Developmental Trajectory for California Tidal Marsh Restoration and Mitigation Projects

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Introduction

In the early 1970s, the main obstacle confronting wetland restoration in the United States was developing the science for successful restoration projects[1] (Race and Christie 1982, NRC 1992, Erwin 2009). For tidal wetland in California, this prompted the development of multiple guidelines and frameworks for project planning and assessment (e.g., Josselyn and Bucholz 1984, Collins 1991, Zedler 2000, Philip Williams LTD and Faber 2004). While the science has advanced (e.g., Whigham 1999, Zedler 2000, Van Diggelen *et al.* 2001, Nakamura *et al.* 2006, Acreman *et al.* 2007), the definition of wetland restoration success and how to measure progress continue to be debated (Confer and Niering 1992, Mitsch and Wilson, 1996; Zedler and Callaway, 1999; Hackney, 2000; Thom, 2000; Brooks *et al.* 2004; Matthews *et al.* 2009, Moreno-Mateos *et al.* 2012).

Early guidance by US Environmental Protection Agency (USEPA) for wetland restoration planning recommends the use of Performance Curves (PCs) to forecast and evaluate project performance relative to desired or reference conditions (Kentula *et al.* 1992). Ideally, PCs indicate the condition a project is likely to achieve at any future date after it is constructed. Wetland PCs are developed by assessing conditions of multiple projects of different age and comparing them to natural wetlands that represent the intended endpoints of projects conditions (Kentula *et al.* 1992; Zedler and Callaway, 1999, Matthews *et al.* 2009). Wetland PCs are based on the assumption that the developmental trajectory of any given wetland can be estimated by the developmental stages of other wetlands of the same kind but differing ages that in aggregate represent the entire developmental timeframe. The key element of a useful PC is a standardized dataset that chronicles temporal changes in habitat conditions.

Here we report the results of the first effort to develop a PC for California tidal wetlands. Bar-built estuaries were omitted from this study. The report is based on a new dataset having four unusual strengths: it comprehensively covers tidal wetlands along the entire California coast; it represents the complete timeframe of tidal wetland development; it is based on a well-vetted standard method to assess project status relative to a uniform definition of success; and it incorporates a detailed understanding of each case history.

Methods

Wetland projects and reference sites were assessed using the California Rapid Assessment Method for Wetlands (CRAM). CRAM has been developed by a consortium of federal and California state agencies as part of a comprehensive California Wetland and Riparian Area Monitoring Plan (WRAMP)[2]. It is a standardized rapid field method for assessing the potential of a wetland to provide high levels of its intrinsic ecosystem services (Stein *et al.* 2009). Formal peer review of CRAM was conducted by the California State Water Resources Control Board (SWRCB 2011). An additional review

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[1] In this paper, restoration and compensatory mitigation are collectively referred to as restoration.

[2] The CA Wetland and Riparian Area Monitoring Plan (WRAMP) is being developed by the CA Wetland Monitoring Workgroup (http://www.mywaterquality.ca.gov/monitoring_council/wetland_workgroup/).

was conducted by the US Army Corps of Engineers (USACE 2008a). Both reviews included a recommendation to build PCs based on CRAM. Ongoing refinement of CRAM and its applications are advised by the Wetland Monitoring Workgroup of the California Water Quality Monitoring Council (http://www.mywaterquality.ca.gov/monitoring_council/wetland_workgroup/). CRAM assessments have been conducted statewide for five different wetland types since 2000, with over 3,500 assessments reported to date by more than 800 trained CRAM practitioners.

The technical aspects of CRAM are fully explained in reports and other documents provided on the CRAM website (www.cramwetlands.org). They are only briefly described here. CRAM is based on the assumption that the potential of a wetland to provide high levels of its intrinsic services is positively related to its physical and biological (floristic) complexity (CWMW 2013). The assumption is supported by field tests (Stein *et al.* 2009). CRAM yields a semi-quantitative numerical assessment of wetland condition for a standard assessment area. For tidal wetlands, the assessment area is a 1-hr circular plot. The assessment consists of an index score that is the average of four separate attributes scores, each of which is an average of two or more metric scores, some of which have sub-metric s (Table 1).

Table 1. The structure of the California Rapid Assessment Method (CRAM) for tidal wetlands. Each metric (or sub-metric) has four possible rating scores (3, 6, 9 or 12). The final Index score is the average of the four attribute scores and can range from 25 to 100.

