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WETLAND RESTORATION THRESHOLDS: CAN A DEGRADATION TRANSITION BE REVERSED WITH INCREASED EFFORT?

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Abstract. Previous attempts to reverse the degradation of a coastal wetland and restore nesting habitat for an endangered bird showed that adding nitrogen could temporarily increase the height of *Spartina foliosa*, but not produce self-sustaining tall canopies. We asked if increased effort (up to five years of N fertilization) would shift canopy attributes across the hypothesized threshold. Thirty plots were treated with 0–5 yr of urea addition, and all were followed for 5 yr. Canopies were robust while urea was being added, but *Spartina* reverted to short stature soon after fertilization ended, supporting R. J. Hobbs and D. A. Norton's concept of an irreversible transition. However, specific outcomes depended on the choice of response variable (six comparisons), the choice of reference data (initial conditions, same-year data, and pooled data), and the choice of statistical design (repeated measures vs. complete design), indicating the need to assess experiments thoroughly before making strong recommendations for management.

Key words: alternative-state theory; cordgrass; fertilization effects; irreversible transition; management actions; nitrogen addition; restoration outcome, evaluating; restoration threshold; Spartina foliosa; *statistical design; wetland restoration, coastal.*

INTRODUCTION

Restoration of degraded ecosystems is limited by the severity of degradation and the effort that can be made to reestablish historical conditions or to match conditions of reference systems (NRC 1992). It remains questionable whether or not degradation is reversible. Hobbs and Norton (1996) depict ecosystems as changing from natural to multiple degraded states, with potential for such transitions to be reversed when the stressor (some disturbance) is removed. Once a threshold of disturbance has been crossed, however, reversal becomes much more difficult, if not impossible (Whisenant 1999). Restoration thresholds can involve altered abiotic conditions at the site or with the landscape (Hobbs and Harris 2001). For example, thresholds have been defined as the length of time that fires have been suppressed (Stephenson 1999); the degree of reduction in the size of savanna remnants (Bowles and McBride 1998); the depletion of soils in arid environments (Carrillo-Garcia et al. 2000*a*, *b*); and the lack of woodland seed banks or the compaction of soil, which reduces water infiltration and allows weed invasion (Yates et al. 2000).

While every attempt to restore a degraded ecosystem tests the reversibility of some transition, restoration ecologists typically cannot predict specific trajectories or determine what is needed to cross degradation thresholds. Rather, one must anticipate surprises, such as unexpected changes in vegetation (Klötzli and Grootjans 2001). There is also confusion about the criteria to be used in judging restoration outcomes (Hobbs and Harris 2001); e.g., which attributes can best indicate that a transition has been reversed more than just temporarily? Here, we offer insights into both the restorability and assessment issues based on a five-year experiment in which restoration effort was increased and the ability to cross a threshold was assessed using multiple criteria.

Several efforts have been made to restore highly degraded *Spartina foliosa* (cordgrass) habitat in southern California so that it can support nesting by the endangered Light-footed Clapper Rail (*Rallus longirostris levipes*). The need to restore habitat is great, because $<10\%$ of the historical area of coastal wetlands remains, all sites are disturbed, and only a few marshes sustain tidal flushing (Zedler et al. 2001). Within the fully tidal marshes, *Spartina* occurs only along the tidal creeks and in the lowest marsh elevations (Zedler et al. 1999). Within the *Spartina*, the only canopies considered suitable for nesting are those with at least 100 stems/m^2 and at least 90 stems/m^2 that are >60 cm tall, of which at least 30 stems/m^2 are >90 cm tall (Zedler 1993). The most degraded sites have had sandy dredge spoils deposited over fine sediments. When such sites are excavated to the elevation appropriate for *Spartina*, the substrate that remains is sandy, and *Spartina* does

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not grow tall (Zedler 1993). A substrate-related threshold is indicated, because *Spartina* does grow tall while nitrogen (N) is being added, but coarse soils do not provide or retain sufficient N to sustain tall canopies (Boyer et al. 2000). Experiments with other *Spartina* species also conclude that growth is N limited in coastal wetlands (Gallagher 1975, Valiela et al. 1976, DeLaune and Pezeshki 1988, Osgood and Zieman 1993, Dai and Wiegert 1996). The questions are: (1) Can increased effort eliminate the stress (N limitation)? and (2) How should one decide if a threshold has been crossed and the transition reversed?

To date, we have shown that larger doses and more applications of urea during a single growing season increase height growth of *Spartina* in constructed marshes (Boyer and Zedler 1996, 1998). In no case, however, has urea addition led to self-sustaining tall *Spartina* on sandy dredge spoils (Boyer et al. 2000). When urea addition ceases and tall stems senesce in fall, the next spring's regrowth is typically short (Boyer and Zedler 1998). Multi-year nitrogen addition might allow plants to cross the threshold; i.e., short-term limitations to soil development and plant growth might be ameliorated with prolonged effort. Hence, we increased effort by extending treatment from 1 to 2, 3, 4, and 5 yr. Our 5-yr experiment tested the effect of increased duration of nitrogen addition (1–5 yr) on *Spartina* growth. We also tested for a legacy of 1–4 yr of nitrogen addition, asking if the growth stimulus persisted after fertilization ceased. In considering how to evaluate experimental outcomes, we compared six *Spartina* responses, all concerning stems: density, maximum length, mean length, total length, number >60 cm and number >90 cm. Second, we explored interannual variability and compared alternative reference data sets to determine their effect on the interpretation of results. Third, we compared two alternative statistical designs (complete design vs. repeated measures). In each case, we asked whether or not the results differed with the approach used.

Methods

The experiment was conducted on a marsh island within Sweetwater Marsh National Wildlife Refuge (32°40′ N, 117°5′ W) on San Diego Bay, California, USA. The 4.9-ha Connector Marsh is a series of eight islands surrounded by tidal channels, all of which were constructed by excavating dredge spoils in 1984 and by planting to *Spartina* the following spring. The marsh sediment ranges from loam to sandy loam (Swift 1988) and contains ~1% organic carbon (Langis et al. 1991). In 1995 we set up the experiment in a 15 × 22 m area dominated by *Spartina foliosa* (South Island 3, elevation 0.3–0.6 m NGVD [U.S. National Geodetic Vertical Datum]). Trampling was avoided by walking on boardwalks (trestles with portable boards in place only during sampling).

The experiment included six treatments, each with $n = 5$ replicates: a control (no urea) and twice-a-week urea addition during the growing season for 1 to 5 yr. Thirty 2 × 2 m plots were placed in five north–south rows and six east–west rows. Plots were 1 m apart east-west and 2 m apart north-south. Each year (1995–1999), urea was added every two weeks from mid-March and repeated every two weeks until early August (11 applications, each at 15 g N/m^2). During the fourth year (1998), however, funding and urea additions were delayed until the first week of May.

