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New Tools for Assessing Coastal Habitats.

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Introduction

Efforts to restore and create coastal wetlands in southern California need to be assessed with extra care and precision, because the resource is so sensitive and highly valued. It is not sufficient for restored or created wetlands simply to be green or to achieve a predetermined species list. The region's natural wetlands are so depleted in area and functioning, that restoration and enhancement efforts must aim to provide self-sustaining ecosystems that are functionally equivalent with the natural wetlands that are no longer in existence. Criteria and standards for "successful projects" need to be very clear (e.g., FWS 1988, CCC 1991) and the assessment very detailed (e.g., PERL 1990). At the same time, sampling needs to be nondestructive or minimally intrusive.

At the Pacific Estuarine Research Laboratory, we have pioneered the development of several tools that are designed to provide high-precision data on the condition of restored and created wetlands, to serve as surrogates for measures of function and to have low impact on the restored or created site. In this paper, we describe the use of: remote sensing to quantify habitat types, a global positioning system to map rare plant distributions, a geographic information system to analyze tidal creek networks, sampling to clarify fish use of different channel types, dataloggers to characterize water quality, soil cores to assess marsh development, height distributions to characterize plant canopy architecture, and a reproductive index to assess the value of habitats to nesting birds.

Quantifying habitat types with remote sensing (high resolution airborne multi-spectral image data)

Remote sensing provides a non-intrusive and repetitive approach for obtaining information on the composition, configuration and condition of coastal habitats from micro to regional scales. To derive accurate data from coastal environments, attention should be paid to the spatial, spectral and temporal resolutions of remotely sensed data. Spatial resolution concerns the ground resolution element (GRE) size and image extent required to detect certain landscape elements. Spectral resolution pertains to the number and location of bandwidths for which reflected or emitted electromagnetic

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radiation is measured (e.g., red and near-infrared wavelengths enable discrimination of vegetation cover types). Specifications for the time of year, day or tidal stage, along with the required revisit cycle for monitoring dynamics are the temporal dimensions. Phinn and Stow (1996a, 1996b) identify characteristics of southern Californian wetland environments to consider when selecting appropriate remotely sensed data. The techniques described below rely upon high spatial resolution (GRE < 2.0m) and multi- or hyper-spectral image data. These data are particularly suited to the fragmented and species-diverse southern California wetlands (Zedler 1982). The next 5-10 years (1997-2007) will see an increase in the public/commercial availability of remotely sensed data from both airborne and satellite platforms (Johnson-Freese 1995; Fritz 1996).

High-resolution multi-spectral image data have been successfully collected from Pacific Coast wetlands and other coastal environments for: (1) mapping the extent and composition of coastal wetlands; (2) assessing the configuration or structure of wetlands and their component vegetation types; and (3) detecting and analyzing changes in (1) and (2) over time. Mapping the composition of wetlands requires preliminary knowledge of the existing vegetation assemblages and image data acquired at a time when vegetation and surface cover types can be differentiated. Image classification approaches have been successfully applied by Phinn et al. (1996) in southern California wetlands and Jensen et al. (1986, 1993) at slightly larger scales on the Atlantic Coast. Improvements in the accuracy of vegetation composition maps can be achieved by incorporating hierarchically structured classification schemes (e.g., Ferren et al. 1995) and digital elevation data (e.g., Bradshaw et al. 1996). Maps of vegetation cover derived from georeferenced images also provide a basis for examining the spatial distribution of ground survey data on the locations of invasive plants and bird habitat (Nyden et al. 1996; Brewster et al. 1996).

The first step in assessment is developing an accurate map delimiting the extent of vegetation cover types. These maps are then subject to analyses by landscape structure metrics or spatial statistical functions. Landscape structure metrics summarize information on the area, boundary features and topology of each vegetation, substrate or channel cover type (Haines-Young and Chopping 1996). Analyses of wetland vegetation and hydrogeomorphic configuration from remotely sensed data have been limited, although extremely promising results were provided by Phinn and Stow (1996a) from southern California wetlands and Mertes et al. (1995) from the Amazon. Biophysical properties of wetland vegetation have also been successfully estimated from remotely sensed data (Phinn and Stow 1996b). Maps of vegetation cover types and hydrogeomorphic features can be established from remotely sensed data obtained at seasonal or yearly periods, allowing analysis of wetland change in relation to the function of the wetland environment (Phinn et al. 1995; Mertes et al. 1995; Stow et al. 1996).

