2006

Restoration Success Of Backfilling Canals In Coastal Louisiana Marshes

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Abstract

The need for effective marsh restoration techniques in Louisiana is a pressing issue as the state continues to lose coastal wetlands. Returning spoil banks to canals, known as "backfilling," is an attractive restoration option because it restores marsh, prevents future wetland loss, and is cost effective. The restoration of 30 canals backfilled 20 years ago was examined in this study and compared to restoration success 5 and 10 years after backfilling. Ultimately, the success of backfilling was controlled by the amount of spoil returned to the canal and the position of the canal in the marsh. Up to 95% of the spoil area was restored to marsh when the spoil banks were adequately removed, but only 5% of the spoil area was restored at sites where spoil removal was poor. Restoration of organic matter, bulk density, water content, and plant communities of the former spoil areas was also constrained by the adequacy of spoil removal. Backfilling restored up to 90% of the organic matter, 92% of the bulk density, and 93% of the water content after 20 years at sites where spoil was properly removed. Canals backfilled in areas of intact marsh showed greater restoration success than canals backfilled in highly degraded marshes. This study indicates that the benefits of backfilling continue to increase over time, although complete restoration will take longer than 20 years. Improving the completeness of spoil removal, coupled with appropriate site selection, could speed up the restoration process and enhance the success of future backfilling projects.

Key words: **backfilling, canals, coastal Louisiana, land loss, marsh restoration, spoil banks.**

Introduction

Long-term monitoring is essential to determine the success of wetland restoration projects. Projects often lack monitoring longer than a few years (Simenstad & Thom 1996; Zedler & Callaway 1999; Craft et al. 2003), and a project's true success, or failure, may go undocumented (Mitsch & Wilson 1996). Traditional restoration techniques have centered around the reinstatement of previous abiotic settings (Suding et al. 2004), the idea being that the system will design itself and return to its predisturbance condition (Zedler 2000). Backfilling dredged canals in coastal Louisiana is a restoration technique that follows this "self-design" model.

Backfilling is the return of material to the canal from which it was dredged and has been used to restore marsh and reduce wetland loss in a coastal Louisiana landscape decimated by oil and gas activity (Neill & Turner 1987*a*). The material removed as a canal is dredged and is placed alongside the canal to form continuous levees known as spoil banks (Bahr et al. 1983). Canals and their associated spoil banks alter hydrology and have both a direct and an indirect role in Louisiana's land loss problem. Directly, canals have turned marsh to open water and spoil banks have replaced marsh with an upland environment (Craig et al. 1979). Indirectly, spoil banks restrict water flow above and below the marsh surface and can cause both increased flooding and drying of the marsh behind them (Swenson & Turner 1987). This hydrologic alteration can limit sediment deposition, stress marsh vegetation, increase subsidence, and lead to marsh deterioration (Mendelssohn et al. 1981; Bahr et al. 1983; Mendelssohn & McKee 1987; Turner 1987, 2004).

Estimates of the total wetland loss attributed to canals and spoil banks in Louisiana vary, particularly in regard to the indirect losses, but the extent of marsh canalization is not trivial. Turner and Streever (2002) reported that the area of canals and spoil banks was 80,426 ha in 1978, with 1.2 ha of spoil bank for every 1 ha of canal. In 1990, approximately 10% of Louisiana's coastal marsh was canal and spoil bank (Baumann & Turner 1990). Britsch and Dunbar (1993) reported that the area of canals alone was 45,866 ha in 1990, but no estimates of spoil bank area were given. However, using the canal to spoil area ratio of 1:1.2 for the 1990 data, the area of canals and spoil banks would have been 100,905 ha (Turner & Streever 2002). To put that into perspective, approximately 395,232 ha of land turned to open water in Louisiana between the 1930s and 1990 (Britsch & Dunbar 1993). Adding to that the area of marsh lost from spoil bank building the direct conversion of marsh to canals and spoil banks would account for over 22% of the total wetland area lost. Indirect losses from canals and spoil banks are even greater than the direct losses (Turner 1987; Turner & Rao 1990) and drastically increase the amount of land loss caused by canals and spoil banks.

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The purpose of backfilling is to restore marsh on the former spoil bank areas, create beneficial shallow-water habitat in the canal, and restore hydrologic conditions via removal of the spoil banks. However, obtaining the proper elevation when removing spoil banks is crucial. Spoil left higher than the surrounding marsh can be recolonized by shrubs and trees, and spoil left lower than the surrounding marsh turns to open water.

Sediments from the spoil banks, which have undergone dewatering and oxidative processes since they were dredged, have a greatly reduced volume (Gosselink 1984), and addition of the spoil banks alone often does not completely fill the canal with sediment. However, this does not detract from backfilling as a viable restoration technique. The canal becomes shallower and provides excellent habitat for a variety of wildlife (Neill & Turner 1987*a*). A few more recent backfilling projects have added dredged sediments from nearby lake bottoms to further reduce canal depth after spoil banks were returned and to promote growth of emergent vegetation. Although these types of projects are relatively new, they appear to have great success at restoring the canal area to marsh.

One method used to reduce the impact of canals on the surrounding marsh is to create a small levee, or plug, at the opening of the canal. Canals were originally plugged to reduce erosion from boat wakes, wave action, and tidal scour, all of which are processes thought to cause the deepening of canals. Unplugged backfilled canals accumulate sediments over time, however, and they become shallower than plugged canals (Reed & Rozas 1995).