Rainfall data were obtained from Lindbergh Field, San Diego (California, USA). Initially (March 1995), we measured soil bulk density and texture in 10-cm-diameter cores taken to a depth of 10 cm. During each late-summer sampling period, additional soil cores (5-cm diameter, 10-cm depth, two per plot outside the plant monitoring area) were taken to the laboratory for measurement of salinity, pH, and nitrogen. Soil was dried at 55°C, ground in a mortar, and passed through a 1-mm sieve. Soils were analyzed for total Kjeldahl nitrogen (TKN; QuickChem Method 13-107-06-2-D, revised July 1988 [Lachat Instruments, Milwaukee, Wisconsin, USA]) on a Lachat autoanalyzer (Model 2100-000). Soil pH and salinity were measured after making a saturated soil paste; pH was measured with a Corning model 125 pH meter (Corning Scientific, Corning, New York, USA) and a drop of soil water was expressed onto a salinity refractometer. Salinity values are for the soil paste, i.e., not adjusted for water volume added. To determine foliar nitrogen levels at the end of the season, four cordgrass stems were randomly selected from each plot (outside the vegetation sampling area). The leaves of the four stems were removed, rinsed, dried at 60°C to a constant mass, ground with a Wiley mill through a 40-mesh (0.381-mm) sieve, and analyzed for TKN as for soil.

The experimental plots were maintained by removing seedlings of species other than *Spartina*, principally the annual *Salicornia bigelovii*. The aboveground biomass of *Salicornia bigelovii* was quantified in 1999 by collecting material from the entire 2 × 2 m plots on 11 and 24 March, 20 May, 7 June, and 7 July, which encompassed the recruitment period. Biomass was dried to constant weight and weights were summed for the five removal dates.

Plants were sampled in September of each year by placing a 0.25-m^2 circular frame offset from the center of each 2 × 2 m plot in order to kneel on the boardwalk and sample without trampling. The central location was chosen to reduce edge effects. All shoots arising inside the quadrat were counted and measured from the base to the tip of the longest leaf, extended manually along a meter stick. Stems that were lying down and decomposing (previous year's dead stems) were not considered. With these data six variables were analyzed statistically: stem density, maximum stem length, mean stem length, total stem length, the number of stems

TABLE 1. Experimental layout and codes for data sets indicating treatment and year of sampling.

No. years of fertilization	Year sampled				
	1995	1996	1997	1998	1999
0	C_{95}	C_{96}	C_{97}	C_{98}	C_{99}
1	$F_{1\text{-}95}$	$U_{1\text{-}96}$	$U_{1\text{-}97}$	$U_{1\text{-}98}$	$U_{1\text{-}99}$
2	$F_{2\text{-}95}$	$F_{2\text{-}96}$	$U_{2\text{-}97}$	$U_{2\text{-}98}$	$U_{2\text{-}99}$
3	$F_{3\text{-}95}$	$F_{3\text{-}96}$	$F_{3\text{-}97}$	$U_{3\text{-}98}$	$U_{3\text{-}99}$
4	$F_{4\text{-}95}$	$F_{4\text{-}96}$	$F_{4\text{-}97}$	$F_{4\text{-}98}$	$U_{4\text{-}99}$
5	$F_{5\text{-}95}$	$F_{5\text{-}96}$	$F_{5\text{-}97}$	$F_{5\text{-}98}$	$F_{5\text{-}99}$

Notes: Each fertilization (F) treatment consisted of one or more years of nitrogen (urea) addition. Controls (C) had no nitrogen added. U = data from F plots sampled after the last fertilization to assess any legacy of nitrogen addition. Each treatment had five replicates; each replicate was sampled in five consecutive years. Code explanation: C_{95} indicates control plots sampled in 1995; $F_{1\text{-}95}$ indicates the one-year fertilization treatment sampled in 1995; U indicates plots that urea previously fertilized but unfertilized during the year of sampling, e.g., $U_{1\text{-}96}$ is the data set one year after $F_{1\text{-}95}$.

>60 cm, and number of stems >90 cm. Too few stems exceeded 120 cm to be analyzed.

Statistical analyses

We tested urea-addition treatments using two alternative statistical designs (Table 1), a complete fully replicated design (the complete design) and a repeated-measures design. The effect of using alternative reference data was tested by comparing results of treatments to different years of data in control plots. Means for data from the experimental plots are coded by treatment and date of sampling (Table 1): C_{99} indicates control plots sampled in 1999; $F_{1\text{-}95}$ indicates the one-year fertilization treatment sampled in 1995; U indicates plots that were previously fertilized but unfertilized during the year of sampling (i.e., $U_{1\text{-}96}$ is the data set one year after $F_{1\text{-}95}$).

For the complete design, six one-way ANOVAs were performed; each analysis compared all fertilized treatments ($F_{1\text{-}95}$, $F_{2\text{-}96}$, $F_{3\text{-}97}$, $F_{4\text{-}98}$, and $F_{5\text{-}99}$ with $n = 5$ replicates) with six sets of control data (C_{95}, C_{96}, C_{97}, C_{98} and C_{99}, all with $n = 5$ replicates, and the control plots combined for all years, i.e., $C_{95+\ldots+99}$, with 25 replicates). Data were analyzed independently for each response variable (density, maximum length, mean length, total length, number of stems >60 cm, and number of stems >90 cm). Data were transformed when necessary after inspection of the residuals to comply with ANOVA assumptions. Multiple comparisons were done with the Tukey hsd method (Day and Quinn 1989).

The repeated-measures design used only the data from the 5-yr treatment plots ($F_{5\text{-}95}$, $F_{5\text{-}96}$, $F_{5\text{-}97}$, $F_{5\text{-}98}$, and $F_{5\text{-}99}$) and consecutive years of data for the control plots (C_{95}, C_{96}, C_{97}, C_{98}, and C_{99}), for a total of five fertilized and five control plots. As with the complete design, data were analyzed independently for each response variable. The repeated-measures design was analyzed using two approaches; repeated-measures ANOVA and MANOVA (Underwood 1997). Because the objective was to test fertilization effects, several approaches were used depending on the response variable to comply with the assumptions of repeated-measures ANOVA. Data were transformed; when no transformation allowed compliance with the analysis assumptions, subsets of the data were chosen either to eliminate highly variable years or to increase replication. When neither of these strategies worked, the Box's ε probability was calculated with adjusted degrees of freedom (Hintze 2000), although this last approach does not allow testing of treatment effects independently from the within-subject (year) effect. Coefficients of variation were obtained to explore variability of the data (Zar 1999), and we used Miller's *Z* statistic for comparing two coefficients of variation to test differences between pairs of coefficients (Miller 1991).

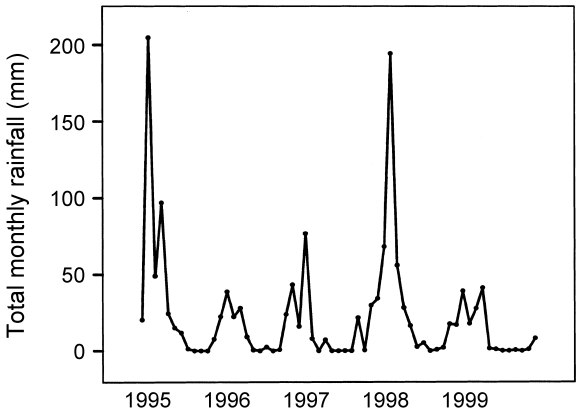

FIG. 1. Rainfall data from Lindbergh Field, San Diego, California, USA.