Remotely sensed analyses of composition, configuration and change are not intended to replace ecological assessments or field-work, but to act as a complementary source of data, enabling more spatially explicit and multi-temporal analyses. Ecological field work and analyses should be conducted in association with remote sensing analyses to maximize the accuracy and utility of information extracted.

Characterizing topographic complexity of marshes using GIS

Coastal wetlands exhibit a great deal of topographic complexity, with intricate networks of creeks, which vary in elevation and size. This complexity is rarely seen in restored marshes, because small intertidal creeks and rivulets are generally not included in restoration plans. Recent studies have linked topographic complexity to habitat function in riverine systems (Hatfield and Milne 1996; Kirchofer 1995; Jungwirth et al. 1995), and we recommend that the complexity of natural systems be mimicked at restored sites. In order to characterize natural complexity, we have obtained quantitative data on the configuration of creek networks in natural systems (Desmond 1996; Desmond et al., in review).

We used remote sensing images along with Geographic Information Systems (GIS) software to obtain quantitative information on the creek network of the Tijuana Estuary, which is the largest remaining natural wetland in San Diego County. Using a remotely sensed image as a template, the Estuary's creek system was manually digitized with the GIS software. Creeks were then classified into stream orders, and the digitized image was queried for information on total tidal creek length, tidal creek density, and other geomorphic parameters.

Using the vegetation classification from the ADAR image, we were further able to characterize the creek systems of different marsh zones (i.e., low-, mid-, and high-marsh). Determining the distribution of creeks with respect to marsh zone is important because the relative proportion of marsh zones will vary depending on the site to be restored, and a recommendation based solely on the area of a site may not be sufficient. We found that at Tijuana Estuary, over 50% of the total creek length was composed of small (first and second-order) creeks, and that nearly all of the tidal creek length was contained within the low-marsh zone. Information on the distribution and density of different creek types readily leads to designs for creek networks at individual restoration sites.

GPS Mapping

Global Positioning System (GPS) Mapping is a technique that is being used by the Pacific Estuarine Research Laboratory to provide very high resolution spatial data (± 5 cm) about vegetation, channel topography and other wetlands attributes. L1 carrier phase GPS receivers and kinematic surveys are used to achieve maximum positional accuracy. A typical survey utilizes multiple carrier phase receivers. One unit is static over a known benchmark, and the others serve as roving units for rapid field measurements. Approximately 20 seconds of occupation time is required for each data point. Data are post-processed using differential correction with a pre-determined network of reference points, and then fine-tuned with geoid modeling (Geoid 96). The results provide spatial coordinates that are accurate to within 2-3 cm in latitude/longitude and 3-5 cm in elevation with optimal satellite constellations. This method can effectively pinpoint a position to within a baseball sized sphere of error from 12,000 miles in space.

The accuracy of data obtained from pocket-sized portable GPS receivers differs by several orders of magnitude. Inexpensive GPS receivers are commercially available for as little as $150. However, their primary shortcoming for scientific application is the large circular error probability, which is approximately 100 m. Most low-cost GPS units calculate distance to satellites and triangulate positions by monitoring coded signals broadcast by the U.S. Department of Defense (DOD) from the 24+ satellites that are available. Carrier phase GPS receivers take maximum advantage of the GPS satellite network by recording the transmitted code information as well as monitoring the subtle shifts (Doppler Effect) in the actual carrier wave frequency as satellites move closer and then farther away from the receiver.