Leaving canals unplugged, or at least partially unplugged, has benefits for wildlife as well. Backfilling canals creates shallow-water habitat, which can be used by waterfowl, fish, and crustacean species. Neill and Turner (1987*b*) found that plugging canals limited the amount of nursery habitat available to migrant fish species, and fewer fish were found in plugged canals than in adjacent open areas (Adkins & Bowman 1976). Along with the shallow-water habitat, backfilling creates marsh edge habitat, which is valuable in its own right, and allows nekton access to marsh habitat (Peterson & Turner 1994).

Past studies examining the restoration of backfilled canals after 5 (Neill & Turner 1987*a*) and 10 years (Turner et al. 1994) found varied levels of success. It was the intention of this study to (1) survey these same canals; (2) reevaluate the restoration success 20 years after backfilling; and (3) identify the factors leading to successful backfilling.

Methods

The restoration success of 30 canals, backfilled at least 20 years ago, was examined in this study. The sites were chosen from a set of 33 canals backfilled between 1979 and 1984, and represent the earliest known examples of backfilling (Neill & Turner 1987*a*). The sites were located all over the Louisiana coastal zone (Table 1) and were sampled on the former spoil bank areas and also in the surrounding marsh to provide reference values. Data were collected on soil structure, vegetation, and canal depth during the summer 2004.

The marsh and former spoil bank soils were sampled in six locations at each site using a 50-cm^3 piston corer with three cores per sample. Samples were analyzed for water content, bulk density, and organic matter. The water content was reported as the percentage of weight lost after drying the sample at 60°C until a constant weight was reached. The bulk density was determined on a dry weight per volume basis (g/cm^3), and organic matter was reported as the percentage of dry sample weight lost after 1 hour of ignition at 550°C.

The percent recoveries of bulk density, water content, and organic matter were calculated with the following formula:

$$\%\ \text{Recovery} = \frac{\text{NR} - S}{\text{NR} - M} \times 100$$

where NR is the average value of bulk density, water content, or organic matter of standing spoil banks that have not been returned to canals as measured by Neill and Turner (1987*a*). NR $= 0.8$ g/cm^3 for bulk density, 26.6% for water content, and 7.6% for organic matter. *S* is the value of bulk density, water content, or organic matter measured on the restored spoil bank area and *M* the value of bulk density, water content, or organic matter measured from the reference marsh.

The former spoil bank area was classified into one of three categories: spoil vegetation, marsh vegetation, or open water. Estimates of spoil cover and percent marsh vegetation in the canal were determined from visual estimates of infrared aerial photographs taken in 2000, oblique aerial photographs from spring 2004, and ground observations from summer 2004. The vegetation composition on the marsh and former spoil bank areas were compared by visually estimating species richness from six 1-m^2 plots from each area. Three evenly spaced plots were surveyed on each side of the canal for the spoil bank and marsh vegetation estimates. More detailed information on vegetation surveys at these sites can be found in Baustian (2005).

The canal depths were measured using a surveying rod in three evenly spaced transects across each canal, five measurements per transect, and averaged to give one estimate of canal depth. Because all sites were in tidal marshes, and water levels changed daily, all canal depths were measured relative to local marsh elevation.

The status of a plug was noted at each canal. Sites were considered plugged if the plug was intact and prevented water exchange during normal tidal fluctuations. Sites were considered unplugged if no plug was constructed or if the plug had deteriorated and allowed water exchange for at least 15 years as determined from aerial photographs.

Statistical Analysis

All statistical tests were done using Statistical Analysis System software (SAS Institute Inc. 2003), with a 0.05 probability level. Comparisons of species richness between the backfilled spoil banks and the reference marsh, and comparisons of canal depth between plugged and unplugged canals were done with *t* tests. Comparisons of soil properties between sample years, and between marsh types were done using an analysis of variance (ANOVA) with Tukey post hoc comparisons. Comparisons of soil properties between the restored spoil areas and the reference marsh at each site were done using an ANOVA.

Results

The backfilled canals examined in this study occurred in all coastal marsh types and varied greatly in length and direct impact (Tables 1 & 2). There were 16 sites in brackish marsh, 4 in salt marsh, and 5 in both intermediate and fresh marshes. The longest backfilled canal was the Pecan Island West site (1,859 m); this site also had the greatest direct impact (11.6 ha). The shortest canal was the Lower Mud Lake site (120 m), and the canal with the smallest direct impact was the Lafitte site (1.7 ha).

The former spoil areas had higher bulk densities, lower organic contents, and lower water contents than the reference marsh at all sites except at Tigre Lagoon (Table 2). A recent deposit of highly organic material on the former spoil area accounts for the high levels of soil restoration at the Tigre Lagoon site. The mean percent recovery of bulk density, water content, and organic matter on the former spoil bank areas were 61.4, 67.1, and 51.6, respectively (Table 2).

Backfilling restored marsh on a portion of the former spoil bank area at all 30 sites, and restored marsh in a portion of the canal at 16 sites (Table 1). The area of spoil bank restored to marsh varied from 5 to 95%, with an average of 58%, and was limited by the area of spoil bank actually backfilled (Fig. 1). The restoration of marsh in the canal was inconsistent, ranging from 0 to 100%, with an

Table 1. Canal attributes and percent recoveries of soil properties.