Attribute	**Metric**	**Sub-metric**
Buffer and Landscape Context	Aquatic Area Abundance	
	Buffer	Percent of AA with Buffer
		Average Buffer Width
		Buffer Condition
Hydrology	Water Source	
	Hydroperiod	
	Hydrologic Connectivity	
Physical Structure	Structural Patch Richness	
	Topographic Complexity	
Biotic Structure	Plant Community Composition	Number of Plant Layers
		Number of Co-dominant Species
		Percent Invasion
	Horizontal Interspersion	
	Vertical Biotic Structure	

The tidal wetland PC was developed from a subset of over 300 publically available CRAM assessments conducted by trained practitioners between 2000 and 2012. About two thirds of the assessments were from a single statewide probabilistic survey of estuarine wetland condition sponsored by USEPA (Satula *et al*., 2008). The remaining assessments were from individual wetland restoration projects or other non-project surveys of wetland condition.

We used current and historical aerial imagery, site-specific reports, interviews with data collectors and project managers, and (in some cases) field visits of assessment areas to determine the suitability of scores for inclusion in the PC. Online sources of information are reported in Table 2. The criteria for including assessments in the PC are listed in Table 3.

Table 2. Online resources used to review and characterize assessment wetlands and estimate time-zero.

Google Earth with historical imagery	https://www.google.com/earth/
USGS San Francisco Bay Area Regional Database (BARD)	http://bard.wr.usgs.gov/histMapIndex15.html
NETR Online (areal images & historical USGS topo maps)	http://www.historicaerials.com/
NOAA Historical Shoreline Surveys viewed in Google Earth	http://specialprojects.nos.noaa.gov/tools/shorelinesurvey.html
USGS Historical Topographic Map Collection	http://geonames.usgs.gov/pls/topomaps/f?p=262:1:1599334439898343
EcoAtlas - project information, maps and online reports	http://ecoatlas.org
NOAA Coast (historical map collection)	http://historicalcharts.noaa.gov/historicals/search#searchInput

Table 3. Criteria for including CRAM assessments in the PC.

1. Assessment was reported in the statewide CRAM database and has adequate assurances of scientific soundness based on the training and experience of the assessment team and close agreement with other assessments of the same or locally comparable wetlands.
2. Assessment area is not within an active stream delta or fan, is not within a swale of an active dune system, does not adjoin the edge of an obviously migrating or eroding tidal channel, or is not within another location subject to natural physical disturbance likely to significantly interrupt or reset habitat development.
3. Assessment area was not subject to management actions such as grading, tidal hydrology control, invasive plant species control, or other interventions that would affect the CRAM assessment.
4. For projects, the year in which the assessment area first supported at least 5% cover of vascular vegetation is known or can be estimated from the known date of tidal action restoration.

It is essential that the age of all assessment areas for projects represented in a PC be based on a standard definition of time-zero. Most tidal wetland restoration projects involve some amount of site preparation before they are restored to tidal action. All of these activities can affect the time required for a site to develop into a vegetated tidal wetland. Therefore, these activities can contribute to the variability in development rate across projects, and to the imprecision of a PC. To increase the precision of the PC, time-zero for projects was defined as the year in which the assessment area first supported at least 5% cover of wetland vegetation, rather than the year in which tidal action to the area was first restored. For most projects, the restoration of tidal action involves breaching a levee and the date is therefore well known. However, the year when plant cover reaches 5% is not as often known. Cases where both dates are known suggest that 5% cover is achieved within two years after a breach, if the breach is adequately large and the on-site tidal elevations at the time are suitable for colonization. In the absence of other information, we therefore assume that time-zero for as project is the year of its breach plus two years. A few older projects had initial tidal elevations that were too low for rapid plant colonization. In these cases, local expertise and aerial imagery were adequate to estimate time-zero within about 5 years.

The PC needs to span the entire length of time required for tidal wetland habitat to fully develop, starting from time-zero as defined above. Early evidence from CRAM surveys suggested that few projects were old enough to be fully developed, as represented by CRAM reference sites and other natural sites of great age. This created a large data gap between the oldest projects (age 40 years) and the youngest reference sites (age 200 years). To fill this gap, sites ranging in age from about 50 years to about 200 years were identified and assessed. The ages of these sites were estimated using areal imagery and historical maps. The certainty of the age estimates decreases with age. We expect that the younger ages are accurate to within 10 years, and the older ages within 25 years, based on the time intervals between maps and other evidence. Some of these wetlands were recreated from accidental levee breaches. Others were formed by natural depositional processes in shallow subtidal or low intertidal areas.