We tested for a legacy of urea addition (comparing fertilized treatments to control conditions in the year after fertilization ended) by using paired *T* tests ($F_{1\text{-}95}$ and $U_{1\text{-}96}$, $F_{2\text{-}96}$ and $U_{2\text{-}97}$, $F_{3\text{-}97}$ and $U_{3\text{-}98}$, and $F_{4\text{-}98}$ and $U_{4\text{-}99}$) on each response variable independently. We used *F* tests for equality of variances (Zar 1999); when variances were unequal, data were transformed; otherwise, Welch's adjusted *T* was used (Statistical Sciences 1999).

One-way ANOVA, repeated-measure MANOVA, paired *T* tests, *F* tests, and Tukey hsd test were done with S-PLUS version 4.5 (Statistical Sciences 1999). Repeated-measures ANOVA were done with NCSS 2000 (Hinzte 2000). Means are reported ±1 standard error.

RESULTS

Site conditions and responses of Spartina foliosa

The soil was primarily sand (64 ± 5.7% at the surface, 71 ± 8.6% at 8–10 cm depth; $n = 5$ samples), with more clay at the surface (27 ± 4.1%) than at 8–10 cm depth (14 ± 3.9%). Accordingly, bulk density

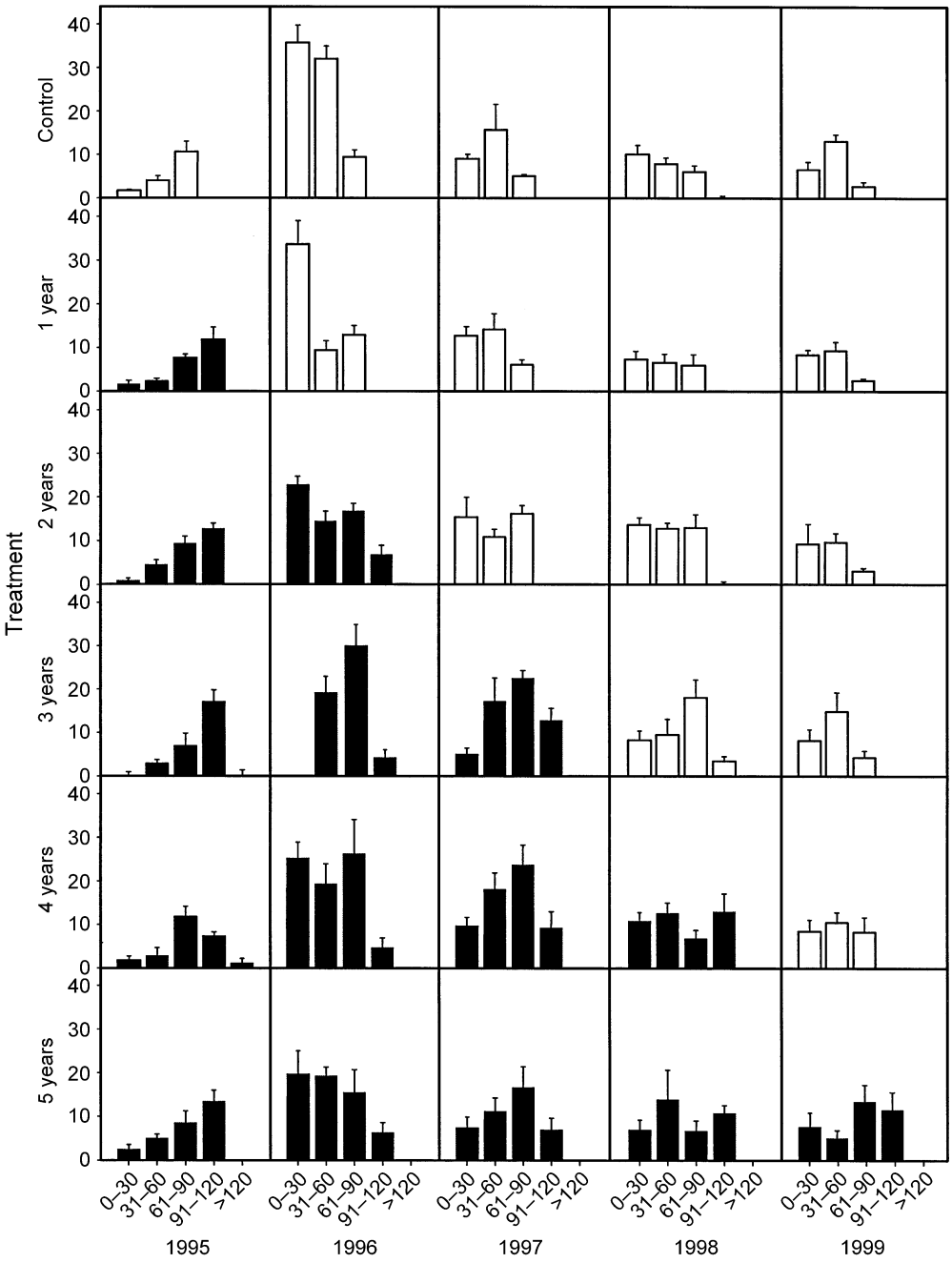

FIG. 2. Histograms of cordgrass (*Spartina foliosa*) stem lengths over time, by treatment. Height classes (in centimeters) are on the *x*-axis; the *y*-axis shows number of stems in each stem class. Black histogram bars show data during years with urea addition. Data are means and 1 SE.

was lower at the surface (0.74 ± 0.05) than at 8-10 cm (1.05 ± 0.08). Environmental conditions were variable over the five-year sampling period, with high rainfall in 1995 and 1998 (Fig. 1). Average soil salinities for the five years (1995–1999) were 42 ± 1.0, 52 ± 1.2, 62 ± 1.6, 57 ± 1.4, and 68 ± 2.4 parts per thousand, respectively (n = 30 samples). These marsh soils are typically hypersaline in late summer, when tidal amplitudes are minimal, evaporation rates are high, and effects of winter rainfall are no longer apparent. Soil pH averaged 6.7 ± 0.04, 6.6 ± 0.05, 6.9 ± 0.03, 7.1 ± 0.03, and 7.1 ± 0.04 for the same five years (n = 30).