Site	*Location*	*Length (m)*	*Canal Depth (m)*	*Age at Backfilling (years)*	*Direct Impact (ha)*	*% Marsh Vegetation on Spoil Area*	*% Marsh Vegetation in Canal*	*% of Site Restored to Marsh*
Hellhole Lake	lat 29°12′N, long 91°06′W	1,432	—	0.9	10.6	90	0	61
Boston Bayou North	lat 29°50′N, long 92°03′W	243	0.7	19.3	4.3	6	0	4
Boston Canal	lat 29°49′N, long 92°04′W	365	0.7	0.3	5.0	20	5	17
Tigre Lagoon	lat 29°49′N, long 91°56′W	152	1.0	0.3	1.9	56	0	55
Golette Bay	lat 29°34′N, long 90°01′W	300	1.0	0.5	3.1	65	0	46
Grand Lac L'Huit	lat 29°46′N, long 92°39′W	487	—	18.3	4.2	88	55	77
Mallard Bay West	lat 29°54′N, long 92°38′W	354	—	0.6	3.7	80	0	54
Mallard Bay East	lat 29°54′N, long 92°38′W	295	—	0.2	3.3	95	5	68
Mermentau River	lat 29°45′N, long 93°04′W	229	0.7	5.0	4.5	65	5	48
Mosquito Bay	lat 29°16′N, long 91°12′W	152	0.7	0.2	2.4	80	0	57
Vermilion River	lat 29°47′N, long 92°09′W	670	0.7	1.9	6.2	83	3	61
Bayou Long	lat 29°41′N, long 91°36′W	457	0.9	6.3	4.5	10	2	8
Four Isle Bay	lat 29°16′N, long 90°49′W	426	1.5	7.3	4.5	93	0	66
Pecan Island West	lat 29°36′N, long 92°23′W	1,829	0.3	34.1	11.6	93	40	77
Lafitte	lat 29°37′N, long 90°03′W	152	—	8.4	1.7	15	0	9
Dupree Cut	lat 29°36′N, long 90°04′W	152	0.0	4.3	2.2	15	100	42
Buckskin Bayou	lat 29°17′N, long 91°02′W	609	1.4	0.2	4.6	75	0	52
Falgout Canal	lat 29°27′N, long 90°49′W	400	1.3	8.3	3.8	83	0	57
Catfish Lake	lat 29°24′N, long 90°21′W	457	0.8	2.8	3.5	50	0	31
Fourleague Bay	lat 29°20′N, long 91°11′W	304	0.9	21.9	2.5	95	0	57
ICWW at Oaks Canal	lat 29°50′N, long 91°59′W	399	0.5	1.5	4.3	90	45	76
Lower Mud Lake	lat 29°45′N, long 93°03′W	120	0.0	0.8	4.5	75	80	76
Boston Bayou South	lat 29°50′N, long 92°03′W	609	0.6	18.6	5.7	50	2	37
Iberia Canal	lat 29°52′N, long 91°52′W	1,219	1.3	2.1	11.1	30	1	22
Delta Farms	lat 29°37′N, long 90°18′W	434	—	1.4	4.2	5	0	3
Rainey Refuge	lat 29°37′N, long 92°14′W	173	1.1	2.0	2.1	55	2	37
Pecan Island East	lat 29°36′N, long 92°22′W	826	—	40.1	5.4	5	0	3
Superior Bridge	lat 29°43′N, long 92°40′W	457	1.4	—	5.9	78	7	62
Long Island	lat 29°46′N, long 92°46′W	457	—	—	3.9	50	30	43
Point a la Hache	lat 29°37′N, long 89°50′W	664	0.7	0.0	5.9	50	5	36
Mean	—	495 ± 71.8	0.8 ± 0.1	7.4 ± 2.0	4.7 ± 0.5	58 ± 5.7	13 ± 4.7	45 ± 4.3

Direct impact, original area impacted by canal and spoil placement; % of site restored to marsh, percentage of the direct impact restored to marsh; —, no data were collected. Means are ±1 SE.

Table 2. Soil properties of the former spoil and reference marsh areas.

