for the 1985 and 1989 sampling dates.

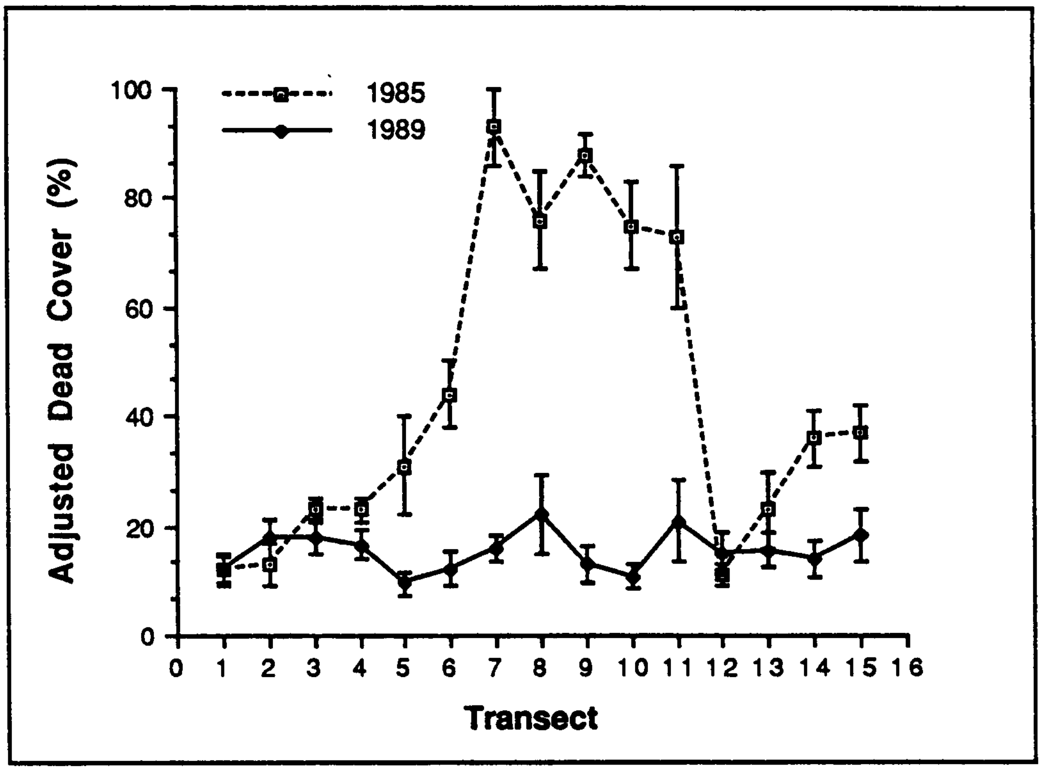

Figure 4. Adjusted dead plant cover (100% x dead cover/total cover) by transect for the 1985 and 1989 sampling dates.

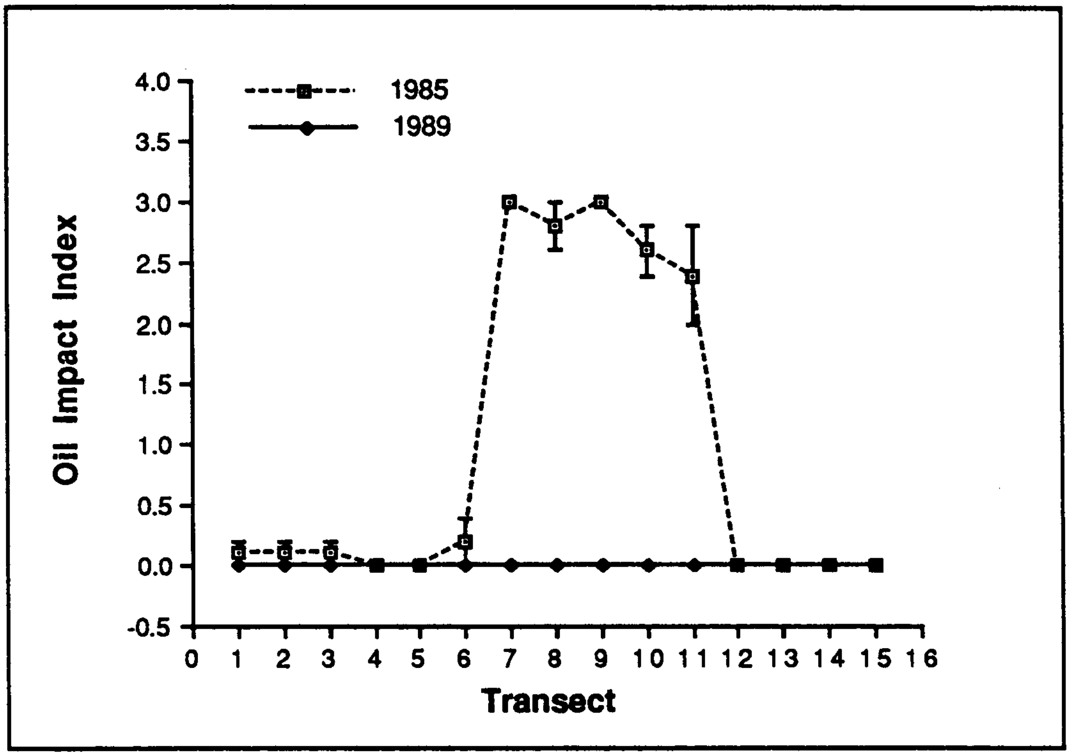

Figure 5. Oil impact index by transect for the 1985 and 1989 sampling dates.

area (Figure 4) between 1985 and 1989, while the other areas did not show an appreciable change in these variables. Highly significant ($P<.01$) area by year interactions for these two variables support this statement.

Transect 7 was located closest to the spill, and as a result, sampling stations a and b on this transect were heavily impacted by machinery during the cleanup activities. From Figure 2 it can be seen that transect 7 showed a negligible increase in total cover four years after the spill, although adjusted live cover did show recovery in 1989 (Figure 3).

Overall trends in species cover values in 1989 were similar to those in 1985 (Figure 6). The same three species (Spartina alterniflora, Spartina patens, and Distichlis spicata) were present in the plots, but Spartina alterniflora displayed the greatest increase in live adjusted percent cover in the 1989 impacted area transects (transects 5-11; Figure 6). Spartina patens and Distichlis spicata also showed some increase in live adjusted percent cover in the 1989 impacted area transects (Figure 6).

Hydrocarbon analysis of the subsample of soil cores collected in November 1989 showed that of the three cores collected from oil-impacted plots, 11-C and 10-A had higher levels of total saturated hydrocarbons (134,000 to 160,000 ppb) than the control cores from 2-C and 14-C (20,000 to 42,000 ppb; Table 3). However, the total saturated hydrocarbons of 9-C (54,000), also an oil impacted plot, did not show as much of an increase over the control levels (Table 3). Interestingly, 9-C and 11-C both showed trace amounts of C1, C2, and C3-dibenzothiophene (characteristic substitution products of parent dibenzothiophene in weathered oil) whereas 14-C did not have detectable levels of these compounds despite the fact that it had the greatest total saturated hydrocarbon value.

Photosynthetic Response of Recolonizing Vegetation

Plant photosynthetic response (net CO_2 exchange rate) showed no significant differences between oiled and control plots for either Spartina alterniflora or Spartina patens (Figure 7). Unadjusted live percentage cover was significantly greater in the control plots (Figure 8). However, all other plant cover values (total cover, dead cover, adjusted live cover) were not significantly different between oiled and control plots (Figure 8). Similarly, there were no significant differences between plots in interstitial water pH, salinity, and sulfide, or soil Eh (Figure 9). Similarity of plant covers between oiled and control plots was desirable to ensure that our comparison of photosynthetic response was

Table 3. Total saturated hydrocarbons (11/89), initial plot oil impact index (7/85), and initial total and dead percentage vegetative cover (7/85) from a subsample of five representative plots.

Plot	Total Saturated Hydrocarbons (ppb)	Initial Oil Impact Index	Initial Total Vegetative Cover (%)	Initial Dead Vegetative Cover (%)
2-C	42,000	0.0	55	5
14-C	20,000	0.0	35	10
11-C	134,000	2.0	15	10
9-C	54,000	3.0	35	32
10-A	160,000	3.0	50	50