Despite urea addition, soil TKN (total Kjeldahl nitrogen) and *Spartina* tissue TKN levels were relatively constant with no treatment effects (grand means = 0.69

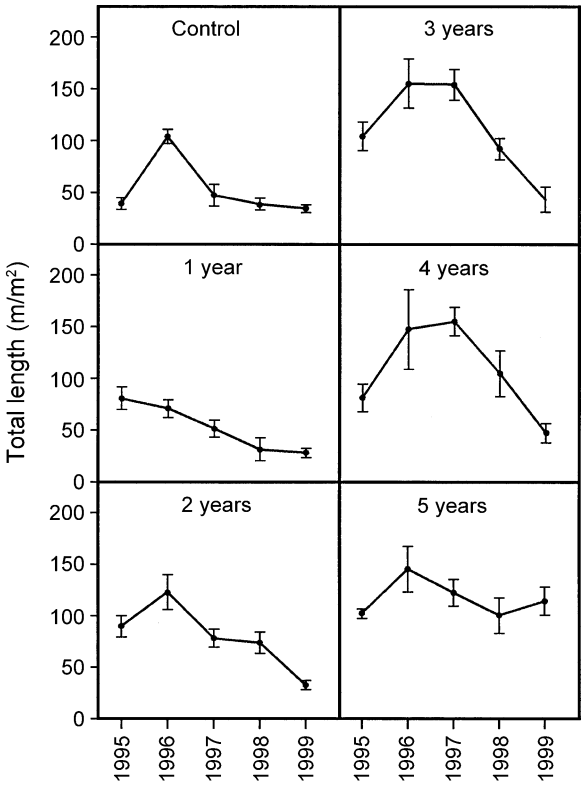

FIG. 3. Total stem length data for *Spartina* over time, by treatment. Data are means ± 1 SE.

± 0.02 mg/g and 23.03 ± 0.32 mg/g, respectively, n = 120 samples) over the four years of measurement (1995–1998). That the system was dynamic, however, was apparent in the *Spartina* density and height data. Significant effects of urea addition were seen in all six *Spartina* response variables (comparing control and fertilized plots, Tables 2 and 3) and are summarized as histograms of stem length (Fig. 2) and graphs of total length over time (Fig. 3). Fertilized plots had more and taller stems than control plots in all years of the experiment. Density ranged from a mean of 16.4 to 77.6 stems/0.25 m² in control plots and 24.2 to 76.6 stems/0.25 m² in fertilized plots. The highest density was found in 1996, the year after heavy rainfall. Maximum length varied from a mean of 71.0 to 85.2 cm in control plots and 95.0 to 114.8 cm in fertilized plots. Mean length ranged from 33.7 to 60.4 cm in control plots and from 48.7 to 88.4 cm in fertilized plots. Total length varied from 8.79 to 26.12 m in control plots and from 20.1 m to 38.8 m in fertilized plots. The mean number of stems >60 cm ranged from 3.0 to 11.2 stems/0.25 m² in control plots and from 20.0 to 35.4 stems/0.25 m² in fertilized plots. The mean number of stems >90 cm ranged from 0 to 0.4 stems/0.25 m² in control plots and from 5.2 to 18.2 stems/0.25 m² in fertilized plots. Only fertilized plots produced stems taller than 120 cm.

Spartina growth showed high interannual variation (Table 2), particularly for density, which was considerably higher in 1996 than other years. The control plots increased 4.7-fold from the minimum in 1995 (16.4 stems/0.25 m²) to the maximum in 1996 (77.6 stems/0.25 m²). Total length, which integrates density and height, likewise increased, although the difference between the highest mean value (C_{97} = 26.1 m) and the lowest (C_{99} = 8.8 m) was less than for density. The means for the remaining four response variables had lesser ranges: maximum length (C_{98} = 85.2 m, C_{99} = 71.0 m), mean length (C_{98} = 60.4 m, C_{99} = 33.7 m), number of stems >60 cm tall (C_{98} = 11.2, C_{99} = 5.8) and number of stems >90 cm when present (C_{98} = 0.4, C_{99} = 0.2).

During the 5th growing season, the biomass of *Salicornia bigelovii* that was removed averaged 27 ± 7 to 80 ± 10 g/m² among the six treatments, with the mean for $U_{4\text{-}99}$ significantly lower than the others. *Spartina* biomass was not harvested due to restrictions on destructive sampling, but total length data for *Spartina* (Fig. 3) agree that $U_{4\text{-}99}$ plots were least productive in 1999. Rough estimates of biomass from those data indicate that the harvested *S. bigelovii* comprised 25% or less of the total biomass in all treatments.

Complete design

The choice of reference data set affected the interpretation of outcomes. In analyzing the complete design, we made six comparisons per variable, i.e., treatment plots were compared to control plots for each of the five years (C_{95} to C_{99}) as well as for all years pooled ($C_{95} + \cdots + C_{99}$). For each of these one-way ANOVAs, the treatment effect was always significant for all response variables with P values always <0.05, but multiple comparisons failed to detect differences between some fertilization treatments and some controls, while differences were detected between several pairs of fertilization treatments (Table 3). Only two closely related variables showed consistent results independent of the year selected as control; for maximum length and the number of stems >90 cm, multiple comparisons detected differences between all controls and all fertilization treatments (Table 3).

The other four variables showed different outcomes for same-year controls and all-year control data, depending on the control data sets. When density responses were compared for each fertilization treatment and same-year control data (i.e., diagonals along the first five columns of multiple comparisons of Table 3), we detected significant differences only for the 3-yr treatment ($F_{3\text{-}97}$–C_{97}). Overall, 15 out of 30 pairwise comparisons between control and fertilization treatments were significant. For mean length, urea addition for 1, 3, and 5 yr produced results that were significantly different from same-year controls ($F_{1\text{-}95}$–C_{95}, $F_{3\text{-}97}$–C_{97}, and $F_{5\text{-}99}$–C_{99}), and 17 out of 30 possible pairwise comparisons between control and fertilization

TABLE 2. Summary of *Spartina* responses to fertilization treatments and control conditions ($n = 5$ replicates).

Response variable	No. years of fertilization	Mean ± 1 SD				
		1995	1996	1997	1998	1999
Stem density (no. stems/0.25 m^2)	0	16.40 ± 4.28	77.60 ± 11.15	29.60 ± 13.24	24.00 ± 6.48	22.40 ± 4.93
	1	**24.20 ± 4.66**	56.00 ± 14.40	33.20 ± 10.21	18.00 ± 12.00	19.40 ± 5.68
	2	26.80 ± 7.69	**62.40 ± 11.78**	43.20 ± 13.08	39.80 ± 7.69	21.40 ± 9.61
	3	29.20 ± 7.19	76.60 ± 24.34	**56.80 ± 12.52**	38.80 ± 6.91	25.80 ± 7.60
	4	25.60 ± 8.82	75.60 ± 33.78	61.20 ± 11.56	**44.00 ± 15.35**	26.60 ± 5.81
	5	32.00 ± 3.94	69.20 ± 19.20	48.40 ± 10.41	40.80 ± 19.15	**40.60 ± 6.27**
Maximum stem length (m)	0	84.00 ± 6.44	71.60 ± 5.86	73.20 ± 5.07	85.20 ± 4.97	71.00 ± 8.00
	1	**114.80 ± 13.33**	82.20 ± 2.28	77.20 ± 5.26	73.20 ± 22.64	69.80 ± 5.59
	2	113.20 ± 3.56	**102.20 ± 5.12**	83.40 ± 7.86	85.60 ± 10.38	79.40 ± 8.79
	3	114.80 ± 10.18	96.60 ± 6.54	**109.60 ± 6.19**	96.00 ± 7.07	74.40 ± 3.05
	4	112.80 ± 20.36	95.00 ± 11.98	98.40 ± 7.83	**105.40 ± 7.06**	77.60 ± 7.09
	5	113.20 ± 7.66	101.80 ± 5.93	98.40 ± 4.39	105.00 ± 3.24	**106.00 ± 8.09**
Mean stem length (m)	0	60.40 ± 5.02	33.73 ± 3.30	40.28 ± 1.36	41.35 ± 7.02	39.47 ± 5.47
	1	**81.79 ± 11.63**	31.90 ± 4.62	38.49 ± 3.20	40.31 ± 7.61	35.70 ± 3.61
	2	84.63 ± 3.73	**48.72 ± 6.92**	46.00 ± 6.32	45.82 ± 7.41	40.96 ± 10.06
	3	88.45 ± 6.77	50.63 ± 9.00	**68.20 ± 6.19**	59.21 ± 8.82	38.97 ± 14.59
	4	80.34 ± 9.78	44.16 ± 12.94	63.30 ± 9.34	**57.00 ± 12.93**	44.31 ± 13.29
	5	80.39 ± 7.07	52.71 ± 11.24	63.02 ± 4.86	63.21 ± 8.53	**70.69 ± 14.93**