			Spoil Area			Reference Marsh			% Recovery		
Site	*Marsh Type*	*n*	*Bulk Density (g/cm^3)*	*% Water Content*	*% Organic Matter*	*Bulk Density (g/cm^3)*	*% Water Content*	*% Organic Matter*	*Organic Matter*	*Water Content*	*Bulk Density*
Hellhole Lake	salt	—	—	—	—	—	—	—	—	—	—
Boston Bayou North	brackish	6	0.53 ± 0.06*	54.8 ± 4.08*	19.8 ± 3.02*	0.14 ± 0.01	83.6 ± 0.80	35.1 ± 1.78	44	49.3	40.2
Boston Canal	brackish	4	0.35 ± 0.05	66.7 ± 3.89*	18.3 ± 2.37*	0.10 ± 0.01	87.8 ± 1.43	49.0 ± 1.45	25.8	65.6	64.6
Tigre Lagoon	brackish	6	0.14 ± 0.03	84.5 ± 2.94	52.3 ± 7.71*	0.22 ± 0.02	76.5 ± 1.64	37.9 ± 1.24	100.0	100.0	100.0
Golette Bay	brackish	6	0.14 ± 0.02	85.3 ± 1.41	52.7 ± 2.76*	0.08 ± 0.01	91.3 ± 0.91	63.6 ± 3.30	80.9	90.7	91.4
Grand Lac L'Huit	fresh	—	—	—	—	—	—	—	—	—	—
Mallard Bay West	fresh	—	—	—	—	—	—	—	—	—	—
Mallard Bay East	fresh	—	—	—	—	—	—	—	—	—	—
Mermentau River	brackish	5	0.57 ± 0.04	53.6 ± 2.54	16.1 ± 1.33	0.45 ± 0.06	59.9 ± 3.76	22.4 ± 2.34	57.6	81.0	67.3
Mosquito Bay	brackish	6	0.35 ± 0.03	66.8 ± 2.30	20.0 ± 1.59	0.31 ± 0.04	69.8 ± 2.86	24.4 ± 2.41	73.8	92.9	92.3
Vermilion River	intermediate	6	0.51 ± 0.08*	55.3 ± 4.80*	21.8 ± 4.59*	0.12 ± 0.01	86.2 ± 1.32	43.2 ± 3.75	40.0	48.1	41.4
Bayou Long	intermediate	6	0.28 ± 0.03	71.2 ± 1.98	33.3 ± 2.8.	0.20 ± 0.01	77.7 ± 1.51	36.2 ± 2.74	89.9	87.3	86.5
Four Isle Bay	salt	6	0.28 ± 0.03	72.0 ± 2.69*	28.2 ± 3.09	0.17 ± 0.01	82.3 ±0.83	34.4 ± 0.91	77.0	81.5	82.1
Pecan Island West	brackish	6	0.39 ± 0.06*	63.6 ± 3.40*	17.6 ± 1.06	0.24 ± 0.02	73.7 ± 1.47	23.5 ± 1.06	62.4	78.6	72.0
Lafitte	brackish	—	—	—	—	—	—	—	—	—	—
Dupree Cut	brackish	5	0.93 ± 0.006*	30.0 ± 2.49*	8.9 ± 1.42*	0.15 ± 0.05	82.6 ± 4.60	44.7 ± 6.97	3.5	6.0	0.0
Buckskin Bayou	brackish	6	0.67 ± 0.08*	46.0 ± 3.60*	12.2 ± 2.57	0.37 ± 0.04	65.4 ± 2.93	19.0 ± 2.77	40.6	50.0	29.0
Falgout Canal	intermediate	6	0.20 ± 0.05	79.6 ± 4.01*	35.0 ± 4.28*	0.07 ± 0.02	92.4 ± 2.62	62.7 ± 5.97	49.7	8.06	81.7
Catfish Lake	salt	6	0.78 ±0.07*	40.5 ± 3.84*	9.8 ± 1.50*	0.15 ± 0.04	84.1 ± 3.45	45.9 ± 3.84	5.8	24.2	2.5
Fourleague Bay	brackish	6	0.34 ± 0.03*	67.5 ± 2.65*	21.8 ± 1.24*	0.20 ± 0.02	78.6 ± 1.44	34.9 ± 4.25	52.0	78.6	77.0
ICWW at Oaks Canal	brackish	6	0.42 ± 0.13*	61.9 ± 7.72*	21.3 ± 4.18*	0.18 ± 0.02	80.2 ± 2.17	30.4 ± 3.42	60.4	65.9	61.0
Lower Mud Lake	salt	6	0.50 ± 0.06*	57.2 ± 3.82*	16.2 ± 1.08	0.31 ± 0.02	69.0 ± 1.60	22.8 ± 1.45	56.6	72.2	61.1
Boston Bayou South	brackish	6	0.29 ± 0.05	71.4 ± 3.82	22.8 ± 1.53	0.19 ± 0.03	78.9 ± 2.28	29.6 ± 3.25	69.1	85.7	83.1
Iberia Canal	intermediate	6	0.27 ± 0.09	74.6 ± 6.23*	36.8 ± 6.55*	0.09 ± 0.00	89.5 ± 0.70	69.7 ± 1.52	47.0	76.3	74.5
Delta Farms	fresh	—	—	—	—	—	—	—	—	—	—
Rainey Refuge	brackish	5	0.60 ± 0.08*	50.9 ± 4.59*	18.2 ± 2.72*	0.07 ± 0.00	92.2 ± 0.48	65.1 ± 1.49	18.4	37.0	26.2
Pecan Island East	brackish	—	—	—	—	—	—	—	—	—	—
Superior Bridge	intermediate	6	0.53 ± 0.08*	55.7 ± 5.06*	17.2 ± 2.47*	0.09 ± 0.01	90.3 ± 0.69	58.4 ± 3.29	19.0	45.7	37.0
Long Island	fresh	—	—	—	—	—	—	—	—	—	—
Point a la Hache	brackish	4	0.23 ± 0.07	76.5 ± 6.72*	39.5 ± 5.25*	0.08 ± 0.01	90.6 ± 0.94	60.0 ± 5.50	60.8	78.0	79.8

*, value of the former spoil area is significantly different from the value of the reference marsh at that site; —, no data were collected at this site. Data are means ± 1 SE.

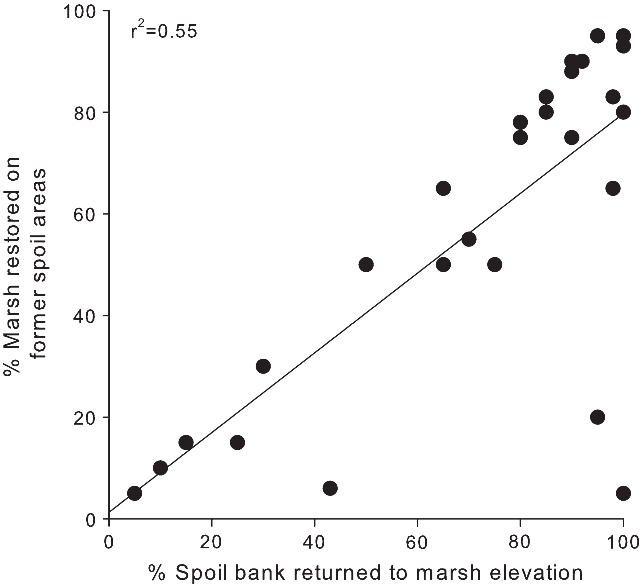

Figure 1. The relationship between the area of spoil bank backfilled and the percentage of marsh restored on the former spoil area. The three sites that do not appear to follow the trend are sites where the spoil was removed too deep and open water persists. A linear regression of the data is shown.

average of 13% cover. However, two sites had their canal area completely restored to marsh conditions—Dupree Cut and Lower Mud Lake. Overall, 3.3–77% of the direct impacts of canal dredging were restored to marsh by backfilling.

