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Development of Restoration Performance Curves for Streams in Southern California Using an Integrative Condition Index

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Abstract

Determining success of stream restoration projects is challenging, due to the disconnection between required monitoring periods and the actual time necessary to achieve ecological success. Performance curves could help address this challenge by illustrating likely developmental trajectories of restored streams. We applied the California Rapid Assessment Method (CRAM), an integrative index of stream condition, in a ten year chronosequence to create performance curves that project the development of functional streams for 30 years following restoration. CRAM scores for high functioning sites between zero and ten years were plotted against time since restoration. Best-fit curves were derived using either power functions or polynomial functions, depending on the CRAM metric. We tested the curves' ability to predict conditions for other projects across a range of ages, flow conditions (ephemeral to perennial), and physiographic settings. The curves are able to predict the time required for projects to achieve reference-level scores for the CRAM index and Hydrology and Biotic Structure attributes , but underestimate the time required for projects to achieve reference-level scores for the Physical Structure attribute. Our research demonstrates the potential to use modeled restoration performance curves based on CRAM scores to guide expectations for restoration project performance.

Keywords: performance curves, chronosequence, stream restoration, compensatory mitigation, California Rapid Assessment Method

Introduction

Evaluating the success of restoration projects is one of the most important, yet most difficult, elements of stream and wetland monitoring. Inconsistencies between ecological recovery periods and monitoring times poses a particular challenge when determining success. Systems can take decades to reach functional maturity (Zedler and Callaway 1999; Craft et al. 2003; Lennox et al. 2011). However, monitoring periods typically end long before projects reach such maturity, making it difficult to determine success before the end of required monitoring. These challenges can be met by performance curves that help forecast how stream restoration projects will perform over time.

Kentula et al. (1992) proposed the use of the performance curve as a key analytical tool for restoration monitoring because they can be used to visually and mathematically demonstrate developmental trajectories of wetland function or condition in years following restoration efforts (Fig. 1). Kentula et al. (1992) suggested that curves may be useful to indicate the best time to begin monitoring, to predict future ecological condition, and to demonstrate whether projects have met their restoration goals.

Chronosequence and time-series methods are two common approaches for assessing the development of ecological function or condition over time. In the time-series approach, curves are developed using ecological data that were repeatedly collected at the same study sites over an extended time period (Craft et al. 1999; Craft et al. 2002; Craft et al. 2003; Gutrich et al. 2009). Collection of time-series data requires foresight and resources to select study sites and sample them consistently over long time periods. In the chronosequence approach, data from multiple restoration projects of different ages are applied to develop curves using space-for-time substitution (Stevens and Walker 1970; Knops and Tilman 2000; Morgan and Short 2002). This method is especially useful for creating curves when long term data are scarce, or when there is a desire to generalize curves across a range of stream or wetland types.

Past studies have developed curves based solely on specific ecological attributes. Many such studies have focused on vegetation-based indicators (Matthews et al. 2009; Matthews and Spyreas 2010). Others have used a wide range of attributes including soil development, microbial processes, algal growth, benthic invertebrate density and diversity, sediment deposition, and organic matter (Craft et al. 1999; Craft et al. 2002; Craft et al. 2003). Because ecological attributes change at different rates post-restoration (Craft et al. 2003), several single-attribute curves are necessary to comprehensively evaluate the recovery of an entire wetland or stream system.

Integrative indices of biotic, physical, and other environmental conditions have the potential to more clearly capture overall ecological performance than single ecological attributes. However, few studies have attempted to develop performance curves with an integrated index of condition to assess restoration success. In this study, we developed performance curves for streams using the California Rapid Assessment Method (CRAM; California Wetlands Monitoring Workgroup 2013a), which integrates information about the surrounding landscape, hydrology, physical, and biotic structure to describe the overall ecological condition of streams and wetlands. CRAM is a validated tool for wetland condition assessment (Stein et al. 2009), and has been used to assess restored streams (Stein et al. 2011). Our goals were: (1) to develop stream performance curves based on a chronosequence of different restoration projects; (2) to use the curves to determine whether restored streams reach condition levels comparable to minimally disturbed reference sites and, if so, to find the time to reach those levels; (3) to evaluate how the performance of different attributes of riverine (stream) CRAM vary in timing and trajectory; and (4) to test the validity of the curves by determining how restoration projects not used in curve development performed when measured against the derived performance curves.