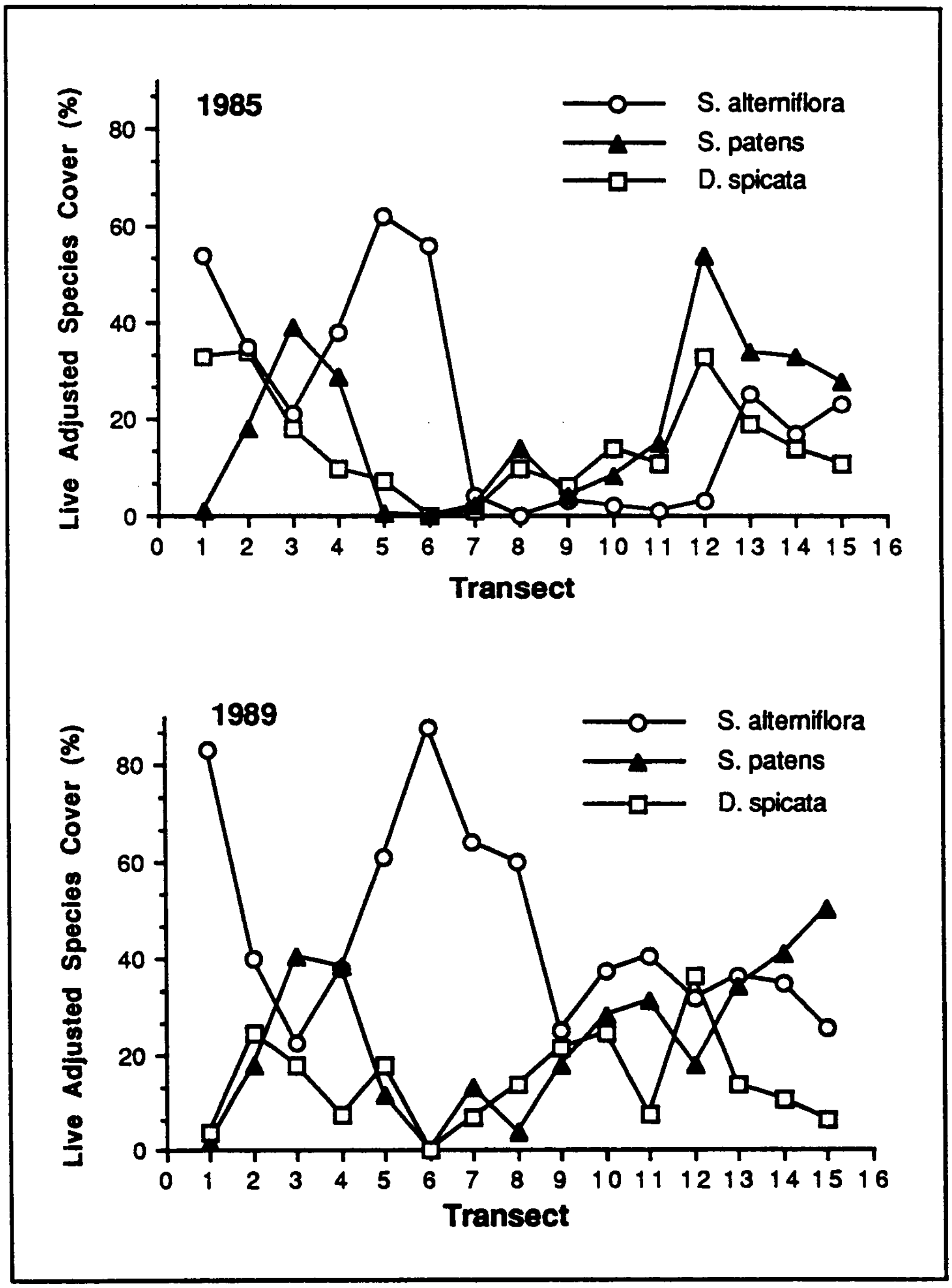

Figure 6. Live adjusted species cover by transect for the 1985 and 1989 sampling dates.

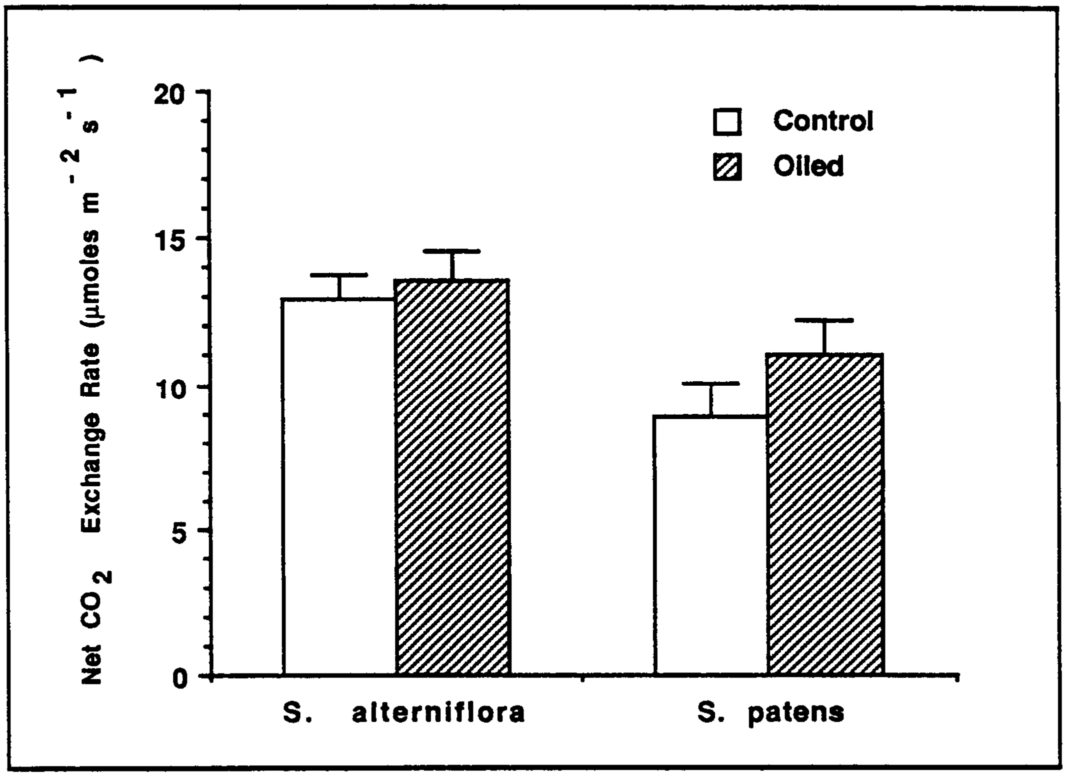

Figure 7. Plant photosynthetic response (mean net CO_2 exchange rate with standard error) of Spartina alterniflora and Spartina patens in control and oiled plots (August 1990; n = 12).

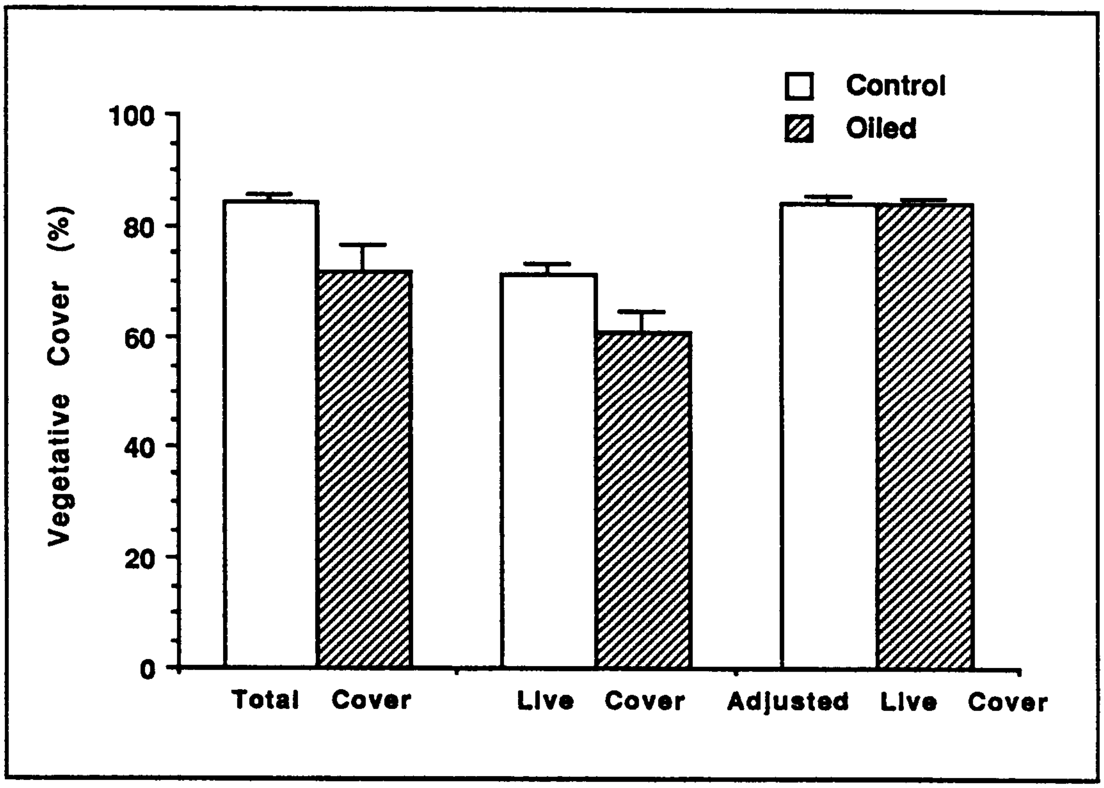

Figure 8. Total, live, and adjusted live vegetative cover (mean with standard error) in the control and oiled plots used in assessing plant photosynthetic response (August 1990; n = 12).