Reference wetlands were defined as prehistoric sites subject to continuous evolutionary processes and not subject to major changes in sediment or water supply (either natural or anthropogenic). Reference conditions therefore represent mature, high-elevation tidal marshes. Candidate reference sites were initially identified as those developed for the recently completed statewide CRAM reference site network (Solek, 2012). Those sites were chosen as reference sites for CRAM practitioners as examples of the best achievable conditions. Additional reference sites were identified from historical maps and previous studies. These sites range in age from a few hundred to nearly three thousand years, and yet they all represent reference condition, as measured using CRAM. This strongly suggests that reference conditions can be achieved within 200 years. Of the 37 reference sites identified from the CRAM reference site network, 7 sites were excluded from analysis because their developmental history could not be confirmed or they were located in bar-built estuaries. Seventeen of these sites were included in the PC as non-project sites because their ages were less than 150 years. The remaining thirteen sites from the CRAM reference network were confirmed to be prehistoric wetlands of uninterrupted natural development. Twelve additional reference sites were identified based on the detailed review process mentioned above, resulting in a total of 25 reference sites identified for this study. The reference sites were not included in the PC because their actual ages in many cases were unknown, and they would extend the timeline of the PC further into the future than warranted to analyze project development rates. Instead, the mean and standard deviation of the reference wetland conditions were used to develop a reference envelope of CRAM scores to which non-reference sites could be compared.

The preliminary dataset for developing the PC included a total of 302 CRAM assessments conducted between 2006 and 2012. Of these assessments, 130 were excluded based on the criteria in Table 3. The remaining 172 assessments were classified as project sites, non-project sites, or reference sites, as defined above. These assessments are summarized in Table 4.

Table 4. Summary statistics of the CRAM assessments used in the development of the California tidal wetland Performance Curve, showing the range in scores and average scores (in parentheses).

Parameter	Project Sites	Non-Project Sites	Reference Sites
Number of CRAM Assessments	53	93	25
Age Range of CRAM Assessment Areas (years)	2-36	1-145	250 – 3,000
CRAM Index Score	40-75 (61)	49-92 (76)	69-93 (83)
Buffer and Landscape Context Attribute Score	42-100 (72)	56-100 (86)	65-100 (91)
Hydrology Attribute Score	33-75 (60)	50-100 (81)	92-100 (98)
Physical Structure Attribute Score	25-75 (52)	25-100 (64)	88-100 (91)
Biotic Structure Attribute Score	39-89 (62)	36-100 (72)	86-100 (91)

Results and Discussion

Production of the CRAM Index Performance Curve

A tidal wetland PC was produced for the CRAM index by regressing the index scores on wetland age using a polynomial regression model (y ~ poly(x,2)) with 95% confidence intervals (Figure 1) .

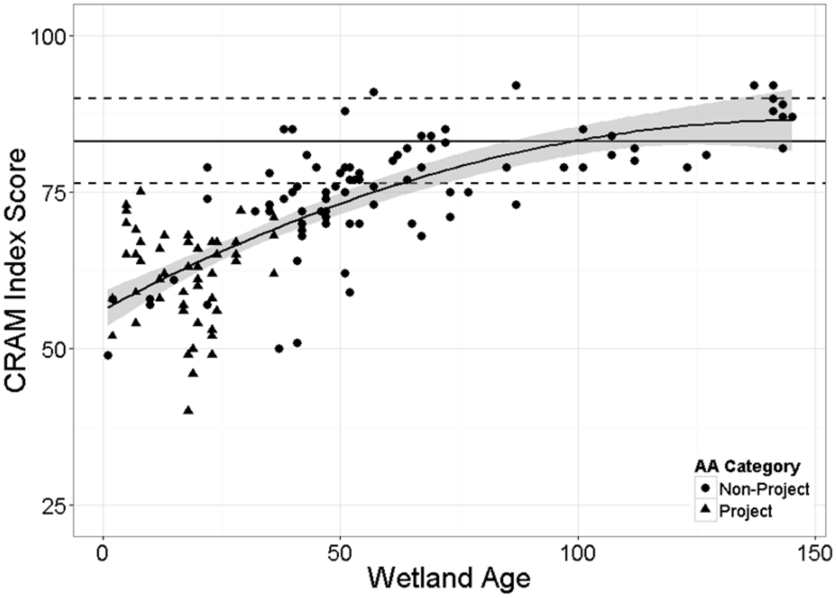

Figure 1. CRAM Index Performance Curve. The mean reference site index score is represented by the solid horizontal line through the PC. The horizontal dashed lines represent 1 standard deviation above and below the mean index score.

Interpretation and Explanation of the CRAM Index Performance Curve

Wetland PCs are based on the assumption that the developmental trajectory of any given wetland can be estimated based on the conditions of other wetlands of the same kind but different ages that in aggregate represent the entire developmental process. For the PCs presented here, it is also assumed that the physical and biotic complexity of a wetland increase as the wetland develops. These assumptions are supported by the clear positive relationship between the ages of wetlands and their physical and biotic complexity, as represented by CRAM scores.