Methods

We developed chronosequence performance curves to demonstrate the hypothetical trajectories of high performing stream restoration projects in southern California. We compiled a list of stream restoration projects that involved stream channel construction from regulatory and natural resource agencies. The projects ranged in age up to 30 years. We assessed the projects using CRAM, and used the highest scoring projects aged 0-10 years old to construct the curves. We determined whether curves reached reference-level performance with reference site CRAM data that approximated natural or near-natural conditions. We tested the curves' validity using projects not assessed as part of curve development.

Study Sites

For construction of meaningful curves, we selected projects using criteria to ensure sufficient homogeneity in our sample pool. The projects were located in 11 coastal-draining watersheds in the southern California region, USA (Fig. 2; Appendix A), which is influenced by a Mediterranean climate. Average 1981-2010 rainfall at locations in the region ranged between 260 - 470 mm, with the majority of rain falling in winter months (http://www.ncdc.noaa.gov/). Wildfire and drought are common.

We focused on projects that employed mechanical channel grading and riparian re-vegetation. Enhancement projects, including those focused solely on invasive species control and/or re-vegetation without actual channel re-contouring, were excluded from curve development. We targeted accessible projects where the restored reach length was near or greater than 100 meters, the minimum length required for a riverine CRAM assessment. The projects were in alluvial stream channels classified by CRAM standards as non-confined, meaning the width of the valley across which the riverine system could migrate without encountering a hillside, terrace, or other feature that was likely to prevent further migration was at least twice the average bank-full width of the channel (California Wetlands Monitoring Workgroup 2013a). This allowed us to calculate the CRAM index score in the same manner for each project.

To locate projects we reviewed publicly available restoration databases and Clean Water Act § 404 permit files, and obtained recommendations from agencies and organizations participating in restoration project funding, monitoring, and research (Table 1). We found 55 projects located in 11 watersheds from Santa Barbara to San Diego counties that met our criteria. Project ages ranged from 1-26 years old post-restoration (Appendix A). For five projects, the exact restoration dates could not be located, so we estimated their ages based on year of Section 404 permit issuance.

CRAM data collection

We conducted one CRAM assessment at each of the 55 restoration projects using the riverine module versions 6.0 (in 2012) and 6.1 (in 2013). Version 6.1 includes minor updates and clarifications, and the two versions do not yield different scores. CRAM is a field-based rapid assessment tool used to evaluate the ecological condition of wetlands in California. It is comprised of separate modules for different wetland types, with the field indicators customized for the specific wetland type of interest. CRAM uses the hydrogeomorphic method wetland classes (Brinson 1993; Sutula et al. 2006). The riverine module of CRAM consists of a series of metric and sub-metric observations grouped into four attributes: Buffer and Landscape Context, Hydrology, Physical Structure, and Biotic [Vegetation] Structure (Table 2). Observations are conducted over a 100-200 meter long stream reach, identified as the assessment area (AA). Sub-metrics, metrics, and attributes are all described by field indicators that are assigned numerical scores based on qualitative and quantitative observations. The scores are applied to an algorithm to produce a numerical CRAM index. The index and attribute scores range from 25 to 100; higher scores imply better ecological condition. We also used CRAM data from the eCRAM database (www.cramwetlands.org) for seven central California region projects and ten southern California reference sites. Reference sites had relatively un-impacted surrounding landscapes and displayed high biotic integrity according to California's stream and river Reference Condition Management Program. The assessments in the statewide CRAM database are performed by trained practitioners and conform to standard methods and quality control measures.

Curve development

With the chronosequence approach, we developed riverine performance curves that display data against project age. We created curves for the CRAM index; Hydrology, Physical Structure, and Biotic Structure attributes; and select metrics and sub-metrics. Although we conducted CRAM in its entirety, we developed performance curves only for CRAM components that are influenced by restoration work inside of the CRAM AA. Therefore, we did not produce curves for the Buffer and Landscape Context attribute, its associated metrics, and the Water Source metric of the Hydrology attribute, items unaffected by restoration actions. However, these components were included in CRAM index calculations.