Carrier phase receivers are unaffected by the periodic and deliberate degradation of the DOD's coded signals (selective availability and anti-spoofing). The primary drawbacks to the carrier phase receivers are their high cost ($20,000-$80,000) and requirement for continuous lock on the satellite signals. Even a brief interruption of a satellite's signal by a tree branch is enough to cause loss of lock. For obvious reasons, these receivers are well suited for short-canopy marshes but not very practical for rainforest monitoring.

Mapping rare plant distributions using GPS

Degraded salt marsh habitats are characterized by low diversity of native plants and dominance by weedy or stress-tolerant species (PERL 1990). Attempts to restore or create salt marshes are hampered by a lack of knowledge of the population and physiological requirements of many component species, especially those restricted to narrow or ephemeral environments (Skinner et al. 1995). Accurately assessing the range and physical parameters of rare populations or those occurring in restricted environments becomes more important with increasing degradation and loss of natural habitat. Further, understanding what limits the distribution of rare species and what is required for their growth and reproduction is critical for constructing fully-functional, self-sustaining salt marsh ecosystems.

Adequate assessment of rare plant populations can be facilitated by utilizing multiple techniques (Menges et al. 1996). We now use GPS to investigate and monitor the spatial and vertical distributions of rare plants of coastal salt marshes, such as *Lasthenia glabrata* at Los Peñasquitos Lagoon and *Cordylanthus maritimus* at Tijuana Estuary and Sweetwater Marsh. Both species are narrowly distributed annuals: *L. glabrata* is found on the margins of salt pans, and *C. maritimus*, a hemiparasite, is restricted to its hosts' ranges. Growth and reproduction of these species vary a great deal both within and between years in response to the quantity and timing of rainfall. GPS not only defines species' spatial distributions, but also their elevational limits. By superimposing data from year to year, we also monitor the temporal dynamics of population growth over time. Temporal differences in distribution can be related to elevation of occurrence, which in turn suggests specific limiting conditions such as soil moisture and salinity. Simultaneous data on covariate factors such as plant density, the identity of co-occurring species, and specific microhabitat conditions can be coded into each three-dimensional position recorded. This type of information is invaluable for planning restoration projects that are designed to support a diverse assemblage of species.

Characterizing fish use of different channel types

Physical structure is an important determinant of fish habitat in coastal wetlands. Channel morphometry, proximity and type of channel vegetation, channel location, flow rate, and sediment type are all known to influence the type and abundance of fishes in Atlantic and Gulf Coast wetlands (e.g., McIvor and Odum 1988, Baltz et al. 1993). We have found correlations between relative fish species composition and the morphology and hydrology of a variety of channel habitats in Sweetwater Marsh National Wildlife Refuge on San Diego Bay (Williams and Zedler, in prep.). Seine samples from narrow, steep-banked channels with clay sediments, elevated salinities, and low dissolved oxygen levels were generally dominated by longjaw mudsuckers (*Gillichthys mirabilis*), a species tolerant of low dissolved oxygen levels. Broad, shallow channels with low slopes, often fringed by emergent vegetation, were dominated by California killifish (*Fundulus parvipinnis*). Finally, samples from broad, deep channels (mean depth of 1.0 m) were generally dominated by topsmelt (*Atherinops affinis*), a schooling pelagic species. Associated research has also shown that shallow, vegetated, first-order creeks may be important habitat for juvenile killifish, which are found in higher proportion here (Desmond 1996). Although the existence of species-habitat associations has been well-established in other regions, these habitat requirements or preferences have not been previously quantified in southern California.

In southern California, coastal wetlands have been constructed to compensate for the loss of deep-water habitat (e.g., MEC 1995) or to provide habitat and food for endangered birds (Haltiner et al. 1997). Such sites have been designed to provide deep subtidal channels with primarily sandy sediments, low sloping banks, and few shallow creeks. While several studies have shown that fish are quick to use constructed tidal habitats (Minello and Zimmerman 1992; Vose and Bell 1994; Havens et al. 1995; Simenstad and Thom 1996), it is important to consider which species of fish are desired and what habitats can attract and sustain them. If the objective is restore habitat for endangered birds (e.g., terns that feed on fish), then we need to mimic as closely as possible the natural systems that still support feeding by the target species. If the objective is to replace fish species that occur in deepwater habitats, then the fish assemblage and its habitat requirements need to be understood. An early understanding of project goals and an intimate knowledge of the system's ecology are imperative in any restoration project.