The main message of the Index PC is that tidal wetland projects are unlikely to attain reference conditions in less than about 75 years. It is also evident that the average rate of development is fairly uniform until development nears the average reference condition, after which the rate of development slows.

Based on the Index PC, we might hypothesize that projects will eventually attain reference conditions regardless of their conditions at time-zero. However, we might also hypothesize that some projects are not likely to ever attain reference conditions. For example, projects that are not fully tidal may never develop naturalistic channel systems, natural levees, ponds, and other features that in aggregate support a complex mosaic of plant and animal populations indicative of the reference sites. Projects lacking full tidal action might also lack adequate deliveries of inorganic sediment essential to maintain marsh elevations as sea level rises. Testing either hypothesis will require tracking the development of individual projects that together represent a broad range of initial conditions.

The variability in CRAM index scores for the PC dataset is notable. There is a uniformly broad range in scores among wetlands at any age less than about 75 years. This reflects the variability in the component attribute scores, which is discussed below. There are at least five sources of the variability in index scores. First, each wetland is represented by a single CRAM assessment. The variability in scores would probably be reduced if each wetland were represented by an average score for multiple, randomly located assessment areas. Second, it is possible that some of the assessment areas were subject to management actions or natural disturbances that interrupted wetland development, despite our efforts to eliminate such areas from the PC dataset. Some site were seeded or planted to encourage plant community development, and some sites were closer than others to source populations for plant colonists. Whether or not these factors affected development rates is unknown. Third, CRAM does not account for natural regional variations in wetland form and structure. Previous surveys of tidal wetland condition using CRAM have shown that that index scores generally decrease from north to south along the California coast (Sutula *et al.* 2008). This variability in wetland form and structure may correspond to variability in development rates, assuming that natural, less complex sites develop faster. Fourth, development rates might be influenced by preexisting site conditions. For example, on-site sediments might be compacted, nutrient-poor, or have other characteristics that hinder plant community development (see discussion of the Biotic Structure PC below). Finally, the development rates of projects are likely influenced by project design. It is clear that some projects start with higher scores, even without being seeded or planted, and are presumably on a faster trajectory to reach reference conditions. In these cases, restoration designs might have been especially consistent with physical and hydrologic factors and processes that control development. Some designs might have been especially consistent with CRAM metrics (i.e., projects can be designed to get high CRAM scores). Figure 2 shows tidal wetlands corresponding to high, medium, and low CRAM index scores.

Photo: Chris Solek

Figure 2. Examples CRAM assessment areas in tidal wetlands of different condition. Example A illustrates good condition (Index Score = 79). Example B illustrates medium condition (Index Score = 61). Example C illustrates poor condition (Index Score = 40).

Production of the CRAM Attribute Performance Curves

A PC was produced for each of the four CRAM attributes by regressing their scores on wetland age using a polynomial regression model (y ~ poly(x,2)) with 95% confidence intervals (Figure 3) .