Performance curve formation involved three steps: choosing a set of projects, establishing how to anchor the curves at time-zero (t_0), and finding the best-fit mathematical functions to determine curve shapes. We used projects ten years old or younger that involved perennial or intermittent flow and with stream channels entirely graded (i.e., in-channel features removed) prior to restoration. Twenty-two projects fit these criteria; none were under two years old.

We withheld older projects over ten years, projects in ephemeral streams, and partially graded projects from curve developing and used these projects to test the validity and robustness of the performance curves. The small sample size of the older projects made them inappropriate for use in curve development, but ideal for testing curve performance. Projects in ephemeral streams and those that involved only partially grading of the stream channel prior to restoration (i.e., some in-channel features retained at the time of restoration) may have unique recovery trajectories due to different hydrologic or physical characteristics. As with the older projects, this made them inappropriate for curve development, but ideal for testing the robustness of the curves. We defined "ephemeral" according to CRAM guidelines where perennial streams conduct water all year long; intermittent streams are dry for part of the year, but conduct water for periods longer than ephemeral streams; and ephemeral streams conduct water only during and immediately following precipitation events (California Wetlands Monitoring Workgroup 2013b).

We set t_0 between initial grading and restoration (e.g., planting). Because the channels were fully graded, we used the lowest Physical and Biotic Structure scores (25) to represent t_0 conditions. We estimated Buffer and Landscape Context and Hydrology scores using planning documents and historical aerial imagery from Google Earth™. We combined the estimated t_0 CRAM scores with field data to develop the performance curves.

We used the highest CRAM index scores of each year to generate curves that represented high performing streams. We also applied the highest yearly scores of each component attribute to create attribute curves. Consequently, the lists of projects used to generate each attribute curve varied by attribute. Metric and sub-metric curves were generated with data from the same projects used to create their parent attribute curves. For example, data forming the Channel Stability and Hydrologic Connectivity curves were from the same projects used to develop the Hydrology attribute curve.

We tested exponential, logarithmic, polynomial, and power functions to develop the performance curves and selected the function with the highest R^2 for regression value of each data subset to represent its curve. A higher R^2 value implied that a function more closely followed the trajectory of actual CRAM data over time. With the best-fitting functions, we extrapolated curve trajectories to 30 years, and drew error bands around the curves using the previously identified tolerances of: ± 10 CRAM points at the index level,, ± 5 at the attribute level, and ± 3 at the metrics and sub-metric levels (Fig. 3). The index and attribute error values are based on the reported inter-user variability for CRAM (California Wetlands Monitoring Workgroup 2009). Metric and sub-metric error values are based on the potential to score one grade higher or lower during assessment.

We formed reference envelopes using an approach similar to that of Craft et al. (2003). For each curve, we calculated corresponding mean data values from the ten reference sites and established 95% confidence intervals around those values. We considered a curve to have reached reference performance when it crossed the reference mean, and also noted when the upper boundary of the performance curve error bands crossed into the reference envelope. Curves were drawn using R version 2.15.3 with ggplot2 version 0.9.3.1.

Performance Curve Validation and Testing

We tested the CRAM index performance curve by comparing it to CRAM scores from sites not used for curve development. Test groups were comprised of four types of sites: older restoration projects (over ten years old), projects located in central California (outside the region used for curve development), projects with ephemeral flow, and partially graded projects. We predicted: (1) CRAM scores from the older projects would fall on the curve, demonstrating its forecasting ability. (2) Central California projects would perform in the same range as southern California projects, with the best sites falling on the curve. CRAM was developed for application to streams and wetlands throughout California (Sutula et al. 2006). Agreement between central California project performance and the curve would support the transferability of the curves to adjacent regions and the validity of the curve shape. (3) Ephemerally flowing projects would score below the curve. The flashy hydrology and limited hydration for riparian vegetation in ephemeral streams may suppress their rate of post-restoration development relative to intermittent and perennially flowing streams, resulting in lower scores. (4) Partially graded project scores would exceed the curve. Because these projects began with better time-zero conditions and experienced less disturbance than those used to form the curves, we predicted they would reach reference conditions faster with better overall CRAM performance.

Results

Curve Development

We produced 18 CRAM-based performance curves that illustrate the expected trajectories of high-performing southern California stream restoration projects for 30 years post-restoration (Appendix B). The CRAM index and Hydrology, Physical, and Biotic Structure attribute curves were described by power functions, with rapid rises in condition followed by flattened rates of change (Fig. 4). Metrics and sub-metric curves were described by a mixture of power and polynomial functions (Table 3, Appendix B).