The plant species richness on the former spoil area did not match that of the reference marsh. The average number of species on the former spoil bank areas was significantly higher ($p < 0.05$) than the reference marsh (Fig. 2). The species richness of the former spoil area was related to the completeness of spoil removal. Sites that had a low percentage of spoil removed had a higher species richness (Fig. 3).

Canals that were plugged were significantly deeper ($p < 0.05$) than unplugged canals (Fig. 4). Canals with plugs were 1.1 m deep on average, whereas canals that were not plugged, or had plugs that deteriorated, averaged 0.7 m.

Marsh type had no impact on soil restoration of backfilled spoil banks. The percent recovery of organic matter, bulk density, and water content did not differ significantly ($p > 0.05$) between marsh types (Fig. 5).

The organic content and water content of the former spoil area increased from 1984 to 2004, but both soil properties were still significantly different than the reference marsh (Fig. 6). Bulk density decreased from 1984 to 2004, but it was also significantly different from the reference marsh.

There were many sites where elevated spoil remained simply because it was missed by the dredge operator. A barge-mounted dredge was used in the early years of backfilling, which put a constraint on the area of spoil bank reachable with the dredge. As a result, dredge operators were not always able to reach the back edges of the spoil banks, and an elevated rim of spoil remained around the outside of the canal (Fig. 7). Although the spoil banks were not completely removed at all sites, enough spoil was removed to reestablish hydrologic connections in the surrounding marsh (Fig. 8).

Discussion

The amount of marsh restored on former spoil areas was limited by the completeness of spoil removal.

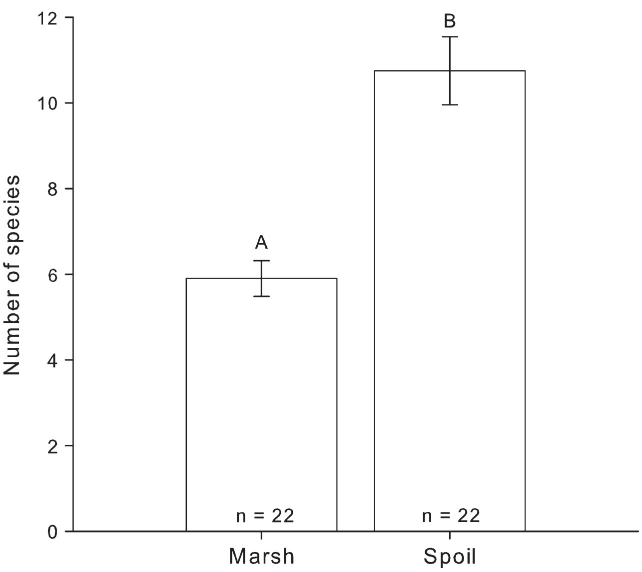

Figure 2. The average number of plant species found in the reference marsh and former spoil areas. Data are means ± 1 SE; values that share the same letter are not significantly different.

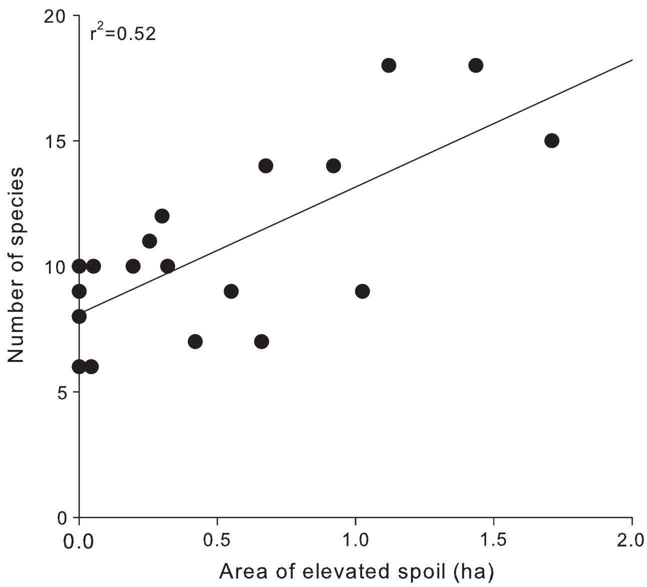

Figure 3. The number of plant species present on the former spoil areas as a function of the area of elevated spoil remaining after backfilling. A linear regression of the data is shown.