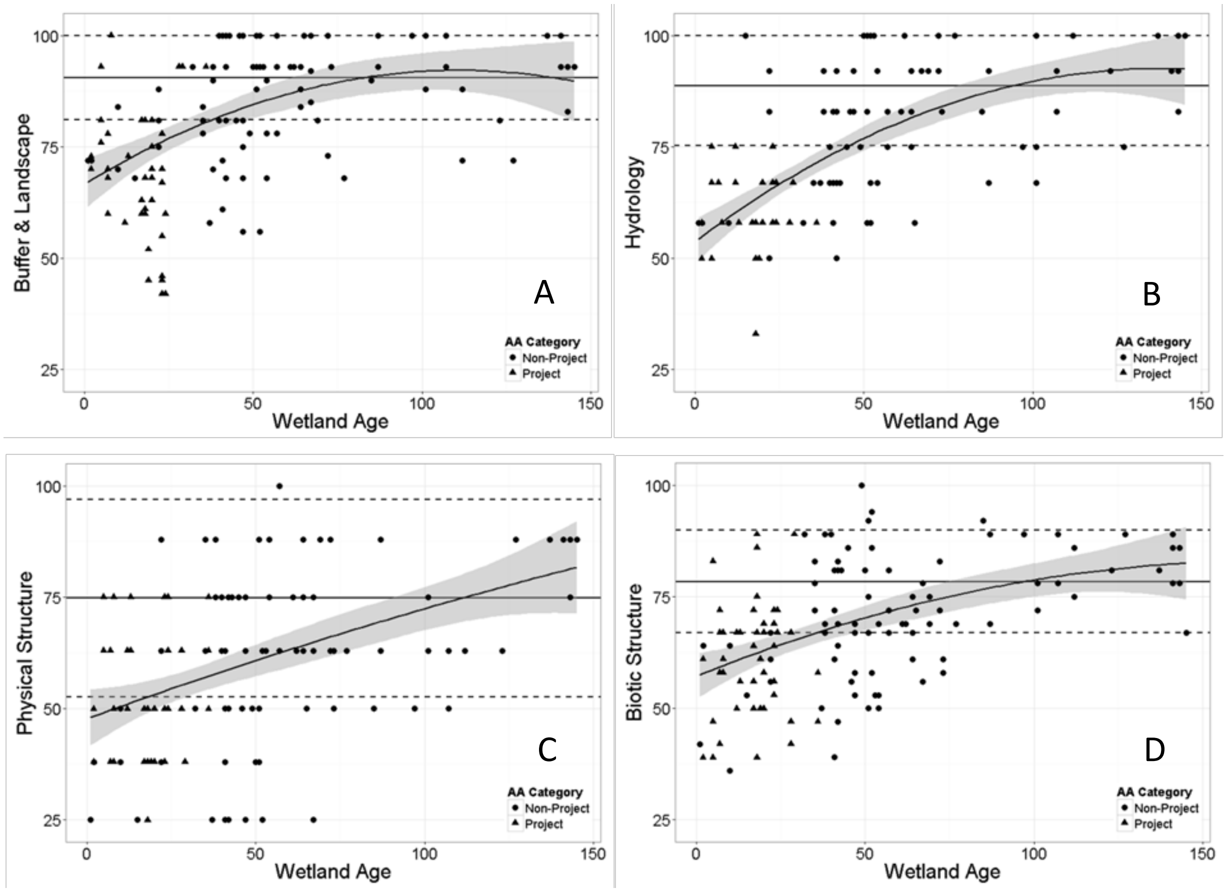

Figure 3. Performance Curves for the CRAM attributes: (A) Buffer and Landscape Context, (B) Hydrology, (C) Physical Structure, and (D) Biotic Structure. For each Attribute PC, the mean of the reference site score is represented by the solid horizontal line. The parallel horizontal dashed lines represent 1 standard deviation above and below the mean reference site score.

Interpretation and Explanation of the Buffer and Landscape Context Performance Curve

The Buffer and Landscape Context PC suggests that projects are likely to attain the lower limit of reference conditions for this attribute within 25-50 years. The fact that the PC recurves downward toward the average reference condition for wetlands older than 125 years is an artifact of the polynomial regression model.

For tidal wetlands, the buffer and landscape context attribute assesses the extent and condition of the area just outside the assessment area, as well as the abundance of aquatic habitats in the greater surrounding landscape. Separate metrics are used to assess buffer condition and landscape context. The buffer metric involves sub-metrics (see Table 1, above). The relatively large number of component scores for this attribute increases the number of possible attribute scores, which increases the ability of the attribute scores to differentiate among wetlands of different condition (i.e., age).

The buffer and landscape context metrics are expected to be sensitive to wetland size (CWMW 2013). Areas of wetland that adjoin an assessment area are considered to be part of the buffer as well as being aquatic habitat. Therefore, as wetland size outside the assessment area increases, relative to the size of the assessment area, the likelihood of high scores for buffer condition and landscape context should also increase. However, we determined that the scores for buffer and landscape context are not correlated to wetland size. This may be because most tidal wetlands are much larger than the standard CRAM assessment area, such that any effect of wetland size on scores for buffer or landscape context is restricted to a small portion of the population of wetlands that is not much larger than the assessment area.

Not only does the standard CRAM assessment area te3nd to be much smaller than its encompassing wetland, its buffer and the rest of the wetland tend to have similar condition. Therefore, the variability in buffer condition tends to be highly correlated to the variability in condition of the assessment areas. For any age wetland, the range in buffer scores is similar to the range in scores for many other metrics.

The younger tidal wetlands tend to have relatively high scores for the buffer and landscape attribute. This probably reflects a recent preference (and perhaps a growing opportunity) to locate new projects near existing wetlands including previous projects.