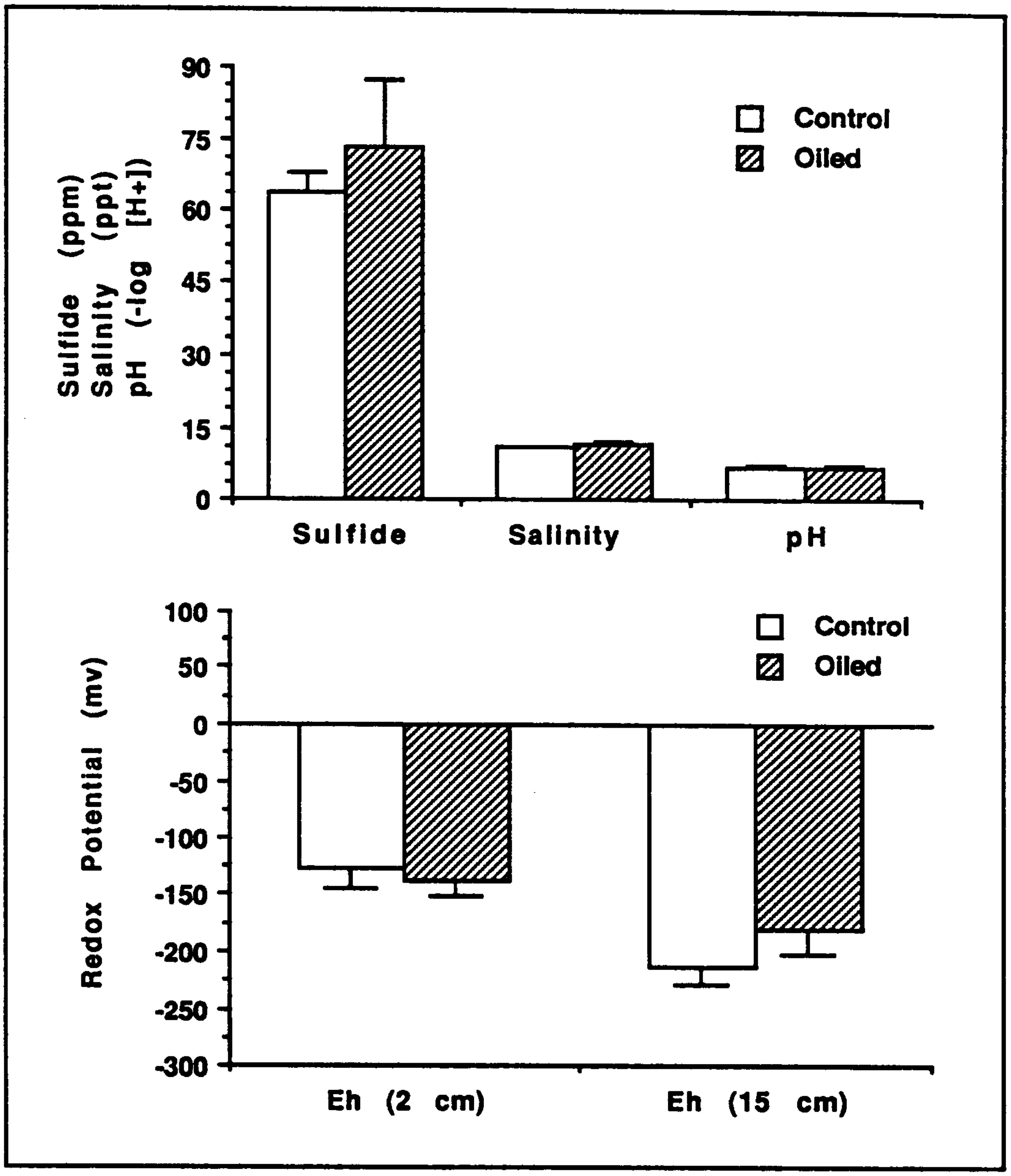

Figure 9. Interstitial water sulfide, salinity, and pH, and soil redox potential (mean with standard error) in the control and oiled plots used in assessing plant photosynthetic response (August 1990; n = 12).

not affected by differences in plot vegetation composition, and therefore was a valid test of any residual oil effect.

Transplant Study

The transplant experiment revealed that substrate elevation is a significant factor controlling the successful establishment of vegetation in these areas that failed to recolonized after the spill. Above- and belowground biomass, as well as numbers of living and total stems were significantly greater in the elevated plots compared to the ambient elevation plots, which averaged less than one live stem per plot (Figure 10). Elevated plots had significantly higher sediment surface redox potentials, and, hence, were less reduced than the ambient elevation plots (Figure 11). Redox potentials at the 15 cm depth did not differ significantly between treatments. Ambient elevation plots had significantly greater interstitial ammonium concentrations and at one site significantly greater concentrations of interstitial sulfides than the elevated plots (Figure 11). There were no treatment effects on pH. Salinities between treatments differed by less than one part per thousand. Importantly, there were no significant differences between the elevated control plots and the elevated oiled plots for any of the variables. Therefore, there does not appear to a residual oil effect that is preventing the successful recolonization of vegetation in these areas. Failure of these areas to successfully revegetate appears to be due to increased flooding stress.

PHOTOINTERPRETIVE ANALYSES

Marsh loss at the study site between 1950 and 1960 (Figure 12) was primarily caused by shoreline erosion, canal dredging and spoil deposition on the marsh, the latter two factors were dominant in the oiled marsh and the north control marsh (Figure 13). Between 1960 and 1970 land loss was relatively small (< 500 m^2 y^{-1}; Figure 12) as a result of the absence of new canal dredging and the paucity of interior marsh loss. The primary cause of the marsh loss was shoreline retreat during this period (Figure 13).

The period from 1970 to 1978 exhibited a general increase in marsh loss rate, especially for the oiled marsh and the north control marsh (Figure 12). The majority of this

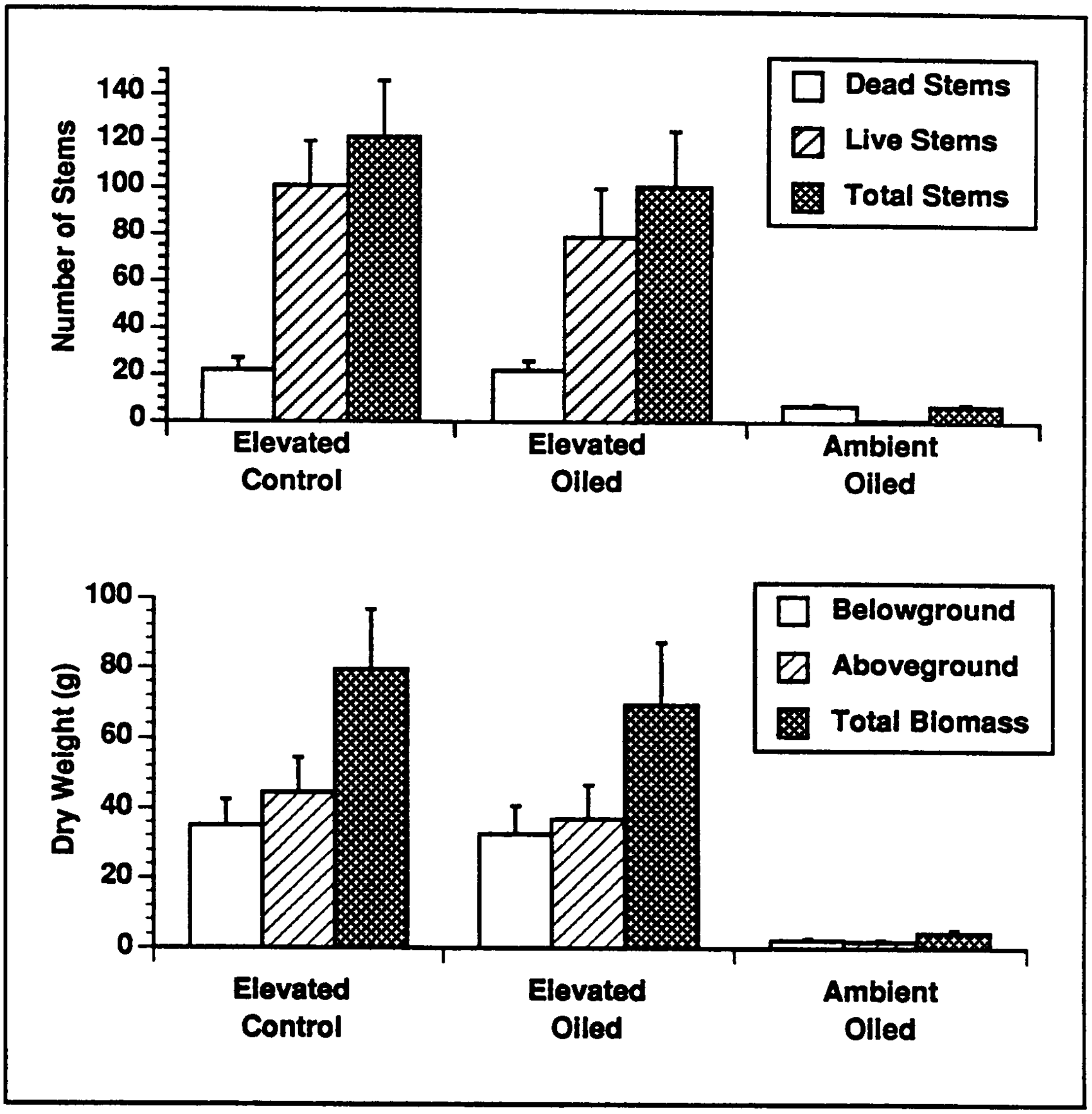

Figure 10. Number of dead, live, and total stems per plot (top panel) and belowground, aboveground, and total biomass per plot (bottom panel) from the Spartina alterniflora transplant experiment in two marsh areas that failed to revegetate following the oil spill. Elevated plots were elevated to the elevation of the adjacent vegetated marsh surface. Ambient plots were established at the elevation of the dieback sediment surface. Control plots had sediment that was not impacted by the spill, whereas oiled plots had sediment that was impacted with oil at the time of the spill. All values are means with standard errors (n=10).