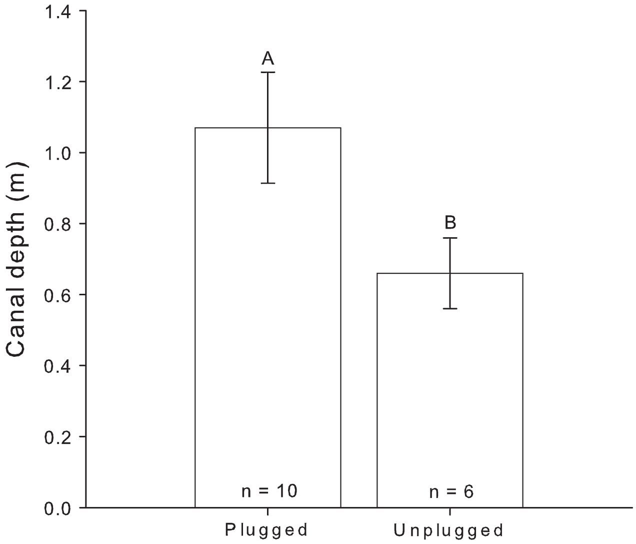

Figure 4. The average depth of plugged and unplugged canals 20 years after backfilling. Data are means ± 1 SE; values that share the same letter are not significantly different.

To improve the completeness of spoil removal, marsh buggies have been used in more recent backfilling efforts. The marsh buggy gives its operator a greater range of movement than the barge-mounted dredge and allows the operator to reach the back edges of the spoil banks. Abernethy and Gosselink (1988) realized the improved efficiency of the marsh buggy during the backfilling of the Louisiana Offshore Oil Port pipeline but thought its uses would be

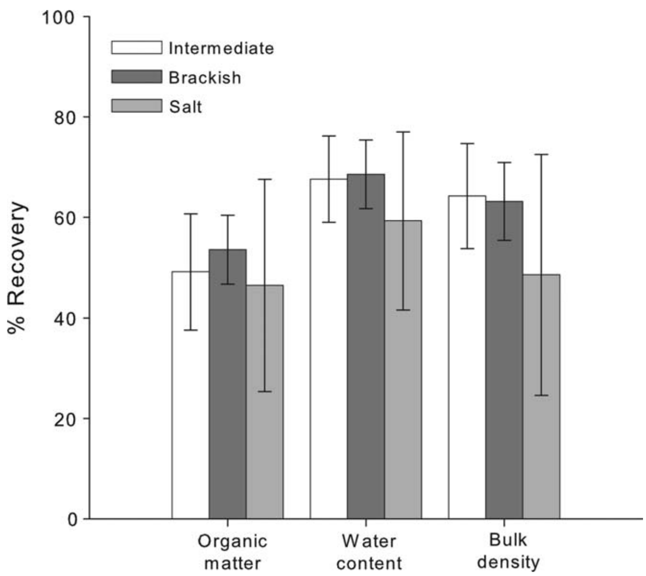

Figure 5. A comparison of soil restoration between different marsh types. Data are means ± 1 SE. There were no significant differences between marsh type for each soil property. Intermediate: $n = 5$; brackish: $n = 14$; salt: $n = 3$.

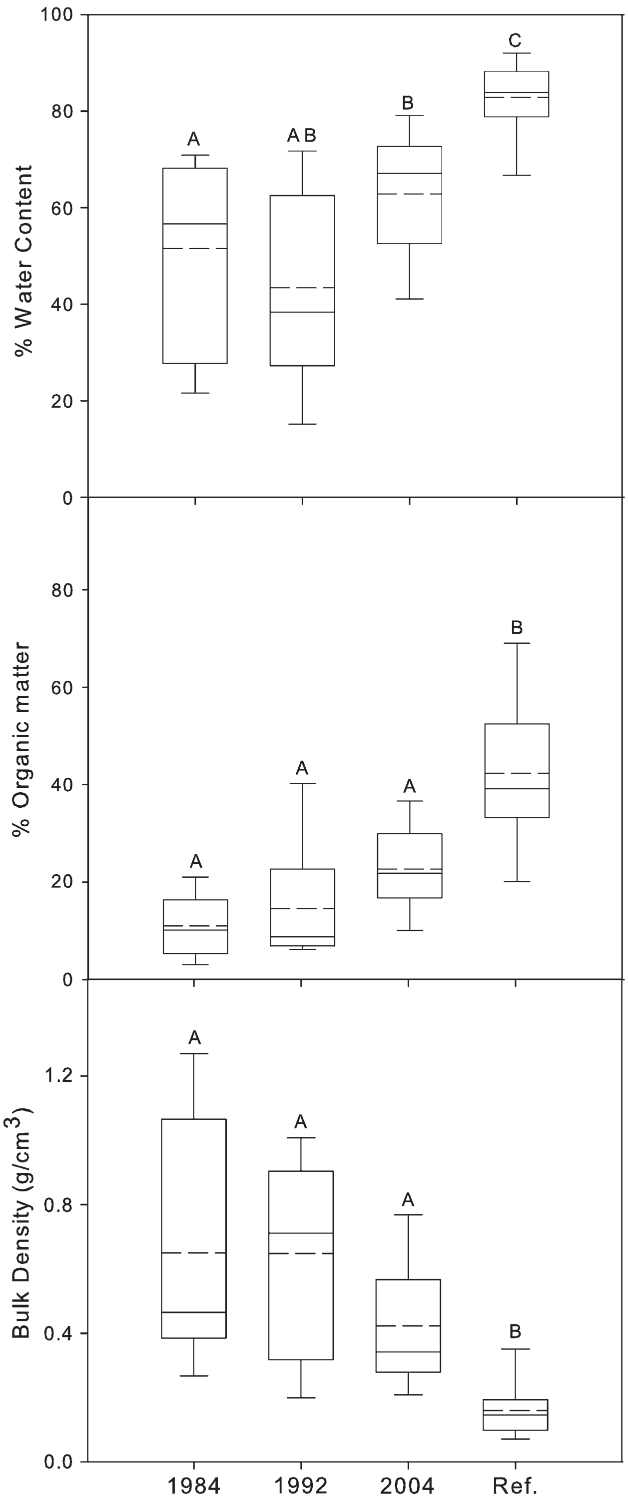

Figure 6. The progression of soil restoration on the former spoil areas over the past 20 years. Data are means ± 1 SE; values that share the same letter within each category are not significantly different. The solid line within the box is the mean, the dashed line is the median, and the whiskers are the 95% confidence intervals. Analysis includes only the canals that were sampled in all three time periods.