There are reasons to question the inclusion of landscape context scores in the PC dataset. The landscape context metric is clearly a useful component of ambient surveys of wetland condition because it provides information about the connectivity between patches of wetlands and other aquatic habitat types. It can also help assess large-scale changes in wetland abundance due to such factors as increases or decrease in wetland protection, increases in wetland restoration, or climate change. However, scores for landscape context are often affected by conditions outside the purview of wetland restoration projects. Although project sponsors and planners can often include buffers in their project designs, they seldom control the conditions of lands and waters outside the project boundaries. Therefore, the inclusion of the landscape context scores in the PC dataset may result in lower or higher expectations for project performance than can be assured. To assess this risk, we developed two versions of the Index PC, one including and another excluding the landscape context scores. The slopes of these alternative Index PCs and their points of intercept with reference conditions were statistically the same. We therefore concluded that there was no compelling reason to exclude the landscape context scores from the PC dataset.

Reasons for the positive correlation between wetland age and attribute scores for buffer and landscape context are unclear. Since there is no overall correlation between these scores and wetland size, any relationship between wetland size and age is irrelevant. However, one possible explanation for the observed correlation is provided by an examination of the landscape settings of tidal wetlands of different age. Most of the older, non-project wetlands are remnants of larger wetlands that have been converted to other wetland types, such as commercial salt ponds, storm water retention basins, or diked farmlands that have varying amounts of non-tidal wetlands due to poor drainage. The remnant tidal wetlands in these settings tend to get high scores for the landscape context metric because they are surrounded by abundant aquatic habitats. They tend to get higher scores for the buffer metric because they are relatively removed from intensive land uses that tend to result in lower buffer scores.

Interpretation and Explanation of the Hydrology Performance Curve

The Hydrology PC suggests that projects are unlikely to attain the lower limit of reference conditions for this attribute in less than about 50 years.

For tidal wetlands, the hydrology attribute involves three metrics that in aggregate assess the degree to which the tidal hydrology of the assessment area is natural. None of these metrics involve any sub-metrics. The number of possible hydrology attribute scores is somewhat restricted by the small number of component scores. This decreases the ability of the hydrology attribute to differentiate among wetlands of different age. As a result, wetlands of broadly different age can have the same hydrology attribute score, as evident in Figure 3. Nevertheless, there is a positive correlation between the hydrology attribute score and wetland age.

Factors that can lower the hydrology attribute score include any dependence on water control structures (i.e., weirs, tide gates, pumps, etc.), artificially low channel density (i.e., the amount of channel edge per unit area of wetland plain is markedly less than reference conditions), and the presence of artificial levees near the assessment area that constrain the horizontal excursion of high tides. Project designs and the management schemes for non-project wetlands address these factors to varying degrees, and this is reflected in the broad range in hydrology attribute scores across the range of wetland age. Also, many projects involve the design and construction of tidal channels to promote habitat development, and some projects also include levees that intentionally resemble natural upland transition zones that meet the CRAM criteria for adequate horizontal tidal excursion. Such designs contribute to higher hydrology attribute scores. The range in scores reflects the inconsistent use of such designs. It is not possible to predict from these data what the shape of the PC would be if the hydrology of all tidal wetlands was entirely natural. It is expected, however, that the hydrology attribute scores would be less variable, and that the slope of the curve would be lowered, such that the predicted time required for project to reach reference condition would be increased.

Interpretation and Explanation of the Physical Structure Performance Curve

The Physical Structure PC suggests that projects can attain the lower limit of reference conditions very early in their development (Figure 3). This is because complex physical structure can be literally built into a project. Many recent projects have incorporated channels, levees, and islands into their designs. Projects with such design features tend to get higher physical structure scores. This contributes to the broad range of physical structure scores among young projects.

However, the physical structure scores are highly variable across the full range of tidal marsh age. There are at least four reasons for this variability. First, it is likely that sites lacking physical complexity are slow to develop it. This is because the topographic relief that accounts for much of this complexity is the result of spatial variations in a variety of relatively slow organic and inorganic sedimentary processes (Collins *et al.* 1987, Callaway *et al.* 1996, Orr et al 2003, Culberson *et al.* 2004, Schile 2014). Second, for tidal wetlands, the physical structure attribute consist of only two metrics, structural patch richness and topographic complexity, neither of which have any sub-metrics. Therefore, the number of possible attribute scores is greatly reduced, such that the same score can apply to wetlands of broadly different age (i.e., physical structure). Third, the scores for these metrics probably reflect natural variations in tidal wetland form and structure that are unrelated to wetland age. For example, some highly developed and older tidal wetlands naturally lack the topographic complexity and patch richness of less developed and younger wetlands. This is reflected in the very broad range of physical structure attribute scores for reference wetlands (see Figure 3). Finally, there is evidence that both of the physical structure metrics are subject to inconsistent interpretation among CRAM practitioners (Lowe *et al.* 2014). This contributes to the statistical variability in physical structure scores across the range of wetland age.