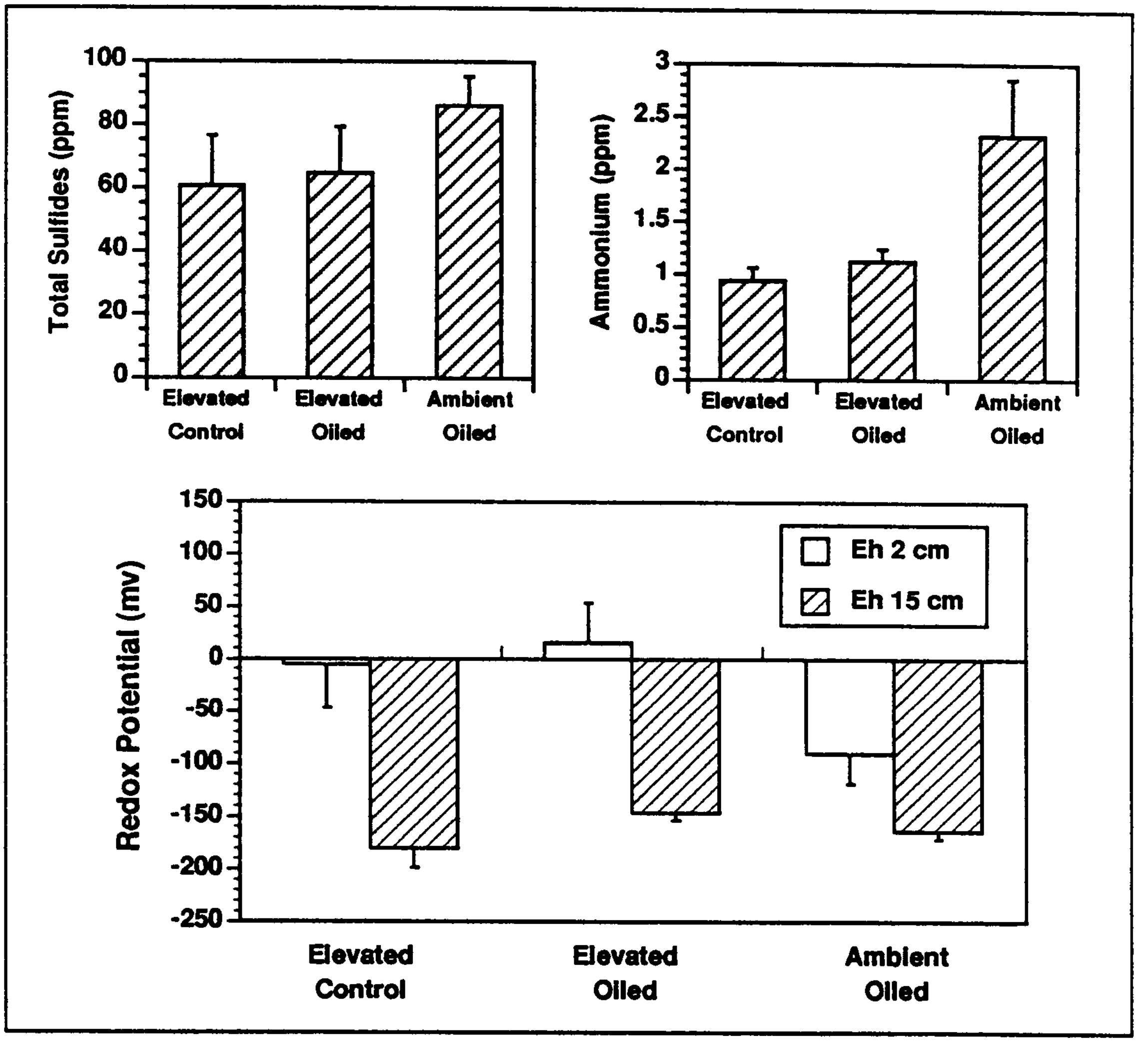

Figure 11. Interstitial water total sulfides and ammonium (top panels) and sediment redox potential (Eh) at two depths (bottom panel) from the Spartina alterniflora transplant experiment in two marsh areas that failed to revegetate following the oil spill. Elevated plots were elevated to the elevation of the adjacent vegetated marsh surface. Ambient plots were established at the elevation of the dieback sediment surface. Control plots had sediment that was not impacted by the spill, whereas oiled plots had sediment that was impacted with oil at the time of the spill. All values are means with standard errors (n=10).

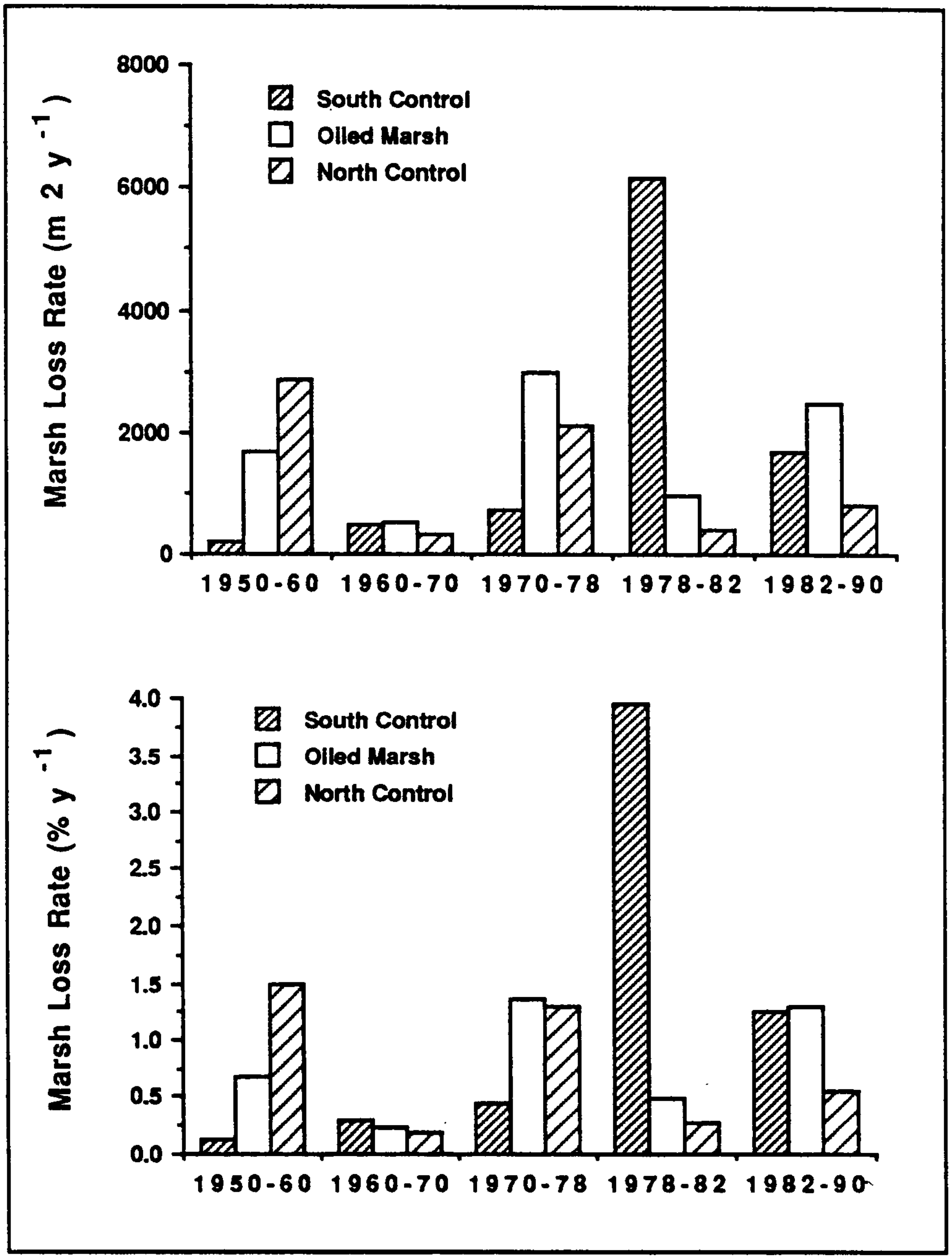

Figure 12. Marsh loss rates in m^2 y^{-1} (top panel) and % y^{-1} (bottom panel) for the south control, oiled, and north control marshes during the periods 1950-60, 1960-70, 1970-78, 1978-82, and 1982-90.

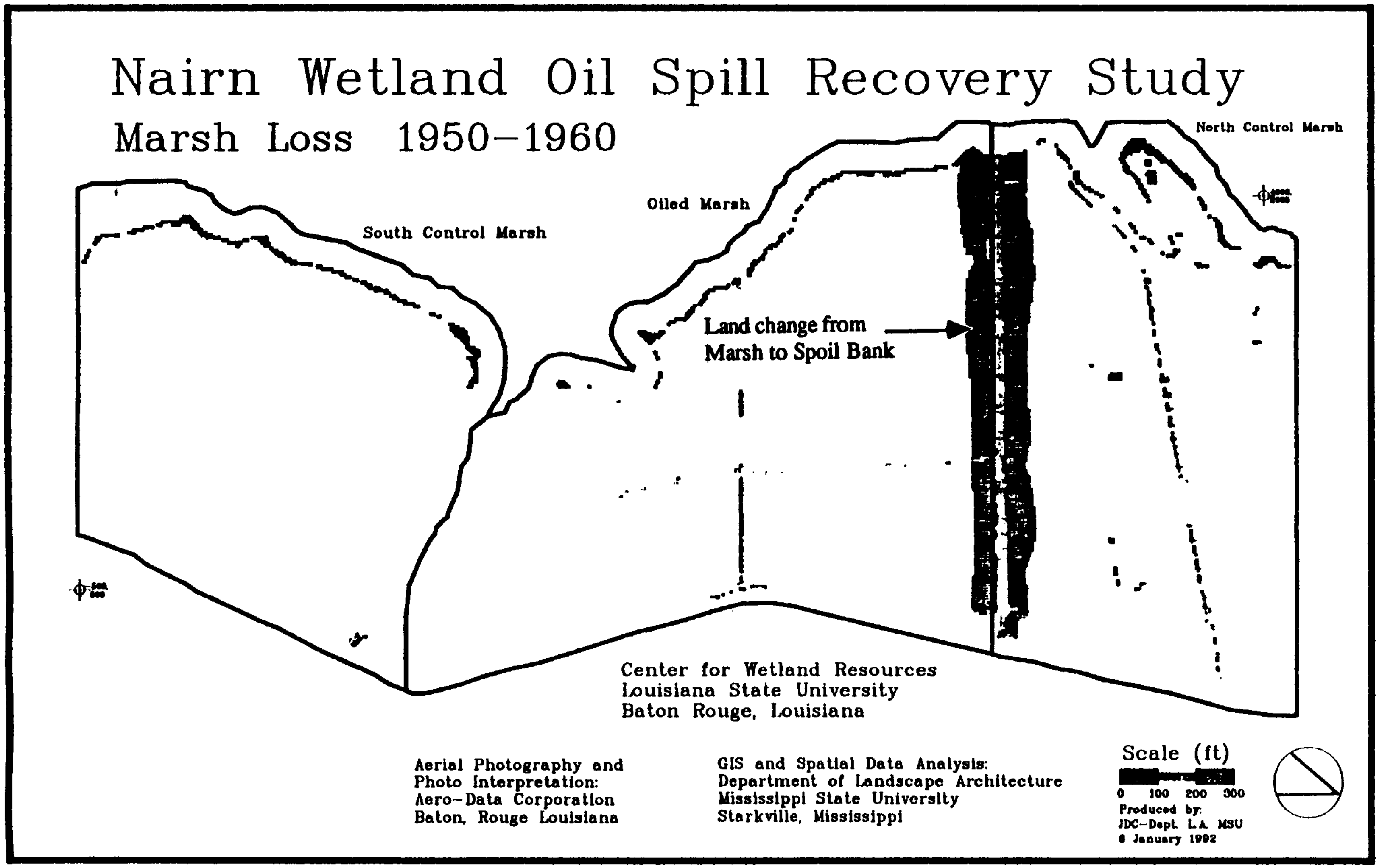

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90.