Notes: Boldface type indicates data for the final year of urea addition. Data for total stem length are in Fig. 3; data for stem length classes are in Fig. 2.

treatments were significant (Table 3). For total length, we found three significant pairwise comparisons ($F_{3\text{-}97}$–C_{97}, $F_{4\text{-}98}$–C_{98}, and $F_{5\text{-}99}$–C_{99}) and 17 out of 30 pairwise comparisons between control and fertilization treatments were significant (Table 3). Lastly, for the number of stems >60 cm tall, pairwise comparisons with same-year controls were significant for ($F_{2\text{-}96}$–C_{96}, $F_{3\text{-}97}$–C_{97}, and $F_{5\text{-}99}$–C_{99}), and 20 out of 30 pairwise comparisons between control and fertilization treatments were significant (Table 3).

Of the four variables that were not consistently significant in the multiple comparisons between fertilization treatments and controls (density, mean length, total length, and stems >60 cm) the two treatments with the fewest significant pairwise comparisons ($F_{1\text{-}95}$ with 15 out of 18 contrasts) and $F_{4\text{-}98}$ (13 out of 18 contrasts) concerned data taken in years of high rainfall, when growth was elevated even in controls (Figs. 2 and 3). Another pattern held for all but mean length; the other five variables had fewer significant contrasts for one year of fertilization than for two years. Finally, pooling the control data ($C_{95...99}$) led to 23 significant paired comparisons between fertilization and control plots, whereas comparisons with individual years had fewer, i.e., C_{95} (20), C_{96} (19), C_{97} (20) and C_{98} (22), except for C_{99} (25).

Repeated-measures design

Repeated-measures analyses found significant treatment effects for density, maximum length, mean length and total length (Table 4). Repeated-measures ANOVA required the use of subsets of data for density and total length and the use of adjusted degrees of freedom (Box's *P*) for mean length, maximum length, stems >60 cm, and stems >90 cm. For these last four variables, neither transformation, the use of subsets of data, nor increased replication led to compliance with repeated-measures ANOVA assumptions; hence, the treatment effect could not be tested by itself, but it could be explored through the interaction (Table 4). For density, mean length, and maximum length, year (within subject) effects were significant, but effects were not significant for total length, stems >60 cm, and stems >90 cm tall. Despite having less stringent assumptions, MANOVA analyses for repeated measures showed fertilization-treatment effects only for the number of stems >90 cm, although there were year effects for all variables.

Variability

Fertilization did not increase variability, as measured by coefficients of variation (Table 2). For mean length, coefficients of variation appeared higher for fertilized treatments than controls in 1994–1998, but only one difference was significant, $F_{3\text{-}97}$–C_{97} ($Z = 1.993$, $P = 0.023$) (Table 2). Total length was more variable; for treatments $F_{1\text{-}95}$ and $F_{3\text{-}97}$ the coefficients of variation were lower than the corresponding control data, but for $F_{2\text{-}96}$, $F_{4\text{-}98}$, and $F_{5\text{-}99}$ they were higher. The number of stems >60 cm tall also showed differences in the values of the coefficients of variation, being lower for treatments $F_{1\text{-}95}$, $F_{2\text{-}96}$, and $F_{5\text{-}99}$ than the corresponding control data and higher for treatments $F_{3\text{-}97}$ and $F_{4\text{-}98}$ than the corresponding control data. In general, changes in the coefficient of variation from year to year and by treatment showed few patterns (Table 2).

TABLE 2. Extended.

Coefficient of variation				
1995	1996	1997	1998	1999
0.26	0.14	0.45	0.27	0.22
0.19	0.26	0.31	0.67	0.29
0.29	**0.19**	0.30	0.19	0.45
0.25	0.32	**0.22**	0.18	0.29
0.34	0.45	0.19	**0.35**	0.22
0.12	0.28	0.22	0.47	**0.15**
0.08	0.08	0.07	0.06	0.11
0.12	0.03	0.07	0.31	0.08
0.03	**0.05**	0.09	0.12	0.11
0.09	0.07	**0.06**	0.07	0.04
0.18	0.13	0.08	**0.07**	0.09
0.07	0.06	0.04	0.03	**0.08**
0.08	0.10	0.03	0.17	0.14
0.14	0.14	0.08	0.19	0.10
0.04	**0.14**	0.14	0.16	0.25
0.08	0.18	**0.09**	0.15	0.37
0.12	0.29	0.15	**0.23**	0.30
0.09	0.21	0.08	0.14	**0.21**

Legacy of urea addition

For most response variables, there were indications that urea addition left a brief legacy (e.g., Fig. 3). However, our ability to detect a legacy was influenced by the choice of reference data (a post-fertilization mean that is significantly greater than either C_{95} or same-year control data indicates a legacy). For density, mean length, and total length of *Spartina* stems, more legacies were detected (i.e., more *T* tests were significant) using initial control data (C_{95}) than same-year control data (Table 5). The reverse was true for maximum length and stems >60 cm tall. Selection of the reference data set was critical, because control plots changed over time (Figs. 2 and 3, Table 2).

Densities were always significantly different from (greater than) 1995 control data but only two of the four same-year comparisons indicated a legacy of urea addition. For mean length, three of four comparisons with C_{95} data were different, but two means were lower ($U_{1\text{-}96}$, $U_{2\text{-}97}$) and one was higher ($U_{4\text{-}99}$). Using same-year control data, only one difference in mean lengths was significant ($U_{3\text{-}98}$–C_{98}).