limited to backfilling canals in intact marshes with highly mineral soils. Intact marshes and marshes of high mineral content are not the norm in Coastal Louisiana, but marsh buggies have been successful at backfilling canals in other marsh types. For example, a marsh buggy was used to effectively backfill two canals at Jean Lafitte National Park, which is in an area of highly organic fresh marsh soils with low mineral content.

The restoration of soils on the former spoil areas is a lengthy process that depends on the build up of organic matter. An increase in organic matter correlates with a decrease in bulk density (Craft 2000) and an increase in the soil's water holding capacity (Neill & Turner 1987*a*). At optimal conditions, backfilling restored 90% of the organic matter, 92% of the bulk density, and 93% of the water content after 20 years. This length of time for soil restoration may seem long, but it is by no means unusual. Craft et al. (2003) reported significantly lower organic matter pools in eight constructed North Carolina salt marshes when compared to paired reference marshes, even after 28 years.

Plant communities on the former spoil bank areas rarely matched those of the surrounding marsh; the former spoil areas had significantly more species. At many sites this was due to incomplete spoil removal, which allowed for a higher species richness. Spoil banks are an upland environment in the marsh (Bahr et al. 1983), and a higher number of species are adapted to upland conditions than the flooded conditions of the marsh.

At several sites the backfilled canal acts as a stream conveying water through the marsh. Natural overbank flooding processes occur at these sites, and the canal and adjacent backfilled spoil areas receive inorganic sediments, similar to a natural streamside levee. The former spoil areas, acting as a streamside marsh, may develop plant communities and soil properties that will never be equivalent to the surrounding marsh. The streamside marsh created may not be identical to the marsh reference site, but it is a restored wetland and provides more wetland habitat value than the elevated spoil bank.

Marsh type had no significant effect on the percent recoveries of soil properties. The three sites with the highest percentages of site recovery to marsh occurred in fresh, brackish, and salt marshes indicating that marsh type, per se, has little effect on backfilling success.

Unplugged canals created more shallow-water habitat than plugged canals. Previous research on this topic came to the same conclusion (Neill & Turner 1987*a*; Reed & Rozas 1995), and this study showed the shallow-water habitat could be maintained over decades.

The restoration of all measured soil properties increased between 1984 and 2004. The comparisons between the 1984 and 2004 data suggest that the restoration process after backfilling has continued for 20 years. The monitoring in this study showed that backfilling's success continued to increase as restoration of soils continued to occur, and marsh took a greater hold on the former

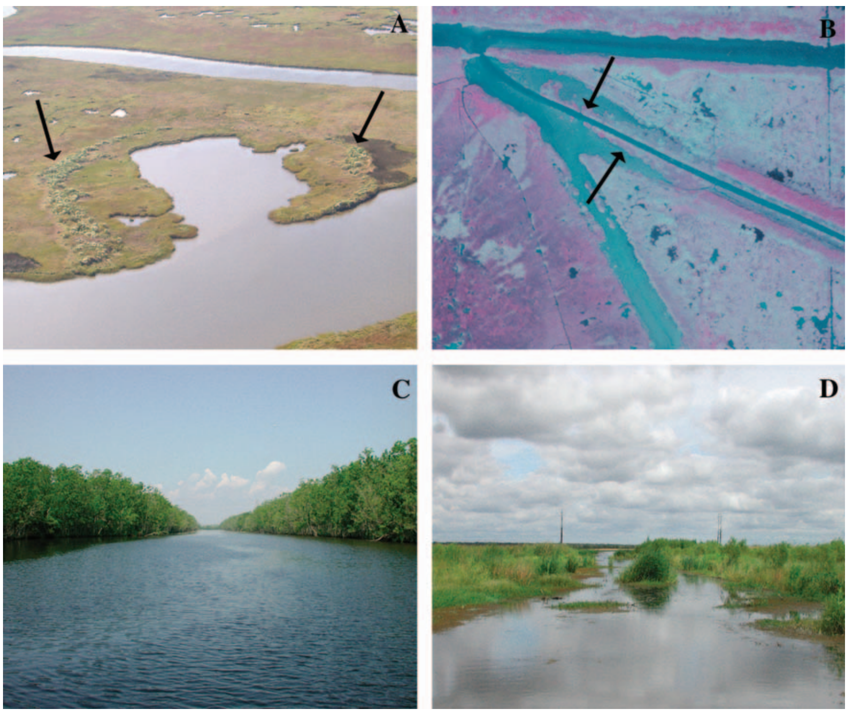

Figure 7. The Mosquito Bay backfilled canal (A), the arrows point to a rim of elevated spoil not reachable by the barge-mounted dredge. A portion of the Pecan Island West backfilled canal (B), the arrows point to marsh building in the canal through overbank flooding. A canal at Jean Lafitte National Park before (C) and 2 years after being backfilled with a marsh buggy (D).

spoil areas. Much would have been missed if the monitoring of these canals ended in 1984.