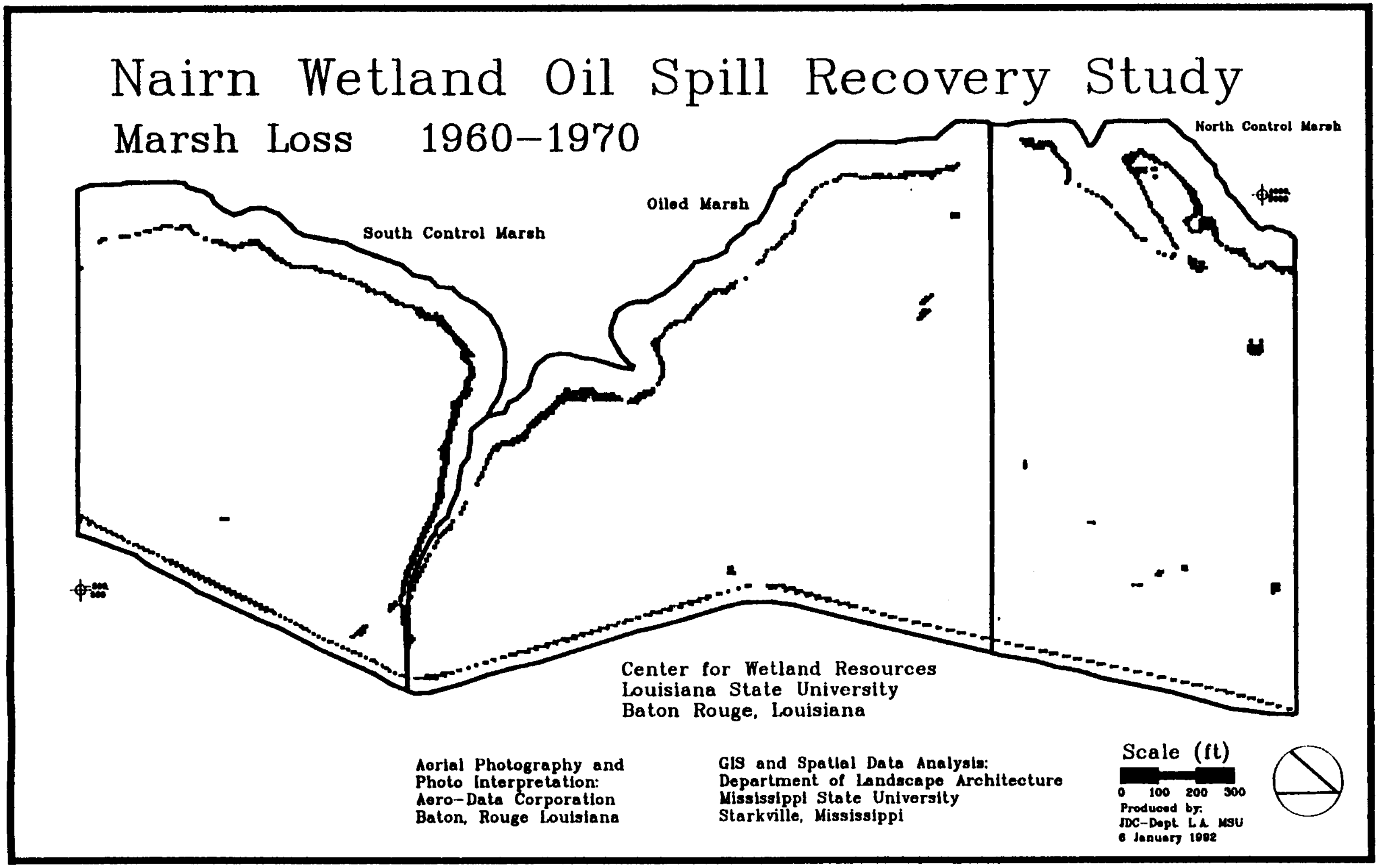

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

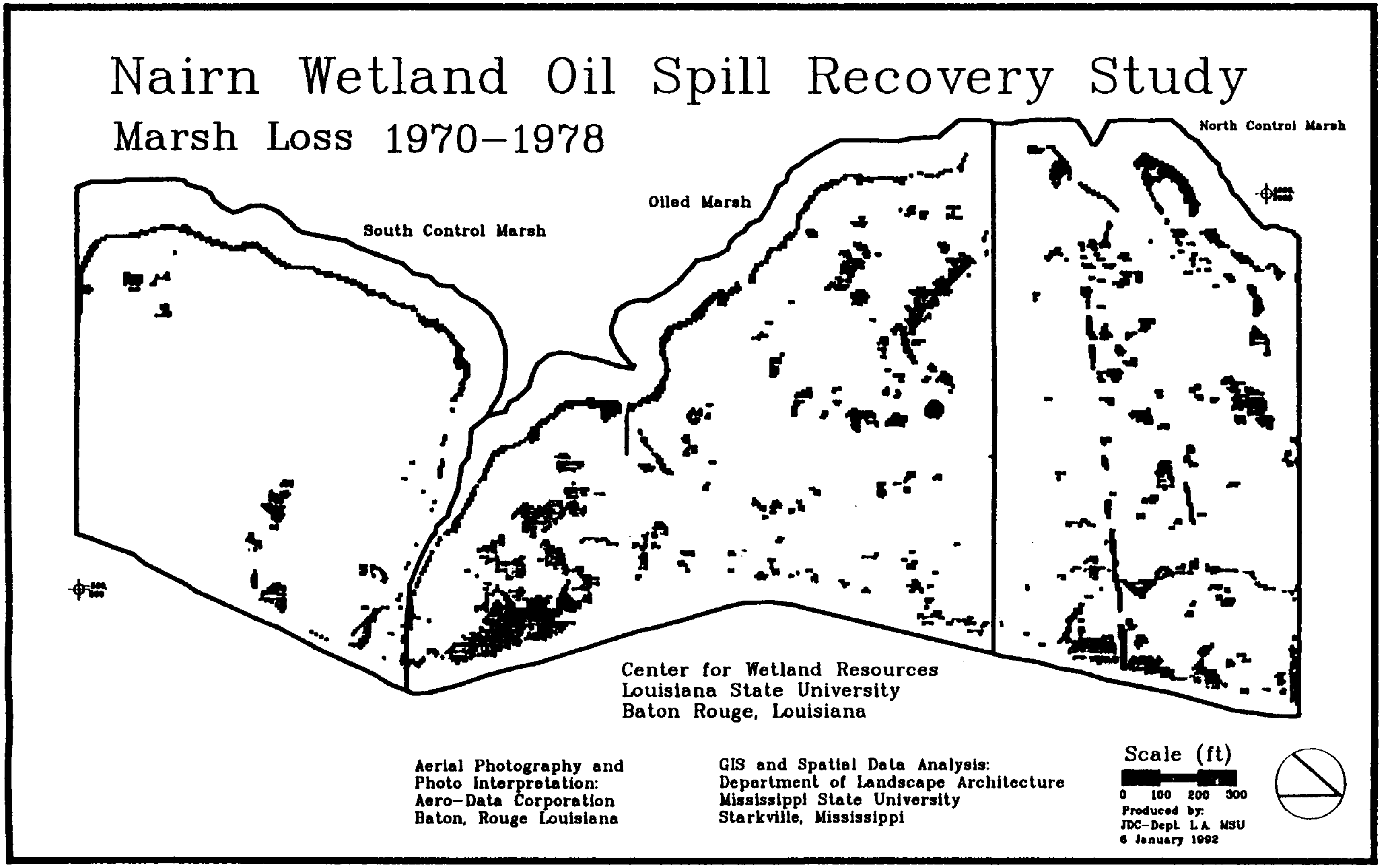

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

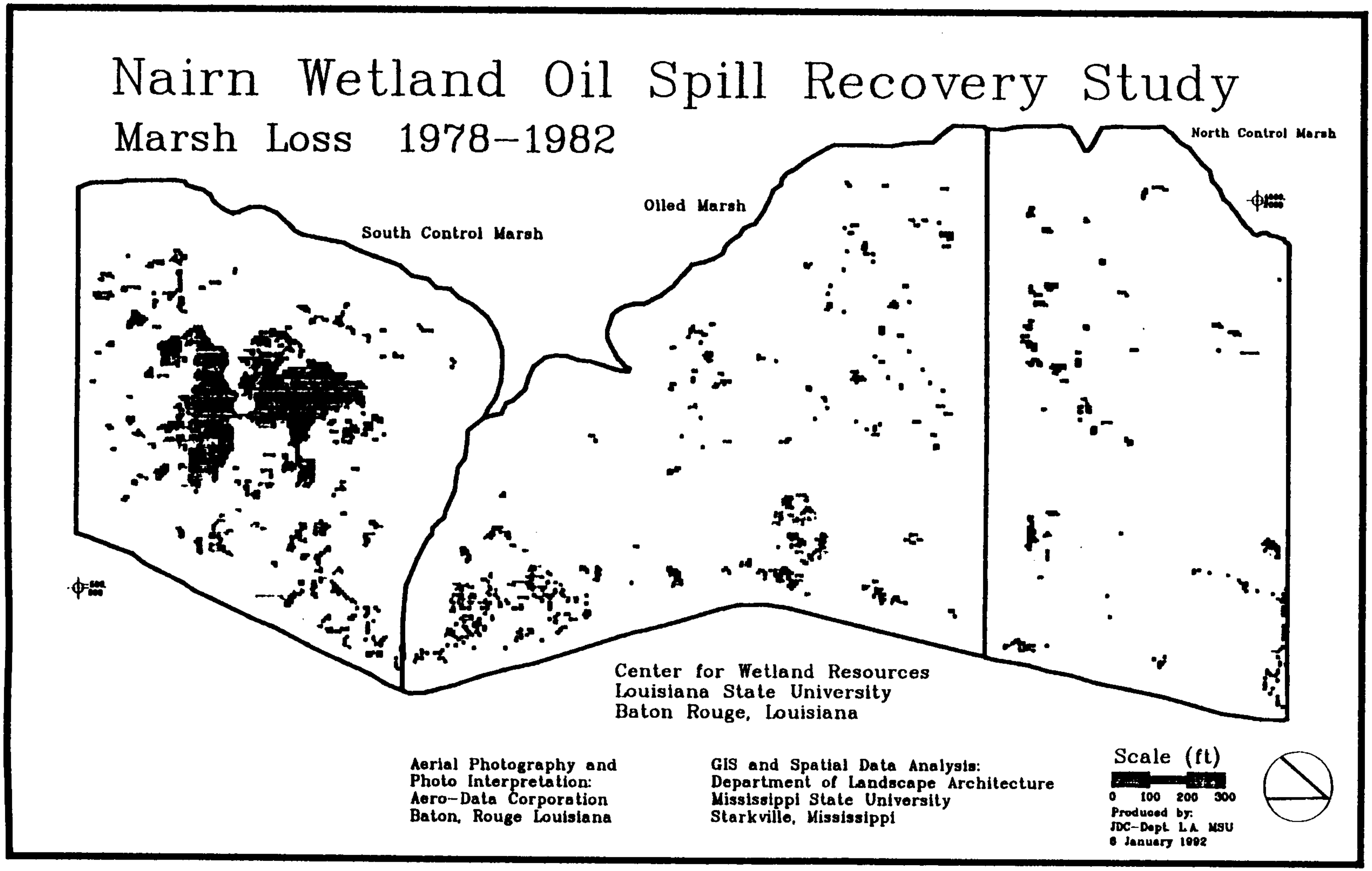

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

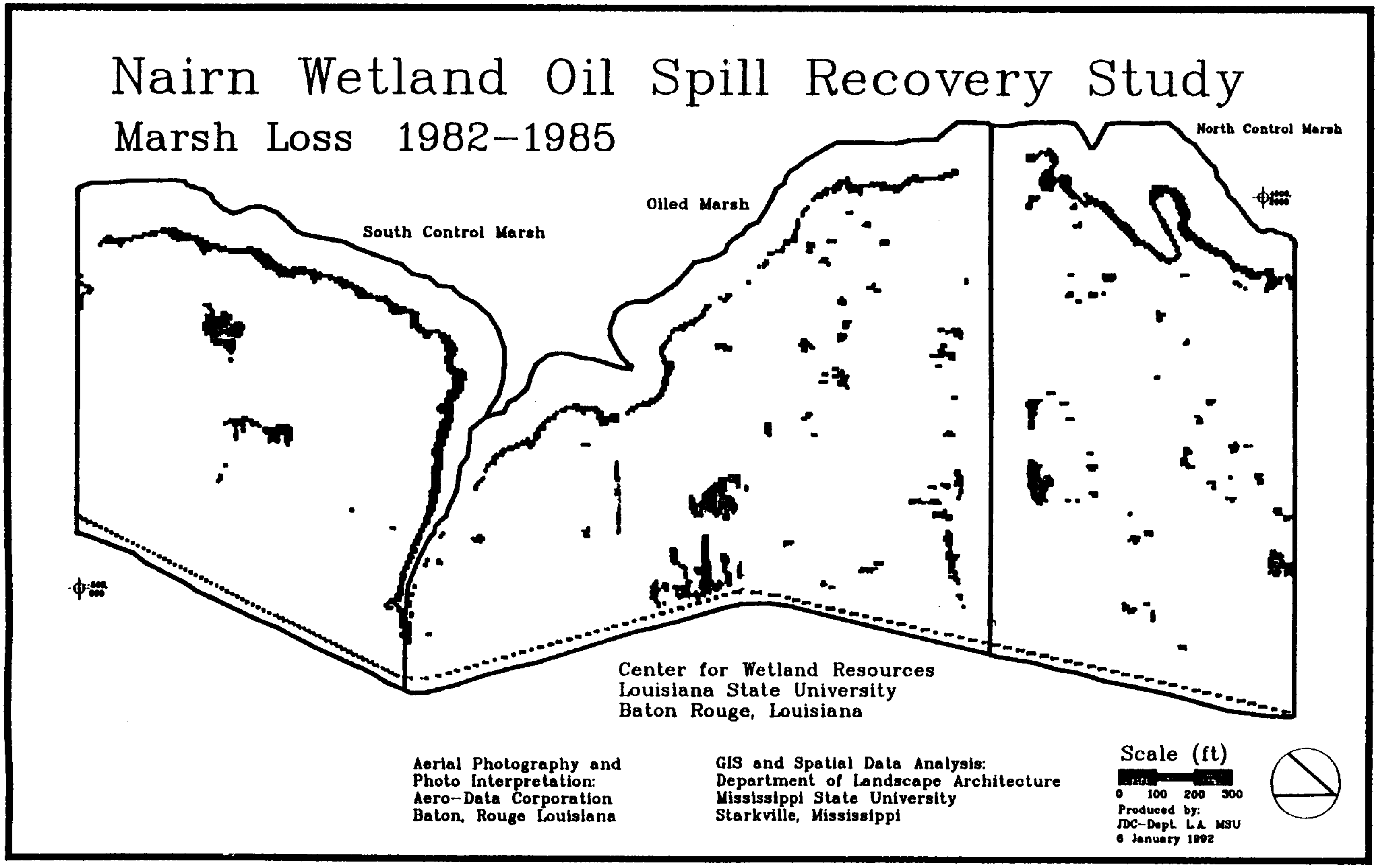

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

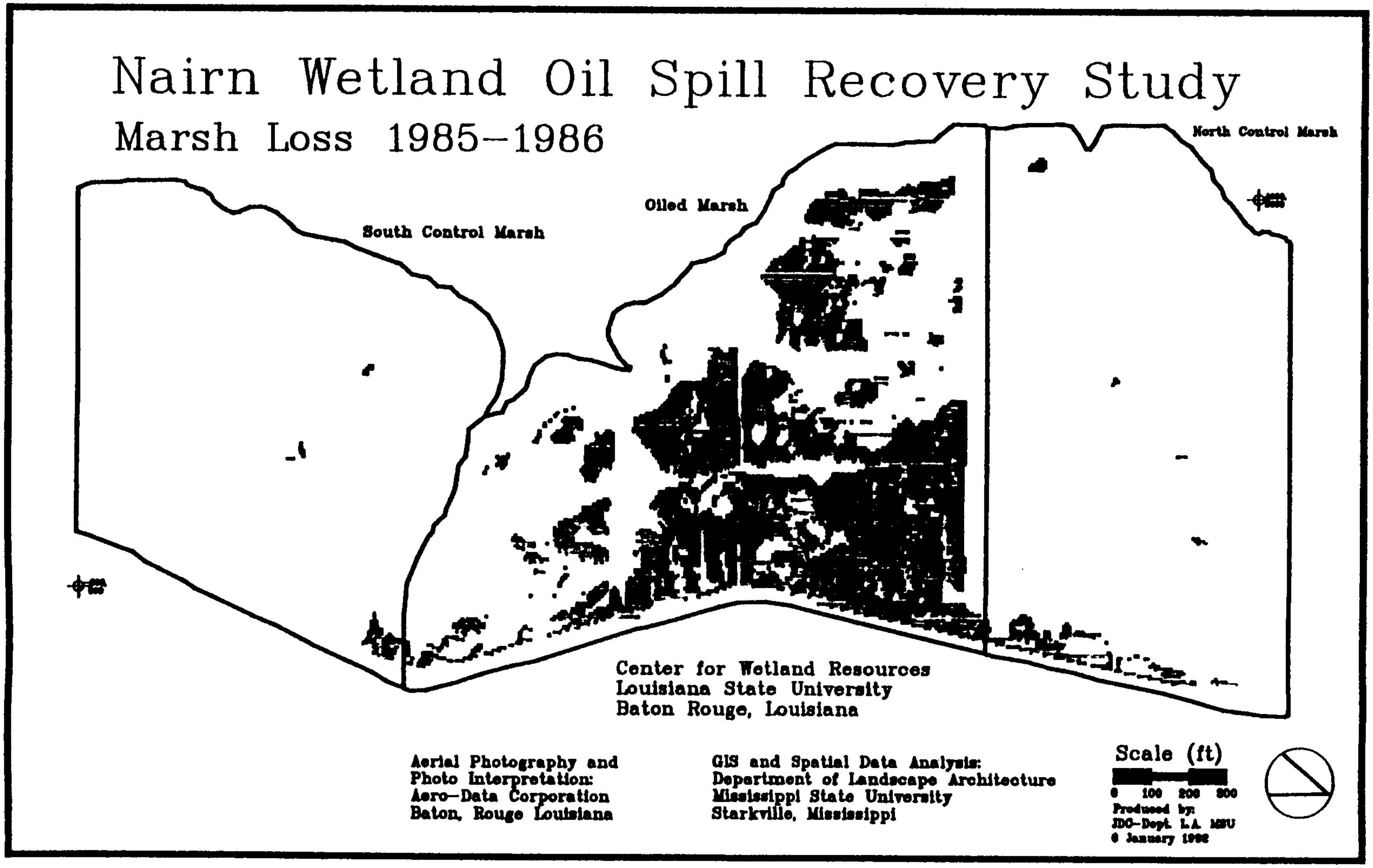

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

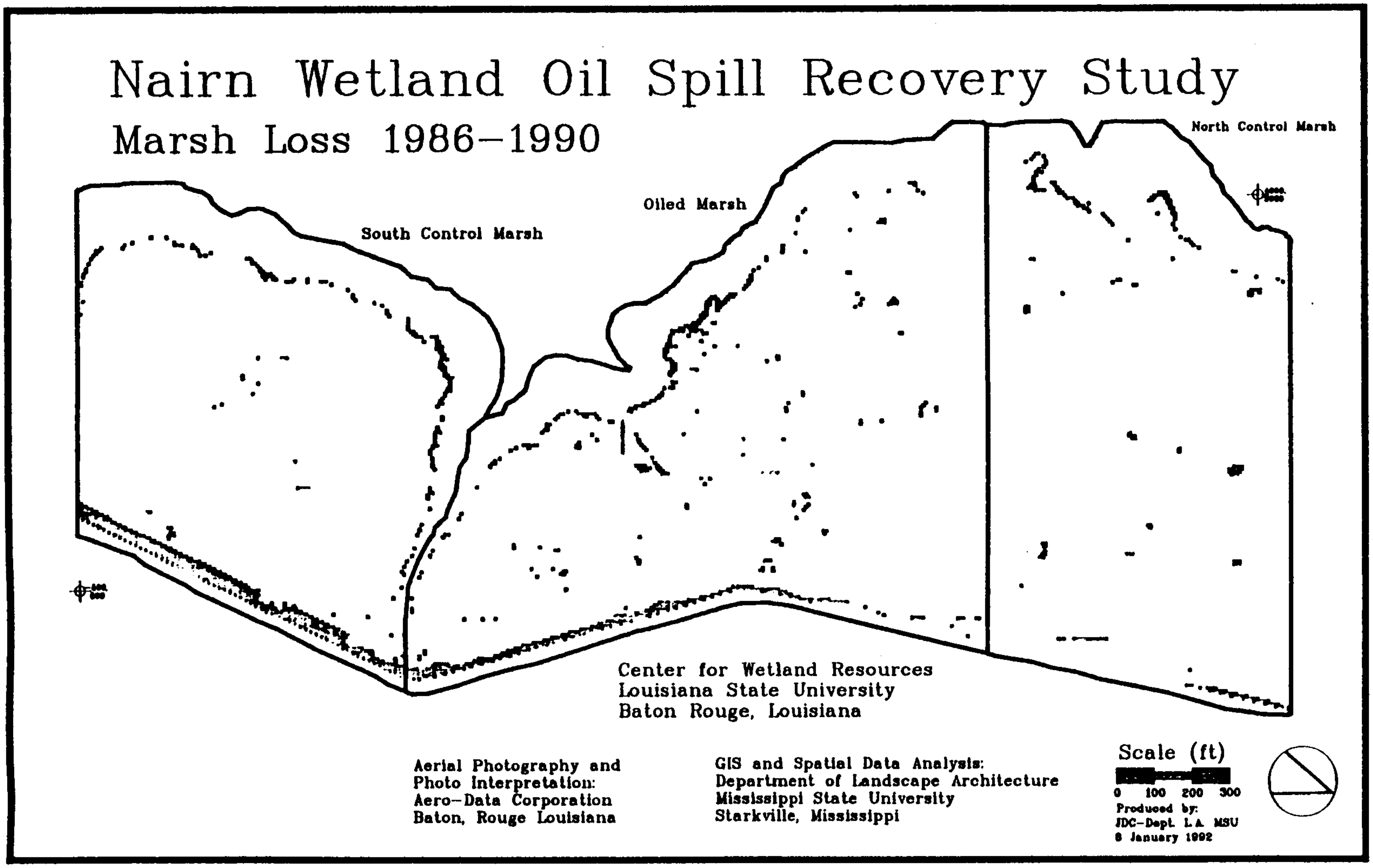

Figure 13. Photointerpreted maps indicating land cover class changes from marsh to water for the periods 1950-60, 1960-70, 1970-78, 1978-82, 1982-85, 1985-86, and 1986-90 (continued).

marsh loss was due to interior marsh degradation (Figure 13). Shoreline retreat contributed to marsh loss as in previous years. Shoreline erosion at the site was rather constant from 1950 to the present (1990), averaging approximately 15 m during the forty (40) year project period. The actual amount varies from area to area. Although the period from 1978 to 1982 exhibited relatively minor additional marsh loss in the oiled marsh and the north control marsh, the south control marsh