For maximum length, fertilized plots had higher values than same-year control data one year after fertilization in three out of four comparisons (only $U_{4\text{-}99}$–C_{99} was not significant); in contrast, only one comparison with 1995 control data indicated a legacy ($U_{3\text{-}98}$–C_{95}). For numbers of stems >60 cm, no legacies were indicated in comparisons with 1995 control data, but two comparisons with same-year data were significant ($U_{2\text{-}97}$–C_{97} and $U_{3\text{-}98}$–C_{98}, square-root-transformed data). Because stems >90 cm were almost entirely restricted to years with fertilization, we did not test this response variable for persistent effects.

Fertilization and thresholds for Clapper Rail nesting

A final approach to the evaluation of treatment outcomes was to ask which plant canopies met criteria for nesting habitat for the endangered Light-footed Clapper Rail, determined by comparing marshes with and without nesting rails (Zedler 1993). At the scale we sampled (0.25 m^2), suitable habitat would have at least 25 *Spartina* stems, of which at least 23 stems would be >60 cm tall and at least 8 stems >90 cm tall (Zedler 1993). Mean densities of the control plots were within the range needed by Clapper Rails in 1996 and 1997 and all fertilized treatments met the criteria in all years (Table 2). Plots fertilized for 1, 2, and 3 yr had legacies that sustained adequate densities for two consecutive years after fertilization ceased. For example, plots fertilized for 1 yr still had 57% more stems than ''needed'' in 1996 ($U_{1\text{-}96}$) and 27% more in 1997 ($U_{1\text{-}97}$); thereafter, densities dropped below the threshold. Plots fertilized for 2 and 3 yr also maintained sufficient densities for two years ($U_{2\text{-}97}$ was 31% higher and $U_{2\text{-}98}$ was 36% higher than needed; $U_{3\text{-}98}$ was 32% higher and $U_{3\text{-}99}$ was 55% higher than needed). Finally, plots fertilized for 4 yr showed a legacy for the one year of available data. This analysis is based on means, and it should be noted that not all plots per treatment met the requirement (Table 6), but at least three plots per treatment achieved a density equal to or higher than 25 stems/0.25 m^2. For treatments 1 and 2 all plots had the required density; for treatment 3 all plots had the required density the first year after the last year with fertilization but during the second year only two plots maintained high densities. Some control plots had a density of 25 stems/0.25 m^2 or higher; in 1996 all plots exceeded the requirement. On a per plot basis, density criteria were more often met

TABLE 3. One-way ANOVA results per variable and Tukey hsd pairwise comparisons for the complete design. Treatment was the addition of nitrogen (as urea) for 1, 2, 3, 4, or 5 years (e.g., F_1 = 1 yr of fertilization).

				Multiple comparisons (Tukey method)‡				
		ANOVA		Treatment × controls				
Variable	Control†	*F*	*P*	F_1–C_i	F_2–C_i	F_3–C_i	F_4–C_i	F_5–C_i
Stem density	C_{95}	15.8	****	…	*	*	*	*
	C_{96}	14.6	****	*	…	…	*	*
	C_{97}	8.6	****	…	*	*	…	…
	C_{98}	12.1	****	…	*	*	…	…
	C_{99}	13.1	****	…	*	*	*	…
	All	3.33	*	…	*	…	…	…
Maximum stem length	C_{95}	8.4	***	*	*	*	*	*
	C_{96}	18	****	*	*	*	*	*
	C_{97}	16.9	****	*	*	*	*	*
	C_{98}	8	***	*	*	*	*	*
	C_{99}	17.2	****	*	*	*	*	*
	All	33.8	****	*	*	*	*	*
Mean stem length	C_{95}	6.3	***	*	…	…	…	…
	C_{96}	14.3	****	*	…	*	*	*
	C_{97}	11.5	****	*	…	*	…	*
	C_{98}	10.3	****	*	…	*	…	*
	C_{99}	11.3	****	*	…	*	…	*
	All	16.7	****	*	…	*	…	*
Total stem length	C_{95}	6.9	***	…	*	*	…	*
	C_{96}	2.7	*	…	…	…	…	…
	C_{97}	5.7	**	…	*	*	…	…
	C_{98}	6.7	***	…	*	*	*	*
	C_{99}	7.6	***	…	*	*	*	*
	All	11.6	****	…	*	*	*	*
No stems > 60 cm	C_{95}	4.8	**	…	*	…	*	…
	C_{96}	5.1	**	…	*	…	*	…
	C_{97}	7.5	***	…	*	*	…	*
	C_{98}	7.1	***	…	*	*	…	*
	C_{99}	8.9	****	*	*	*	*	*
	All	21.3	****	*	*	*	*	*
No stems > 90 cm	C_{95}	6.7	**	*	*	*	*	*
	C_{96}	7.8	***	*	*	*	*	*
	C_{97}	7.8	***	*	*	*	*	*
	C_{98}	7.4	**	*	*	*	*	*
	C_{99}	7.8	***	*	*	*	*	*
	All	35.1	****	*	*	*	*	*

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; **** $P < 0.0001$.

† C_{95} = control plots sampled in 1995, etc.

‡ The first five columns under ''Multiple comparisons'' show results for fertilized treatments × six alternative control data sets. Using stem density as an example, ANOVA showed significant responses to urea addition, but multiple comparisons did not detect differences among all treatments and all controls. The remaining columns compare treatments with one another.

than height criteria. While being fertilized, an average of 4.4 plots met the density criterion, while only 3.2 plots, on average, achieved the first threshold (23 stems/0.25 m^2 >60 cm tall) and 3.5 plots met the second (8 stems/0.25 m^2 >90 cm tall; Table 6).

DISCUSSION

In 1995 (p. 233), Underwood called for ''a massive research effort to use ecological experimental procedures to evaluate the effects of (the hypotheses proposed by) managerial decisions.'' That same year, we began a five-year experiment to address the hypothesis that increased effort could achieve a difficult restoration target. Consistent with local management aims, we evaluated vegetation canopies in relation to rare-bird-nesting potential. Underwood (1995: 237) also asked ecologists to ensure that ''experimental treatment is accompanied by relevant and appropriate controls,'' and White and Walker (1996: 347) advocated research that tests ''sensitivity of restoration to variation in reference information.'' Our evaluation of alternative control data sets and alternative statistical designs help fill a general need for restoration projects to be assessed more comprehensively (Michener 1996), as well as a need to repeat experiments to strengthen confidence in findings (Underwood 1997). We demonstrate that assessing outcomes can be very complex, because decisions about the choice of response variable, the reference data set, and the statistical design all affect perceptions of experimental outcomes.

Response variable

In our salt-marsh case, all six response variables indicated differences between controls and treatments,

TABLE 3. Extended.