The hydrologic benefits of backfilling were directly observed at multiple sites. The Vermilion River site was backfilled in 1982, and within a few years a stream had developed between the canal and an adjacent open water area. Over the next two decades the stream maintained this connection, allowing for more natural flooding and draining cycles in the marsh, and the open water area began to shrink. The hydrologic improvements allowed for marsh to become established in the area that had been open water.

In this study the success of backfilling was controlled primarily by two factors: (1) the dredge operator's efficiency at spoil bank removal and (2) the position of the canal in the landscape. Returning spoil banks to the proper elevation during backfilling is essential because the future success depends so heavily on the initial restoration action. Returning the spoil banks to marsh elevation allows for faster recolonization by marsh vegetation, which begins the process of soil restoration, and removes the hydrologic barrier that spoil banks impose. Surveys done during backfilling could help ensure that proper elevation is reached and the restoration potential is maximized.

Backfilling a single canal was most successful in areas where the effects of canals, spoil banks, subsidence, and other factors had not claimed a large portion of the surrounding marsh. For example, canals backfilled within large oil fields or impounded areas restored marsh on the former spoil banks but showed little hydrologic benefit to the surrounding marsh in those areas. It is these authors' opinion that the immense hydrologic modifications in those areas could not be overcome by the backfilling of one canal alone. However, backfilling multiple canals in one area is a strategy that could be used to maximize local hydrological restoration. This would provide increased benefits to surrounding marshes as natural drainage patterns reemerge and marshes receive sediment from more regular flooding cycles.

The negative effects of canalization on coastal marshes are not solely a Louisiana problem. Ditches dug for mosquito control have altered hydrology and plant communities in many marshes along the east coast of the United States (Stearns et al. 1940; Bourn & Cottam 1950). In Nigeria, pipelines that crisscross the Niger River Delta are one of the many environmentally negative aspects of oil exploration (Jike 2004). Findings from this study on restoring canals in coastal Louisiana could also guide wetland restoration efforts worldwide where natural conditions have been altered by channelization.

Conclusions

Backfilling is a restoration technique that creates marsh and restores local hydrologic conditions by removing spoil banks and reducing canal depths. Marsh created from backfilling 20 years ago has been sustained, and additional marsh has since been restored. The increased success of backfilling over time illustrates how ecological processes often operate on longer timescales than those allowed for by restoration monitoring plans.

The damage to Louisiana marshes caused by canals and spoil banks is widely acknowledged, but there has been a disconnect between the causes of land loss and the focus

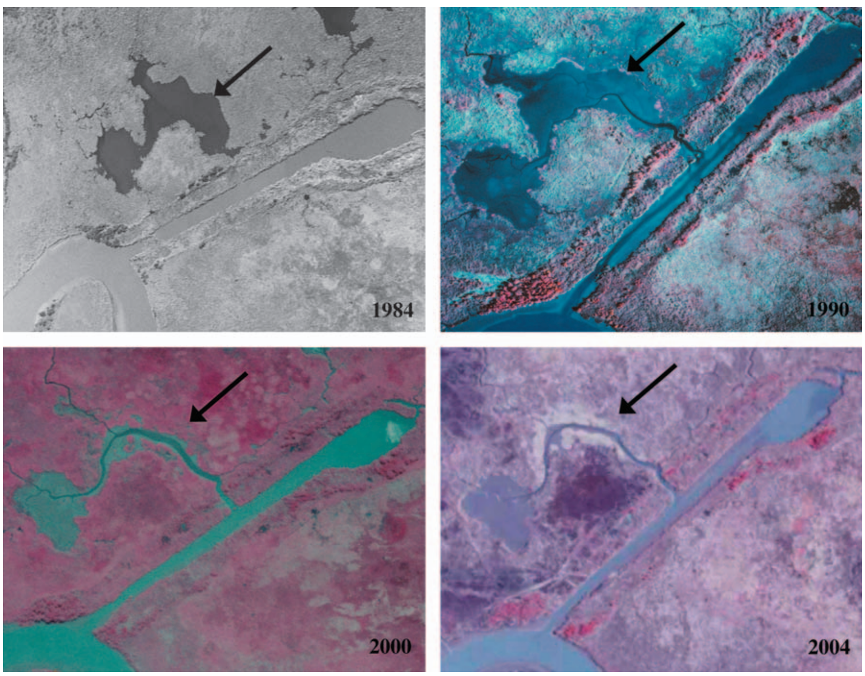

Figure 8. A pond adjacent to the canal converts to marsh after the Vermilion River site was backfilled. The arrows point to the same area in all photos.

of coastal restoration. If the direct land losses from canals and spoil banks account for 22% of the total land loss, then it seems reasonable that a comparable effort be put toward canal and spoil bank restoration. Yet, backfilling abandoned oil and gas canals has been overlooked and underutilized by restoration managers. The 30 sites in this study, for example, actually represent the majority of all known backfilled canals.

Backfilling is a simple, yet effective, restoration technique that can be used to mitigate the effects canals and spoils banks have on coastal marshes, and the information in this study can help restoration managers make more informed decisions on the best restoration techniques available.

Implications for Practice

- Restoration of marsh soils is a slow process, which is still incomplete 20 years postbackfilling.
- Removing spoil banks to the proper elevation maximizes potential restoration of hydrology, vegetation, and soils.
- Backfilling canals is a cost effective restoration technique with wide applicability.

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