Characterizing water quality using dataloggers

Like channel morphology, water quality has a strong influence on fish use of wetland habitats, and is an important consideration in designing and monitoring constructed wetlands. At various wetlands in San Diego County, we have used dataloggers to characterize variability in physical-chemical conditions at reference sites as well as to monitor restoration sites.

Data on water quality (salinity, dissolved oxygen, pH, depth) have been collected (with measurements taken at 30-minute intervals) since 1995 from the main channel at Tijuana Estuary. Long-term monitoring of this site, which serves as a reference for the region (Zedler et al. 1992), will eventually allow us to develop water quality guidelines for future restoration projects. At Los Peñasquitos Lagoon, we have employed dataloggers to evaluate the effects of periodic mouth closures on lagoon water quality (Williams 1996). And in an evaluation of fish use of small intertidal creeks, dataloggers were used to compare tidal attenuation at two study sites in San Diego County. Greater tidal attenuation in creeks at one site, and the resulting decreased habitat availability, may have partially explained lower fish use (Desmond et al., in review).

Because human activities have negatively impacted the hydrology of many estuaries in southern California, improved tidal flushing is a main goal of several restoration projects. We are using dataloggers to evaluate one such restoration site at Tijuana Estuary; water depth data measured from either end of a newly excavated channel (prior to and after the excavation) will allow us to determine whether the channel is bringing about the intended changes in tidal amplitude and duration of tidal flushing.

Dataloggers allow analysis of fluctuations in water quality on a finer scale than was previously feasible. Detailed data from both restored and natural systems improves our ability to monitor current restoration projects and allows us to develop water quality guidelines for future projects.

Assessing marsh development with soil cores

Slow development of soils is a problem at many coastal wetland restoration projects. Because restoration projects are often completed using dredged material or other coarse-grain sediments, restoration sites frequently have sandier soils and lower organic matter and nutrient concentrations (especially total Kjeldahl nitrogen, TKN) than natural wetlands (Langis et al. 1991). It is anticipated that, as material accumulates within the restoration site, soil conditions will improve, both through the accumulation of organic matter and nutrients in the existing soil, and through the accretion of new sediment on the surface of the marsh (this method has been proposed for many restoration projects in sediment-rich San Francisco Bay). However, there are few data to determine if the desired changes actually occur at restored wetlands.

We have collected soil cores periodically from 1988-1996 to assess soil development at a restoration site in San Diego Bay. Despite predictions that restoration sites will follow a "trajectory" or predictable path of improvement, the data from San Diego Bay fail to indicate consistent improvements in any soil characteristics. On the contrary, annual changes in sediment organic content and TKN have been similar to changes at a nearby natural marsh, indicating that interannual variability is greater than any trend in accumulation of organic matter or nitrogen at this site. At present both sediment organic matter and TKN remain less than 70% of that in the natural marsh. Sediment texture is very coarse at this restored marsh and is the likely factor limiting nutrient accumulation. Even with additions of fertilizer there have been little retention of nutrients or accumulation of organic matter (Gibson et al. 1994; Boyer and Zedler 1996a, 1996b, in review).

Sedimentation rates are low at this site (Haltiner et al. 1997), so there is unlikely to be significant accumulation of fine sediment. We have documented a thin layer of new sediment on the surface of the marsh that is significantly higher in clay content and is likely to have more organic matter and nutrients. However, this thin layer has not significantly affected plant growth in the marsh. In addition, the marsh was designed with "target" elevations in place; if substantial amounts of new sediment were to accumulate, this would result in changes in marsh elevation and in the plant community (Haltiner et al. 1997).

The long-term comparison of soil texture, soil organic matter concentration and soil TKN is a useful tool for tracking the development of wetland soil. If these attributes follow a trajectory, one can predict when the site will achieve functional equivalency with natural wetlands and thus indicate when mitigation projects should be judged in compliance with reference wetlands. If they fail to show progressive development, the factors responsible need to be explored and corrective measures undertaken or alternative mitigation measures identified.