The Hydrology ($R^2 = 0.531$) and Biotic Structure ($R^2 = 0.934$) curves achieved reference means at fourteen and seven years following restoration, respectively (Fig. 4b, 4d). Both curves crossed the reference envelopes around year one. While the CRAM index curve ($R^2 = 0.848$) did not cross the reference mean within 30 years, its error band crossed the reference envelope at year 27 (Fig. 4a). Neither the Physical Structure main curve ($R^2 = 0.320$) nor its error band reached any reference standard within 30 years (Fig. 4c).

Curve Testing

Of the projects over ten years old (n = 6), one score was near the main CRAM index curve, and another within the lower bound of the error band (Fig. 5a). No projects scored above the curve, and four scores were below the band. The older projects did not generally adhere to the curve, indicating they were in poorer condition than expected. However, the sample pool was likely not representative of the range of projects, so our results were inconclusive as to whether the curves accurately predict older projects' performance.

Scores of four central California projects (n = 7) were near the main curve, one was above the upper error band boundary, and two were below the lower band boundary (Fig. 5b). The close proximity of four projects to the curve and one that exceeded curve predictions suggest that these curves are suitable for central California projects; greater support for this conclusion should be developed through collecting CRAM data from additional restoration projects outside the southern California region.

Two of seven scores from ephemeral flow projects were near the main curve, and the remaining five were below the error band (n = 7; Fig. 5c). Two scores were farther below the curve than projects from any other test categories. Ephemeral projects may encompass a wide variety of characteristics resulting in a relatively large range of scores, which is important to consider when assessing their performance. In rare cases they may achieve scores close to those expected for intermittent or perennial sites, but their group's collective performance suggests they generally yield lower CRAM scores.

Most of the partially graded projects performed near the curve and within the error band, but not all projects exceeded the curves as predicted. Half the scores (10 of n = 20) were above the curve; three of those were above the error band. Ten scores were below the curve; one of those was below the band. The concentration of the scores around the main curve suggest the curve predicts the performance of these types of projects. However we think the development of separate curves for this category would provide more appropriate targets for partially restored projects because many partially graded projects exceeded the curve that demonstrated optimal performance.

Discussion

Performance Curves

This study is one of the first efforts to operationalize the performance curve concepts promoted by Kentula et al. (1992). They proposed using performance curves to identify the time needed for projects to reach stable states, and to compare curves to reference conditions to measure the replacement of wetland function in human-manipulated (e.g., created or restored) wetlands. However, in the 20 years since Kentula et al. (1992) introduced the concept of performance curves, we are not aware of any example of curve development and application for streams. Kentula et al. (1992) suggested that curves can be used to represent condition or function over time; our results validated their hypothesized concepts. Previous studies used ecological indicators (e.g., plants) as surrogates for function (Craft et al. 1999; Craft et al. 2003; Matthews et al. 2009; Matthews and Spyreas 2010; Stefanik and Mitsch 2012). Results of this study suggest that curves based on CRAM reflect development of overall stream condition. The CRAM attributes performance curves based on ecologically comprehensive attributes or condition indices can be used to reliably depict systemic development over time. Kentula et al. (1992) also suggested a recovering system approaches a natural reference standard and reaches a steady state, a concept supported by our CRAM index curve. Our index and attribute data consistently fit best with power functions, implying that recovering stream trajectories generally assume that function shape.

This study also shows that CRAM, an ecological condition index, provides an efficient way to measure ecological condition in the context of a chronosequence. CRAM is not a tool that directly incorporates individual restoration project histories, nor is it a gold standard of wetland assessment. However, CRAM is an appropriate tool for generating these restoration performance curves because is grounded in ecological theory and has been previously validated against intensive measures of wetland condition (Stein et al. 2009). CRAM was developed to be a rapid, scientifically defensible, easily repeatable tool to assess wetland condition for management purposes. It was validated and calibrated against quantitative data including riparian bird diversity, an index of biotic integrity based on benthic macro invertebrate diversity, plant community composition, and indices of landscape context or condition (Sutula et al. 2006; Stein et al. 2009). These intensive measures of wetland condition verified that CRAM attributes accurately represent ecological condition. Therefore, curves based on CRAM provide robust predictions of expected ecological condition.