Multiple comparisons (Tukey method)‡									
Among treatments									
F_2–F_1	F_3–F_1	F_4–F_1	F_5–F_1	F_3–F_2	F_4–F_2	F_5–F_2	F_4–F_3	F_5–F_3	F_5–F_4
*	*	*	…	…	…	*	…	…	…
*	*	…	…	…	…	*	…	…	…
*	*	…	…	…	…	…	…	…	…
*	*	…	…	…	…	*	…	…	…
*	*	…	…	…	…	*	…	…	…
*	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
*	…	*	…	…	…	*	…	…	…
*	…	*	…	…	…	…	…	…	…
*	…	*	…	…	…	*	…	…	…
*	…	*	…	…	…	*	…	…	…
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…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…

but four of the six variables were inconsistent in indicating *which* treatments exceeded controls, based on multiple comparisons. Only maximum length and the number of stems >90 cm tall had consistent outcomes for all comparisons with reference data (Table 3). In addition to statistical-significance tests, we used previously determined criteria for stem densities and heights to determine if increased effort (more years of urea addition) could produce nesting habitat suitable for an endangered bird. This is a restrictive approach to judging the outcome, but it demonstrates an additional assessment alternative, namely, using central-tendency variables vs. the number of plots with the required characteristics. We found different outcomes when we required only that means met the criterion vs. requiring that all replicate plots comply with height criteria (Table 6). The latter approach was more conservative, because treatments could achieve the desired mean even when some plots were not in compliance. For example, $F_{2\text{-}96}$ averaged 25 stems/m^2 that were >60 cm tall, but only two plots had more than the necessary 23 tall stems. Finally, we detected legacy effects for some attributes, particularly density, but not for the number of stems that were >60 cm or >90 cm tall. The most robust outcome would be for response variables to show consistency in treatment effects and for differences in means to be supported by consistent results among replicate plots. Lacking that, we believe it is worth extra assessment effort to know about inconsistencies, i.e., knowledge of complexity is preferable to the uncertainty of measuring just one response and having to assume that it is representative.

Reference data

We document high interannual variability and contradictory interpretations from using initial vs. same-year reference data. The doubling of *Spartina* total length in control plots between 1995 and 1996 was as great a difference as the ±urea response. The cause of this interannual variation could be the unusually high

TABLE 4. Results of repeated-measures analyses.

Response variable	Source of variation	Repeated measures						
		ANOVA			MANOVA			
		F	df	*P*	Pillai trace	Approx. *F*†	df	*P*
Stem density‡	Treatment (Trt)	13.3	1	0.002	0.89	10.2	4	0.012
	Year	33.8	3	<0.001	0.99	124.1	4	<0.001
	Trt. × Year	3.9	3	0.029	···	···	···	···
Maximum stem length	Treatment	···	···	···	0.66	2.5	4	0.174§
	Year	11.7	3	<0.001§	0.96	39	4	<0.001§
	Trt. × Year	3	3	0.064§	···	···	···	···
Mean stem length	Treatment	···	···	···	0.77	4.2	4	0.074§
	Year	15.3	3	<0.001§	0.98	75.4	4	<0.001§
	Trt. × Year	0.92	3	0.41§	···	···	···	···
Total stem length‖	Treatment	35.5	1	<0.001	0.66	2.5	4	0.169
	Year	1.8	3	0.174	0.83	6.5	4	0.032
	Trt. × Year	0.8	3	0.532	···	···	···	···
No. stems > 60 cm	Treatment	···	1	···	0.74	3.6	4	0.096§
	Year	2.3	3	0.136§	0.85	7.2	4	>0.026§
	Trt. × Year	2.3	3	0.143§	···	···	···	···
No. stems > 90 cm	Treatment	···	···	···	0.98	63.4	4	<0.001§
	Year	2.1	3	0.151§	0.98	63.5	4	<0.001§
	Trt. × Year	1.9	3	0.178§	···	···	···	···

† *F* value approximated by statistical procedure since an exact value cannot be obtained due to the lack of compliance with all the analysis assumptions.

‡ For stem density, 1996 and 1998 data were excluded in ANOVA and MANOVA; response variables were square-root transformed.

§ *P* values calculated using Box ε.

‖ For total stem length, 1996 data were excluded in ANOVA and MANOVA.

rainfall in 1995, that is, favorable growing conditions could have led *Spartina* to increase carbon storage belowground with a lag effect on vegetative propagation in 1996. Indeed, control plots had more than 10 times as many short stems in 1996 as in 1995 (Fig. 2). Knowing that total length of *Spartina* can vary two-fold without urea addition is essential to the assessment of restoration efforts and the selection of reference data for restoration. Although it is common to use initial conditions for comparison, and although it is tempting to rely on a single-year's data as a reference, we recommend that reference data be obtained both initially and during treatment in order to understand interannual variability in environmental conditions and/or plant growth. The strongest conclusions about management actions would derive from treatment effects that exceed initial *and* same-year control data. When effects differ from same-year controls but not initial conditions, a management effect is still indicated, while the reverse, i.e., a difference from initial conditions but not same-year controls, suggests a spurious result.

Ecologists can choose from a variety of reference states in selecting restoration targets (Pickett and Parker 1994). Stated somewhat differently by White and Walker (1996: 342), ''no one reference site observed at an arbitrary time should be used to determine goals for a restoration project.'' Annual monitoring of *Spartina* at Tijuana Estuary (J. Zedler, *unpublished data*) shows a ten-fold range in total stem length for four stations sampled over 13 yr. One can find low and high targets among both years and stations. While choices for restoration targets involve a much larger scale issue than the one addressed here (i.e., which control data sets are most appropriate for comparison with experimental treatments), we show that even for a narrow range of options, the choice of comparison data sets affects the judgment of the outcome.

Statistical design

It is a common management practice to assess the effects of long-term treatment by monitoring several variables on the same plot over a series of years and analyzing the result with repeated-measures procedures (Michener 1996). It is especially tempting to employ permanent plots when the experimental treatments are costly and time consuming. The temporal nonindependence of monitored plots can, however, lead to a false rejection of the null hypothesis (Underwood 1995). Gurevitch and Chester (1986) argue that some of the constraints of repeated measures can be overcome through multivariate analyses of such data; indeed, our use of MANOVA allowed more direct tests of treatment effects than ANOVA and did not show an effect of treatment on maximum length, while ANOVA indicated that four null hypotheses be rejected through treatment effects (density, total length) and interactions (maximum length, mean length). Overall, we demonstrated several benefits of fully replicated experimental design; it allowed a more straightforward analysis of the results, and we separated treatment and legacy ef-

TABLE 5. Test of legacy effects of urea fertilization.