Because of its imprecision, the Physical Structure PC is less useful than the other PCs for predicting the developmental rate of tidal wetland restoration projects. Producing a more useful

Physical Structure PC will require improving the ability of CRAM to consistently differentiate among lesser variations in the physical structure of tidal wetlands.

Interpretation and Explanation of the Biotic Structure Performance Curve

The Biotic Structure PC suggests that projects are not likely to attain the lower limit of reference conditions for this attribute in less than about 50 years. Similar rates of project development are therefore expected for all the CRAM attributes except physical structure, which can be built into projects as explained above.

For tidal wetlands, the biotic structure attribute consists of three metrics to assess the species richness and three-dimensional architectural complexity of plant cover. One of the metrics includes multiple sub-metrics. The relatively large number of component scores translates into a larger number of possible attribute scores, which increases the ability of the attribute scores to differentiate among wetlands of different age (i.e., biotic structural complexity).

Scores for the biotic structure attribute are uniformly, broadly variable for wetlands younger than about 100 years. The possible sources of this variation in biotic structure scores are especially complex. Site history (including the manifest conditions of the soils), site preparation, project design, and project management can individually and, in combination, affect the initial biotic structure of a project and its development rate. At time-zero, the biotic structure attribute score will be especially sensitive to the tidal elevations of project substrates, their permeability, and their fertility. As mentioned above, any effort to plant or seed a project site, or to otherwise artificially encourage plant community development will affect the early biotic structure scores. Whether such treatments actually change the long-term trajectory of tidal wetland development, or whether they only affect conditions early-on is uncertain. However, as with the scores for physical structure, the scores for biotic structure probably reflect natural variations in tidal wetland form and structure that are unrelated to wetland age. For example, the plant community structure of some highly developed and older tidal wetlands is naturally less complex than that of less developed and younger wetlands. We note that the average score for reference sites is lower for the biotic structure attribute than for the other attributes having a comparably precise PC. This reflects the broad range in biotic structure across older, well developed tidal wetlands. Furthermore, recent history of natural changes in water salinity regime, due to such factors as drought or deluge, can be reflected by plant community structure for tidal wetlands of any age. It was not possible to develop a PC dataset that controls for all of these important factors. While a PC that does not reflect the vagaries of nature and the variations in project design and management would be more precise, it would also be unrealistic.

The indication that biotic structure can develop coincident with hydrology and physical structure is somewhat surprising. We expect the reference conditions for tidal marsh biotic structure are the manifestation of many density-dependent and density-independent processes operating continuously at variable rates. Disease, herbivory, inter-species competition, variations in the quantity and quality of inorganic sediment supplies, variations in aqueous salinity regimes, and variations in the rate of sea level rise must contribute to the biotic structure of tidal wetlands, as assessed using CRAM. Simply stated, it might be expected that biotic structure is the last aspect of tidal marsh condition to fully develop. However, the PC dataset indicates otherwise. The Biotic Structure PC may be further evidence that species richness tends to be maximum at intermediate levels of environmental disturbance (e.g., Roxburgh et al 2004, Catford *et al.* 2012, Alvarez-Molina 2012) rather than at some particular time along the physical developmental trajectory.

Tidal wetlands can achieve reference conditions for biotic structure in less time than predicted by the Biotic Structure PC. We found that some projects and non-project sites less than 25 years old had achieved the range of reference conditions for biotic structure (see Figure 3). Most of these sites were designed and managed in ways that intentionally nurtured rapid plant community development. As stated above, whether or not the conditions thus achieved at these particular sites will be sustained in the long-term cannot be known without monitoring the biotic structure of these sites into the future.

Implication for Tidal Wetland Restoration Design and Assessment

In general, the CRAM index PC and the Attribute PCs indicate that tidal wetland restoration projects are likely to take 50-75 years to achieve reference conditions This should not discourage project sponsors or the agencies responsible for wetland protection and restoration. The success of a project is commonly defined as its attainment of specific performance criteria that represent progress toward reference conditions. The CRAM PCs can be used to formulate performance criteria based on CRAM that reflect an acceptable developmental rate. In other words, adequate progress can be defined as CRAM index and attribute scores that are within the confidence intervals of their respective PCs. Furthermore, CRAM can be used to guide project design. If CRAM scores adequately represent the potential of a project to provide intrinsic ecosystem services, then designing projects to yield high CRAM scores seems like a reasonable strategy to help assure restoration success.