The power function fit of the hypothetical performance curves is a valid post-disturbance recovery pattern. Past studies demonstrated this development pathway in restored wetland invertebrate density and species richness (Craft et al. 2003), soil organic matter (Zedler and Callaway 1999), aboveground biomass (Morgan and Short 2002, Craft et al. 2003), plant species richness (Morgan and Short 2002), and Floristic Quality Index (Matthews et al. 2009). McMichael et al. (2004) created a chronosequence of post-fire chaparral vegetation recovery in central California based on leaf area index (LAI) values found using satellite data. LAI describes the total transpiring leaf surface, and therefore general vegetation development, above a given ground area. Their LAI-based curve followed a power curve shape over a 0 to 81 year post-disturbance timespan. Hope et al. (2007) demonstrated the same developmental shape through a time-series examination of a single, fire-disturbed site in the same region using the normalized difference vegetation index as their measure of ecological function. The development and stabilization of ecological function depicted in these studies indicated that post-disturbance maturation of the system can be characterized by this function.

Variability among environmental trajectories should be considered when evaluating system responses to restoration. The different development rates among CRAM attributes reflect the fact that ecological components advance along distinct pathways. We found in restored streams that the biotic attribute developed more quickly than the physical. Morgan and Short (2002) also developed chronosequence curves to track the increase in constructed salt marsh function over time by measuring primary production, plant diversity, soil organic matter accumulation, and sediment filtration and trapping. Their curves indicated that aboveground biomass and plant species richness reached reference standards before 10 years, sediment deposition at 10 years, and soil organic matter at 15 years. Their curves also varied in shape and direction because they illustrated trajectories of biological and physical ecological components with different developmental patterns. Craft et al. (2003) evaluated biological, soil, and microbial metrics along a chronosequence of constructed salt marsh development. Based on their observations, they proposed that upon construction processes related to hydrology (e.g., sedimentation, soil C and N) are the first to achieve or exceed reference equivalence, followed by biological processes, then soil development after a much longer time.

In contrast to our Hydrology and Biotic Structure curves, Physical Structure did not meet the reference envelope. This could be due to the relationship between riparian vegetation and physical habitat structure development in streams. Riparian vegetation may interact with stream flow to affect fluvial geomorphic processes (Corenblit et al. 2007) such as channel widening (McBride et al. 2010), in-stream habitat formation (Lennox et al. 2011), and the rates of erosion and deposition (Hupp and Osterkamp 1996). Therefore, we might expect physical structure metrics to mature after riparian vegetation is well-established to facilitate in-stream physical complexity.

The delayed response implied by the Physical Structure curve could also be due to project-specific restoration design. For example, stream channels at several projects we visited were engineered for stability with willow or straw wattles, and geotextile fabric, preventing the undercut bank physical patch type. We had little evidence that physical habitat features were included in project design. Several physical structure CRAM metrics need time to develop. For example, standing snags contribute to Physical Structure scores, but time is needed for trees to grow and die to create this feature. If we included older projects in curve development, then the

Physical Structure curve might more closely approach reference conditions because those projects have more time for physical features to develop naturally.

Vegetation growth rates and active planting to support rapid establishment of native riparian species (in order to comply with mitigation plan requirements) boosted the Biotic Structure scores and curve. Because plants can establish and grow quickly, floral indicators of functional replacement in restored or created wetlands are able to match reference conditions in under five years after project installation (Craft et al. 1999; Craft et al. 2003; Gutrich et al. 2009).

Restoration projects often implement in-stream flow modifications with a goal of supporting the growth and establishment of wetland or riparian plant communities. However, few projects allow for episodic or channel-forming events that support natural fluvial processes critical for long-term health and recruitment of instream and riparian communities. This is reflected in the physical structure attribute curve, which never reaches reference conditions. Hill and Platts (1998) also observed substantial development of riparian vegetation and in-channel habitat features within the first five years of stream restoration in a passively restored project associate with establishment of an appropriate hydrologic regime (i.e., flow volume and timing pattern). However, no attention was given to establishing fluvial processes of physical channel structures. Similar approaches in the sites we studied resulted in the physical and biotic structure attributes reflecting reduced development over time. These patterns were especially pronounced in projects with ephemeral flow, where lack of attention to fluvial processes led to low performance for both the physical and biological structure attributes.