experienced massive interior deterioration resulting in the highest annualized land loss rate of the study (Figures 12 and 13). The absence of measurable shoreline retreat during this period may have been an artifact of the aerial photography used for mapping since this was the only period that appeared to have no shoreline erosion.

Between 1982 and 1990, a period which brackets the date of the oil spill (1985), land loss rates were similar to other periods in the past (Figure 12). Although the spill caused significant short term mortality of the vegetation, the marsh vegetation showed near complete recovery by 1990 (Figure 14) and marsh loss rates were not accelerated over previous time intervals. Background interior marsh loss (except for that caused by canal dredging) and shoreline erosion appeared to have slowed considerably since 1982.

Rates of land loss at the study site fall into the range of land loss rates determined by the U. S. Army Corps of Engineers (Dunbar et al. 1992) between 1932 and 1990 for the Empire 7.5 ^{o} quadrangle, in which the study site is located, with one notable exception. The south control marsh exhibited an exceptionally high marsh loss rate of 3.95 % y^{-1} during the 1978-82 period. This rate exceeds that determined for the Empire quadrangle (1.92 - 2.01% y^{-1}) by almost 2 % y^{-1} for the same general time period (Dunbar et al. 1992). The high rate of land loss in the south control marsh was due to interior marsh degradation as depicted in Figure 12, 1978-82 Marsh Loss. The reason for such an extreme rate of marsh loss during this four year period at the south control marsh, but not at the oiled or north control marshes, is not immediately apparent. However, it is likely that these spatial differences in marsh loss are characteristic of the highly site-specific nature of the land loss process. Even at larger spatial scales these site-specific differences in marsh loss rate are evident. For example, annualized rates of land loss during the past 20 years for the Empire quadrangle (1.55 - 2.01% y^{-1}) are approximately 5 times higher than that for the entire Mississippi River Deltaic Plain (0.36 - 0.42 % y^{-1}, Dunbar et al. 1992).

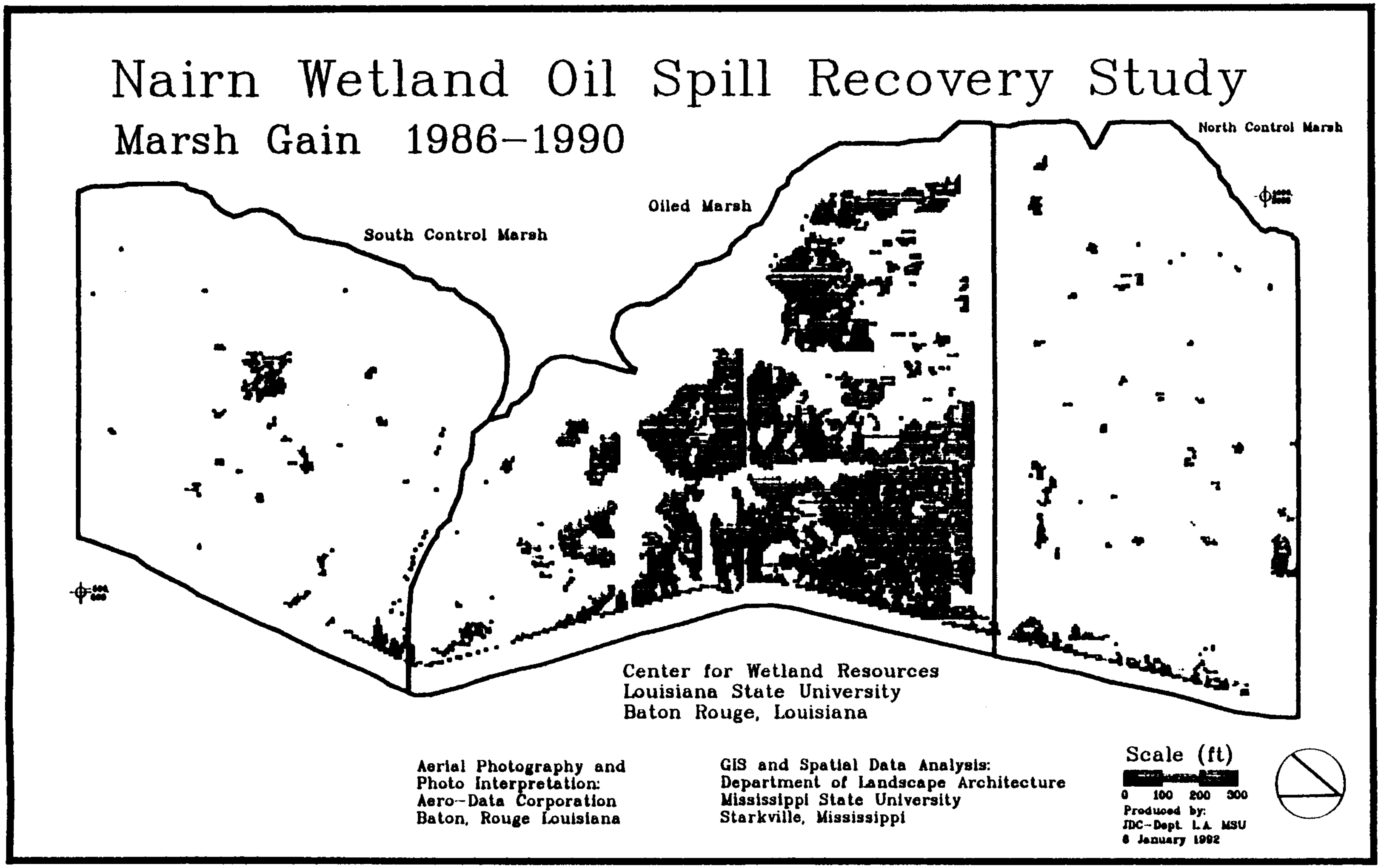

Figure 14. Photointerpreted map showing recovery of the oil-impacted marsh as change in land cover class from open water to marsh during the 1986-90 time period.