Determining plant responses to nitrogen fertilization through experimentation

Experimental manipulations are useful tools for assessing problems at restoration sites. We have used nitrogen fertilization to increase cordgrass height growth in sandy constructed marsh soils (Gibson et al. 1994; Boyer and Zedler 1996b; Boyer and Zedler in review), and we have used several methods to monitor the response of plants to increased nitrogen (N). Along with height histograms (see below), aboveground tissue nitrogen (TKN) and biomass (as estimated by total stem length; Zedler 1983) have proved useful in assessing the development of cordgrass in these constructed marshes (Boyer and Zedler, in review). The standing crop of N (which incorporates both N concentration and biomass) is higher in natural cordgrass stands and remains similar before and after fertilization, suggesting adequate nutrient supply from soils and internal recycling. In contrast, cordgrass in constructed marshes increases its N standing crop significantly with fertilization, matching that of reference natural marshes, but returns to pre-fertilization conditions in the next year (Boyer and Zedler, in review). As a result, the functions provided by taller, more robust and more N-rich cordgrass may also be lacking; these functions include habitat support for arthropods and nesting birds (Boyer and Zedler 1996a; Boyer and Zedler, in review).

When measured in the winter after aboveground tissue has senesced, N crop in the belowground tissues suggests the potential for growth in the next year. In constructed marshes fertilized for one growing season, belowground N crop of cordgrass approaches that of natural marshes; however, we know that this N retention response does not result in sustained high aboveground biomass (see above). We conclude that recycling in the tissues is inadequate to support optimal growth without sufficient soil N pools to augment supply. Thus, through experimentation, we have learned how important adequate soil N is to the structure and function of salt marshes. In other words, larger soil N pools are needed to sustain tall vegetation. Continued N additions over multiple years might eventually improve nutrient supply through increased organic matter deposition, building of N pools, and recycling within tissues.

While fertilizers may improve growth of salt marsh plants, and plant response to N additions may be used to compare nutrient sufficiency in constructed and natural marshes, fertilizers should be used with some caution. First, herbivory can increase with fertilization, although herbivorous insects did not increase following our experimental N additions (Boyer and Zedler 1996a). Second, fertilizing mixed-species stands can lead to changes in community composition (Boyer and Zedler, in preparation). Finally, fertilizers can lead to eutrophication and associated problems. Opportunistic green algae may be useful as an *in situ* indicator of changes in water column nutrients if N pollution of open waters is a concern (Fong et al., in review).

Characterizing marsh canopy architecture

Marsh vegetation varies in composition and vertical structure, and both attributes help determine the value of the site for nesting birds. A comparison of the canopy architecture of cordgrass stands that are and are not used by light-footed clapper rails for nesting indicates that suitable nesting habitat can be identified using height histograms (Zedler 1993). Light-footed clapper rails were found to nest where there were $\geq$100 stems m^{-2} and where at least 90 stems were taller then 60 cm and at least 30 of those stems were taller than 90 cm. Tall stems are woven into a canopy over the nest, which presumably protects the eggs and hatchlings from aerial predators, e.g., raptors. Tall stems are also presumed important for preventing the flotable nest from being washed away by a high tide.

Sampling for suitable nesting habitat is accomplished in September, after the nesting season. Sampling sites of 10-m radius or 20x20-m dimension should be selected within areas of about 2 ha, each of which might be a suitable home range for one pair of birds (based on densities of 0.52 nests/ha, Jorgensen 1975). A stratified random procedure is recommended to locate 10 circular quadrats per sampling site, with each quadrat being 0.25 m^2 in area. A random starting point can be identified and the 10 quadrats placed at 2-m intervals in a regular pattern that coincides with the shape of the patch of the most robust cordgrass. Plant heights are measured for every stem that is present within the quadrat; the tallest leaf is extended along a meter stick to record height. Flowering stalks are not included in height measurements, as they are not present during the nesting season; the above height standards relate only to leaf extension. It is not necessary to establish permanent quadrats for multi-year comparisons, as the tallest stand of cordgrass may occur in a different location the following year.