Variable	*F* test for variance equality		*T* test†	
	F	*P*	*T*	*P*
Stem density				
U_{1-96}–C_{95}‡	0.292	0.260	−6.794	<0.001
U_{2-97}–C_{95}‡	0.293	0.262	−4.976	0.001
U_{3-98}–C_{95}	0.383	0.376	−6.165	<0.001
U_{4-99}–C_{95}	0.541	0.567	−3.160	0.013
U_{1-96}–C_{96}	0.599	0.632	2.652	0.029
U_{2-97}–C_{97}	1.024	0.982	−1.634	0.141
U_{3-98}–C_{98}	0.880	0.905	−3.494	0.008
U_{4-99}–C_{99}	0.719	0.757	−1.232	0.253
Maximum stem length				
U_{1-96}–C_{95}	7.914	0.070	0.589	0.572
U_{2-97}–C_{95}	0.672	0.709	0.132	0.898
U_{3-98}–C_{95}	0.830	0.861	−2.805	0.023
U_{4-99}–C_{95}	0.825	0.857	1.494	0.174
U_{1-96}–C_{96}	6.596	0.095	−3.771	0.006
U_{2-97}–C_{97}	0.416	0.416	−2.438	0.041
U_{3-98}–C_{98}	0.494	0.511	−2.794	0.023
U_{4-99}–C_{99}	1.272	0.821	−1.380	0.205
Mean stem length				
U_{1-96}–C_{95}	1.180	0.876	9.336	<0.001
U_{2-97}–C_{95}	0.632	0.668	3.990	0.004
U_{3-98}–C_{95}	0.324	0.301	0.263	0.799
U_{4-99}–C_{95}	0.143	0.086	2.533	0.035
U_{1-96}–C_{96}	0.511	0.531	0.720	0.492
U_{2-97}–C_{97}§	0.046	0.011	−1.980	0.113
U_{3-98}–C_{98}	0.634	0.670	−3.542	0.008
U_{4-99}–C_{99}	0.169	0.113	−0.753	0.473
Total stem length				
U_{1-96}–C_{95}	0.485	0.500	−3.011	0.017
U_{2-97}–C_{95}	0.449	0.457	−3.636	0.007
U_{3-98}–C_{95}	0.330	0.308	−4.455	0.002
U_{4-99}–C_{95}	0.394	0.389	−0.702	0.503
U_{1-96}–C_{96}	0.696	0.734	3.082	0.015
U_{2-97}–C_{97}	1.456	0.725	−2.191	0.060
U_{3-98}–C_{98}	0.310	0.283	−4.526	0.002
U_{4-99}–C_{99}	0.700	0.114	−1.246	0.248
Stems > 60 cm				
U_{1-96}–C_{95}	1.242	0.839	−0.759	0.470
U_{2-97}–C_{95}	1.442	0.731	−1.828	0.105
U_{3-98}–C_{95}	0.285	0.251	−2.080	0.071
U_{4-99}–C_{95}	0.493	0.510	0.488	0.638
U_{1-96}–C_{96}	0.906	0.925	−0.960	0.365
U_{2-97}–C_{97}‡	0.244	0.200	−5.943	<0.001
U_{3-98}–C_{98}‡	0.296	0.265	−4.070	0.004
U_{4-99}–C_{99}‡	0.519	0.541	−1.806	0.108

Notes: For comparison code key, see Table 1. For all analyses, df = 1.

† Nonsignificant *T* tests indicate that treatment did not leave a legacy; i.e., *Spartina* reverted to levels found in control plots.

‡ Data transformation (sqrt).

§ Used Welch's adjusted *T*.

fects from interannual effects, thus eliminating the risk of temporal nonindependence problems common in repeated-measures designs (Underwood 1997). The trade-off, of course, was the need for increased effort. In our case, 30 plots instead of 10 were treated and monitored over five years. There was an ''economy of scale,'' however, because of the time involved collecting materials and travelling to and from the research site. We believe the benefits outweighed the extra costs for this system with its high interannual variability and enhanced risk of false rejection (Type I error).

Conclusion

Our five-year experiment and rigorous analysis led to a strong conclusion: increased effort did not reverse the degradation transition caused by coarse soil. Thus, Hobbs and Norton's (1996: 96) concept of ''multiple states with thresholds of degradation that can be crossed only with difficulty'' was useful in characterizing events at San Diego Bay (California, USA). The deposition of sandy dredge spoils over historical tidal wetland was a major transition for the intertidal wetland, and the nesting function of the salt marsh could not be restored. It was not sufficient to excavate sediments and plant *Spartina foliosa*, because soils remained coarse and canopies were too short to attract the principal nesting bird, an endangered clapper rail. Even though adding urea twice a week could produce tall canopies, it was not sufficient to do so for a single growing season. Not even prolonged fertilization (4 yr) allowed *Spartina* to sustain high density or tall stems after urea addition ceased (year 5). Our findings support earlier indications that tall *Spartina* is extremely difficult to restore on coarse-textured soil, in part because belowground reserves do not accumulate (Zedler and Callaway 1999, Boyer et al. 2000). Having found no internal mechanism, such as sufficient N storage, that could shift short plants to tall, we conclude that perpetual urea addition would be needed to sustain tall *Spartina* canopies on coarse sediments, given suitable levels of other environmental factors (e.g., low elevation, creekside location, absence of competitors).

TABLE 6. Number of plots (out of five) that were in compliance with the requirements for Light-footed Clapper Rail nesting, by treatment and year.

Response	No. years of fertilization	No. plots in compliance				
		1995	1996	1997	1998	1999
Density	0	0	5	3	3	2
	1	3	5	5	1	1
	2	3	5	5	5	2
	3	3	5	5	5	2
	4	4	4	5	4	4
	5	5	5	5	5	5
Stems > 60 cm	0	0	0	0	0	0
	1	2	0	0	0	0
	2	3	2	0	0	0
	3	3	4	5	1	0
	4	2	3	4	2	0
	5	5	3	4	2	4
Stems > 90 cm	0	0	0	0	0	0
	1	4	0	0	0	0
	2	5	2	0	0	0
	3	5	2	4	0	0
	4	3	2	3	4	0
	5	5	3	2	4	4

At least some types of degradation appear to cause transitions that are not easily reversed. The consequence for ecological restoration in general is that *planners cannot begin with the assumption that every degradation can be reversed*; rather, they would be prudent to consider a range of targets, not just one previous state (or one reference site, White and Walker 1996), in setting the objectives for specific sites, and they should identify a range of approaches to be taken in achieving each potential target. Wherever possible, alternative targets and alternative approaches should be tested experimentally, so that the outcomes can be best understood.

Our understanding of an endangered bird's habitat requirements (tall plants) and the limiting factor for height growth (nitrogen) made this degraded coastal ecosystem useful for testing alternative analytical approaches. We were confident that we would find some positive responses to N addition; we were not certain that we could detect responses in all variables, all plots, all years, or all analyses. Our ability to detect responses was indeed a function of the approach taken, although the differences were in the details (e.g., multiple comparison tests, not treatment effects of ANOVA). Still, the details can be important when restoration is taking place within a mitigation context and when a finding of ''significantly different from reference conditions'' means that a mitigation project is not in compliance with permit conditions. Assessing the results of management actions demands careful consideration of the response variable, the reference data set, and the statistical design used to evaluate treatment effects. We were able to narrow the range of options because we knew some of the canopy requirements of the target nesting species, but even then we had six response variables, three reference data sets, and two statistical designs to choose from in assessing just one management action, namely, prolonged urea addition. While the need is great to conduct rigorous tests of hypotheses posed by management actions (Pickett and Parker 1994, Underwood 1995, Michener 1996), the task is far from simple. The most rigorous analytical process is warranted when the management decision is critical (as in determining if damages to endangered species habitat have been mitigated).

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