DISCUSSION

The 1985 oil spill investigated in this study released approximately 300 barrels of Louisiana crude oil and impacted approximately 20 ha of Louisiana brackish marsh dominated by a mixture of Spartina patens, S. alterniflora and Distichlis spicata. The initial impact of the oil on the marsh vegetation three months after the spill resulted in a 64% reduction in adjusted live vegetative cover compared to non-impacted areas (Figure 3). A number of other studies have reported that oil additions not only result in the death of the marsh vegetation, but may also reduce subsequent regrowth (Cowell 1969; Bender et al. 1977; Hampson and Moul 1978; Holt et al. 1978; de la Cruz et al. 1981). Bender et al. (1977) reported that the addition of 3 barrels of Louisiana crude to a 695 m^2 area of salt marsh (0.82 l per m^2) in Virginia resulted in a 66% reduction in live biomass after one year. De la Cruz et al. (1981) demonstrated that 1.5 l per m^2 of crude oil killed the salt marsh rush, Juncus roemerianus, and suppressed regrowth for one to two years in a Mississippi salt marsh. Holt et al. (1978) also found reduced growth and inhibited plant recovery in a Texas salt marsh due to an oil spill, with the degree of recovery being a function of the intensity of the spill.

We estimate that 0.28 l of Louisiana crude oil per m^2 area of marsh ([300 barrels x 190 l per barrel] / 202,350 m^2) was introduced in 1985 into the impacted marsh in this study. By 1989, vegetation in the oiled plots appeared fully recovered. There were no longer any visual signs of oil on the vegetation nor on the marsh sediment surface, and there was substantial vegetative regrowth, such that there were no longer any significant differences in adjusted live vegetative cover between oil-impacted and non-impacted areas (Figures 3 and 5). Nonetheless, a subsample of 1989 soil cores showed that some of oil-impacted plots still had higher levels of total saturated hydrocarbons than the control plots (Table 3). Other studies have shown that oil may still be present in the sediment following vegetative recovery (Baker et al. 1993). Vegetative recovery of a salt marsh in Wales began within one year following a spill of heavy fuel oil despite the fact that a distinctive oil layer was still visible in cores 15 years later, at which time vegetative recovery of the marsh was reported as complete and live plant parts were observed growing below, through and above the oil layer (Baker et al. 1993).

Some studies have indicated no effect, or even an enhancing effect, of oil on salt marsh growth. Webb et al. (1981) monitored the effect of a spill of No. 6 fuel oil in a salt marsh near Galveston Bay, Texas and found that vegetative regrowth the following spring was unaffected by the spill, even though the oil had covered much of the vegetation. Webb et al. (1985) added 1 l per m^2 of No. 2 fuel oil to a Spartina alterniflora dominated marsh in Texas and found regrowth complete after 1 year, although the aboveground tissue was initially killed. Hershner and Moore (1977) reported that a spill of No. 6 fuel oil in a salt marsh adjacent to Chesapeake Bay actually increased the growth of the salt marsh grass Spartina alterniflora. Stebbings (1970) observed a similar response in a salt marsh in Great Britain. Mackin (1950a and b) also observed stimulations in productivity of salt marsh plants subsequent to oil additions. Delaune et al. (1979) added as much as 8 l per m^2 of Louisiana crude oil to a S. alterniflora dominated salt marsh in south Louisiana and found no significant effect on shoot biomass after 4 and 16 months. Crow (1974) sprayed Arabian crude oil on the bottom 7.5 cm of the stems of S. alterniflora and found no detrimental effect.

The reasons for the apparent contradictions between reported effects of oil on coastal marsh vegetation are likely due to the large number of factors that can influence the response of marsh vegetation to petroleum hydrocarbon spills (Webb et al. 1985). Factors such as the type of oil, concentration of oil, degree of coverage of the plants, persistence of oil, extent of soil penetration, season, species affected and cleanup activities can all affect the response and recovery of marsh vegetation impacted by petroleum hydrocarbons (Baker 1993; Webb et al. 1985). Water levels in Louisiana coastal marshes are to a large extent controlled by meteorological events with astronomical tides of lesser importance (Byrne 1977). At the time of the spill reported in this study, water levels were relatively high in the marsh due to predominant southeast winds (NOAA 1985). We estimate that the high water level allowed the oil to come in contact and cover as much as 30 - 70% of the vegetative canopy. In addition, subsequent lowering of water levels allowed the penetration of the oil into the marsh substrate to a depth of approximately 15 - 20 cm (personal observation). The presence of petroleum hydrocarbons in the marsh sediment two months (June 19, 1985) after the spill (Table 2) verified that the oil had penetrated the marsh surface. We suspect that oil penetration of the marsh occurred primarily along the culms of the grasses and also via burrows of fiddler crabs (Uca spp.). The prolonged contact of the oil with the photosynthetic leaf tissue and the subsequent movement of the oil into the marsh substrate may have been the primary causes for the plant death and low live percentage cover exhibited after this spill, even at a relatively low dosage of 0.28 l per m^2. Ongoing experiments have demonstrated that Spartina alterniflora and Spartina patens are highly susceptible to oil damage when the oil comes in direct contact with leaf tissue, as we believe occurred in this spill incident (Lin and Mendelssohn unpublished data).

Measurements of plant photosynthetic response in the recolonizing vegetation five years after the spill indicated that there was not any residual effect of oiled sediment on plant photosynthesis (Figure 7). This is in agreement with a recent study by Mendelssohn et al. (1993), which reported that an oil application rate into the sediment of greater than 8 l m^{-2} was required to significantly reduced net photosynthesis of Spartina alterniflora three weeks after oiling. An oil application rate into the sediment of 4 l m^{-2} resulted in significantly depressed leaf elongation rates (after three weeks) and significantly reduced regrowth of Spartina alterniflora through the oiled sediment (Mendelssohn et al. 1993). Soil physicochemical variables in our study (at the time photosynthesis was measured) were also indicative of recovery in the oiled marsh, since no significant differences in interstitial water salinity, pH, redox potential , or sulfide were detected between control and previously oiled plots (Figure 9).

The results of our transplant study showed the importance of marsh sediment elevation in successfully re-establishing vegetation into degraded marshes. Increasing the substrate elevation by only 10 - 15 cm had a significant effect on whether transplants of Spartina alterniflora grew vigorously or were stressed to the point of not surviving (Figure 10). Other studies of naturally subsiding marshes in Louisiana have similarly found marsh elevational differences to have a significant impact on plant stress and productivity (Mendelssohn and McKee 1988; Burdick et al. 1989; Wilsey et al. 1992). In our study, the failure of certain areas to revegetate can certainly be linked to increased flooding stress, and not a residual oil effect, since there were no significant differences between elevated residual oiled plots or elevated control plots for any of the variables. Ambient elevation plots had significantly lower sediment surface redox potentials, and at one site significantly greater concentrations of interstitial water sulfides than the elevated plots, indicating that the sediment was more reduced in the ambient plots than in the elevated plots (Figure 11).

Photointerpretive studies prior to and following the oil spill have indicated that rates of land loss in the oil-impacted marsh were not accelerated by the spill (Figures 12-14). Other than land loss caused by canal dredging, marsh loss in the study area (the Empire quadrangle) has historically been due to a combination of shoreline retreat and interior marsh degradation to open water. Rates of marsh loss in the Empire quadrangle during the time period of this study ranged from approximately 1.9 - 2.0% per year , whereas the oil impacted marsh averaged about 1.4% per year and the control marshes 0.7 - 1.3% per year between 1982 and 1990 (Figure 12). Since rates of land loss in the Empire quadrangle have been averaging four to five times higher than those of the entire Mississippi River

Deltaic Plain during the past 20 years, it is not surprising that insufficient sediment elevation (with accompanying flooding stress) was found to be a major factor inhibiting successful re-establishment of marsh vegetation in certain areas impacted by the spill that had not vegetatively recovered. Although subsidence is an ongoing process in Louisiana's deltaic marshes, marsh sediment elevation may be further decreased in certain areas following an oil spill either from accelerated erosion following death of the vegetation, or from mechanical trampling and compaction by heavy equipment during cleanup operations. Our results indicate that successful restoration of dieback areas in oil impacted marshes that are slow to vegetatively recover may require sediment addition to reduce the intensity of flooding stress before vegetation may be successfully transplanted and re-established.

CONCLUSIONS

This study has shown that a relatively low dosage of Louisiana crude oil ($0.28\ l\ m^{-2}$ marsh area) spilled into a coastal brackish marsh can have a considerable negative short-term impact on the marsh vegetation. High water levels at the time of the spill resulted in the oil coming in direct contact with the leaves and stems of the vegetation, and is believed to be largely responsible for the large decrease in live adjusted vegetative cover (64%) following a relatively low dosage spill. Subsequent lowering of water levels resulted in the oil penetrating the marsh sediment surface.

Vegetative recovery of the area was essentially complete five years after the spill, even though a subsampling of the oil impacted plots revealed that they still had higher levels of total saturated hydrocarbons than control plots. The health of the recolonizing vegetation (as assessed via photosynthetic response of Spartina alterniflora and Spartina patens that had re-established in oiled plots) was found not to be significantly different than that measured in control plots. Similarly, soil physicochemical variables were also not significantly different between control and previously oiled plots.

Patterns of land loss can show considerable spatial variability. Although the reported oil spill had a significant short-term negative impact on the marsh vegetation, an analysis of historical photography revealed that land loss rates in the oil impacted marsh during the period that brackets the spill were similar to other periods in the past, and that loss rates were not accelerated over previous time intervals.

An investigation of factors that may have limited the vegetative recovery of two sites within the oil-impacted marsh revealed that increased flooding stress resulting from a lower sediment surface elevation, and not a residual oil effect, was primarily responsible for the failure of these sites to revegetate following the spill. Localized increases in sediment erosion following death of the vegetation or compaction from heavy machinery during cleanup operations, in combination with a marsh that is already experiencing high rates of subsidence on a regional scale, apparently led to an intolerable level of flooding stress for vegetative re-establishment. It is important to note that an increase in elevation of only 10 to 15 cm resulted in significantly greater transplant success as indicated by greater survival, and higher stem numbers and biomass per area. These findings suggest that restoration plans for degraded, oil-impacted marshes should consider whether an adequate sediment surface elevation exists prior to conducting a large-scale restoration planting. In many cases sediment addition, followed by planting or natural colonization, may greatly improve the long-term vegetative recovery success of oil-impacted marshes.

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