In our studies of constructed marshes at San Diego Bay, we have found few areas of cordgrass tall enough to support clapper rail nesting, and the rails have not nested in the transplanted cordgrass. The problem appears to be soil quality (texture too coarse, organic content too low, nitrogen concentration too low; Langis et al. 1991). Thus, special attention should be paid to the sediment provided. Nitrogen additions can increase cordgrass height, but the effect is not sustainable in coarse soils (Boyer and Zedler, in review).

Vertical structure is important to a variety of insects, spiders, and other birds. Belding's Savannah sparrows perch on the tallest plants and build their nests at elevations where tidal inundation is less likely (Brewster 1996). Pickleweed (*Salicornia virginica*) appears to be the preferred vegetation, but we do not yet have standards for pickleweed canopy architecture. Tall, dense vegetation may not be sufficient for sparrow nesting to succeed, however. In the next section, we indicate the need to protect marsh habitats from predators.

Monitoring avian use in coastal marshes using a reproductive index

Monitoring wetland birds in this region is often focused on rare or endangered species. For example, Belding's Savannah sparrows (*Passerculus sandwichensis beldingi*) are endemic to coastal wetlands of southern California and Baja California, Mexico. The subspecies is a metapopulation, with each marsh representing a distinct local population. Statewide totals of Belding's Savannah sparrows have been compiled by individual researchers and the USFWS since 1973. Based on these results, it appears that the metapopulation increased dramatically from 1973 to 1987, then experienced a decline. However, any assumptions about population growth or decline based on these numbers are tenuous because of inconsistent and inefficient monitoring efforts (Bradley 1973, Massey 1979, Zembal et al. 1988, James and Stadtlander 1991).

We (the San Diego Field Station, USGS-Biological Resources Division) conducted intensive research on Savannah sparrows at Sweetwater Marsh from 1994-1996. This area is highly disturbed, and several of its associated wetlands are distinct fragments surrounded by an urban landscape. Past surveys used walk-through census techniques and revealed high variability in local population size. We used a combination of walk-through, line-transect and spot mapping techniques to determine nesting densities. Line-transects and spot-mapping showed that walk-through censuses grossly underestimated the number of sparrows. Densities (i.e., number of birds/ha), varied among seasons, tides, and vegetation zones within the marshes. In spring, densities were highest in the high-marsh zones, which was consistent with preferred nesting habitat (Powell 1993). Interestingly, densities were higher during high tides in all zones of the marsh. This may be because birds were more easily seen when perched high in the vegetation. In addition, line-transect data also showed that detectability of birds decreased dramatically with distance from the transect. For example, at low tide, detectability was less than 50% only 10 m from the transect line.

We also used mark-recapture and spot-mapping to examine productivity of Belding's Savannah sparrows within the Sweetwater Marsh Complex. We used a reproductive index to evaluate reproductive success that was based on specific observed behaviors as well as the presence of fledglings within territories (Vickery et al. 1992a and 1992b). The high-marsh zones of Sweetwater Marsh appeared to be population sources because they produced an excess of young during the breeding season. Mid-marsh habitats within Sweetwater Marsh and at a connected marsh fragment produced enough young to maintain their populations. However, a small marsh isolated from the marsh complex produced no fledglings, and it was therefore a population sink. We saw little evidence of movement of birds between marshes.

Presence/absence data can establish basic information on extirpation and colonization of avian populations in coastal marshes. However, information on population size should be determined more accurately with density estimates. Unfortunately, we are currently lacking accurate information on actual areas of suitable habitat that is available to wildlife. Focusing on avian productivity may be the most useful information for managing the remaining marsh remnants and planning restoration. Management efforts should then key in on source and sink habitats to ensure sustainability of metapopulations. It is essential that clear objectives for monitoring are established in order to obtain the best information for effective management of these species.

APPENDIX 1. REFERENCES

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