However, a distinction must be made between a project's potential and actual support of specific ecosystem services. Almost all projects necessarily have performance criteria focused on such services as the support of wildlife species or communities, flood control, pollution control, and recreation that cannot be monitored using just CRAM or any other rapid assessment method. Monitoring such services requires specific assessment methodologies. Since CRAM PCs help forecast the rate of overall project development, they can be used to help schedule monitoring some services that are expected to begin at particular developmental stages, but CRAM cannot usually substitute for the service-specific monitoring.

Federal and California state regulatory guidelines for monitoring wetland projects commonly require a 5-year minimum monitoring period to demonstrate that project-specific performance criteria are being met(e.g., USACE 2008, ODSW 2012). Unless a much longer monitoring effort is undertaken, the actual long-term performance of a project is not likely to be known. Few projects are monitored longer than this minimum period (Ambrose *et al.* 2006). This puts a premium on developing PCs that adequately represent performance criteria, and on designing projects to have conditions within the PC confidence interval within the first five years of project development.

The future of natural and restored tidal marshes along the California coast is threatened by accelerated sea level rise (SLR) due to climate change. SLR projections for the West Coast have recently been provided by the National Research Council and Ocean Protection Council (NRC 2012, OPC 2013). There is strong agreement among the various climate models for the amount of SLR that is likely to occur by 2050. After mid-century, projections of SLR become more uncertain due to unknown rates of global greenhouse gas emissions and uncertainty about their effects on land ice melting and other processes affecting SLR. Intensive studies of the likely effects of accelerated SRL on tidal wetlands have been initiated for San Francisco Bay (Callaway *et al.* 2007, Stralberg *et al.* 2011ab, Takekawa *et al.* 2013). The general prediction is that existing tidal marshes are likely to survive accelerated SLR over the next 50 years, although the tidal elevations of some marshes will be lowered. In the context of these predictions, the PCs indicate that marshes restored now might achieve reference conditions, despite accelerated SLR. However, it is also possible that SLR will reduce developmental rates, thus lengthening the time required to attain the reference conditions of mature, high-elevation marshes. I can be assumed that SLR will continue to accelerate beyond 2050 (NRC 2012). Therefore, the longer marsh development takes, the less likely that the conditions of mature, high elevation marshes will be attained. It is possible that accelerated SLR will prevent the existing reference conditions from ever being attained. In this case, a new set of reference conditions representing lower elevation marshes might be appropriate. Comparing the development of projects to what is expected, based on the current PCs, can be used to help forecast and document the effects of SLR on tidal marsh development.

Conclusions

In general, CRAM provides useful measures of changes in the visual condition of tidal wetlands due to their natural development. Performance Curves (PCs) based on the CRAM index score and attribute scores show that tidal wetland restoration projects along the California coast are likely to attain reference condition within about 50-75 years. The PCs represent statistically significant positive correlations between the age of tidal wetlands and their structural complexity in a landscape context.

The precision of the PCs is affected by many factors, including but not limited to project site history, project design and management, methodological limits on the ability of CRAM to differentiate among changes in condition, and inconsistent CRAM applications. Precision tends to increase with the range and number of possible CRAM scores that can be generated for any given CRAM attribute, which is a function of the number of metrics scores.

CRAM can be used to track the overall development of tidal wetlands and to assess their potential to support their intrinsic ecosystem services. However, additional monitoring is needed to assess the degree to which the services are actually being supported (CWMW 2013). CRAM PCs can therefore be used to forecast the overall developmental rates of tidal wetland restoration projects, and to help schedule monitoring for some specific services that are expected to begin at particular developmental stages.

Recommendations

Based on the findings of this study, we provide the following recommendations.

- Revise CRAM to improve its ability to differentiate among differences in hydrology and physical structure of tidal wetlands. The revision should involve the addition of metrics for the hydrology and physical structure attributes to increase the range and number of their possible scores.
- Assuming that CRAM scores adequately represent the potential of tidal wetlands to support their intrinsic ecosystem services, develop project performance standards based on CRAM PCs, and design tidal wetland restoration projects to achieve high CRAM scores. Given the short (5-yr) monitoring period for most projects, the performance criteria should emphasize the need for projects to have initial CRAM scores within or above the PC confidence interval.
- Continue to develop the CRAM Index and Attribute PCs by adding qualified case studies to the PC datasets presented here. The development of regional PCs might also be warranted to account for natural regional differences in tidal wetlands for and structure.
- Track the long-term performance of selected tidal wetland restoration projects using CRAM. This is essential to know the relationship between the time-zero score for a project and its subsequent developmental rate, as assessed using CRAM.

- If long-term monitoring indicates that the current reference conditions of mature, high-elevation tidal wetlands are not likely to be attained, due to accelerated sea level rise or other immitigable causes, alternative reference conditions should be developed.

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