Watershed condition also influenced restoration success. CRAM’s Buffer and Landscape Context attribute evaluates landscape context, buffer size, and connectedness to other aquatic resources. As mentioned, we did not develop curves for this attribute because its components are unchanged by most stream restoration projects. We observed that most projects involve relatively minimal manipulation of the surrounding landscape and rather attempt to design restored streams to function within the existing stream corridor. Several of the projects we assessed either abutted or were surrounded by golf courses, highly maintained urban parks, roads, and commercial and residential development. For example, a project on Las Virgenes Creek at Agoura Road, the highest performing five-year-old project, is sandwiched by a shopping center and a business center. Less than 100 meters upstream of the restored reach, the creek emerges from beneath a nine lane interstate highway. The project removed the concrete flood control apron, and established a natural channel and planted floodplain within the existing flood control corridor. The engineered landscape limits the ability of the stream channel to migrate naturally. Furthermore, the site receives constant flow from urban runoff, rather than experiencing a natural hydroperiod. In cases like this, project surroundings reduce the potential for restoration sites to achieve full functionality. There are other cases with less limited landscapes, such as the Jamul Creek and Dulzura Creek projects, located on a few thousand acres of preserved land managed by a mitigation bank. In any scenario, we recommend that more attention be paid to restoring the physical and hydrological foundation on which a project is established so that robust ecological performance can be achieved.

Application of curves for stream restoration management

Results of our analysis suggest that many sites will not reach functional maturity until at least 10 years post restoration (or longer in some cases). Extending the required monitoring period would improve the ability to directly evaluate restoration success. This conclusion is also supported by other studies, such as Osland et al. (2012), who observed various soil properties in created mangrove wetlands reaching equivalency between 18-28 years. Similarly, Craft et al. (2003) observed soil C and N levels at constructed marshes to be lower than those found in corresponding natural marshes after 28 years. However, longer monitoring periods may involve more resources than are feasible for either project proponents or regulatory agencies. If longer monitoring is not feasible, performance curves provide a valuable tool to help achieve long term ecological success. Curves can be used to establish performance targets and restoration goals, and to predict whether a project is on track and likely to reach ecological targets in the future. If project sites miss the correct trajectory, additional remedial measures can be implemented.

Although the curves were based on southern California projects, our results indicate that they have broader applicability. CRAM was designed to be consistent across regions in the state (Sutula et al. 2006). Furthermore, the developmental patterns for the same wetland type and function should be similar among different regions (Kentula et al. 1992). Preliminary evaluation of central California projects using these curves supported their applicability in that region, a conclusion that could be further supported with additional data.

Now is an appropriate time to develop these ecologically comprehensive performance curves because regulatory agencies are implementing performance measures for compensatory mitigation projects that encompass a range of environmental components. The US Army Corps of Engineers-South Pacific Division (SPD) has issued performance guidelines that include ecological function and condition assessment methods including CRAM (US Army Corps of Engineers 2013). They also provided a suite of uniform performance standards for mitigation project managers (US Army Corps of Engineers 2012). As restoration projects are increasingly judged by overall ecological performance, these curves could be powerful tools in restoration management.

Improve and expand performance curves

We generated performance curves using the available relevant data for southern California stream restoration projects. As data for additional projects becomes available, future research can validate the curves produced here with more intensive data and refine them with longer term data. In addition, curve development could be expanded to include additional restoration types. While CRAM evaluates overall ecological condition, intensive measurements of ecological components such as macroinvertebrates, algae, and soil lend different insight into stream development. Metric selection and results interpretation should be conducted with consideration that intensive metrics have varying units of measurement (e.g., Craft et al. 2002), mature at different rates (e.g., Morgan and Short 2002; Craft et al. 2003), and have not been integrated into an ecologically comprehensive index in California.

Because we lacked CRAM data from a range of projects 10-30 years old, we are uncertain of these curves' present ability to predict the performance of older projects. Inclusion of CRAM data from additional projects 10-30 years old would help resolve this gap First, it may verify whether physical structure can reach reference standards within 30 years, versus the ten year period used for our curves. Second, data from older projects may change some of the polynomial-shaped metric curves to be power-shaped, reflecting long-term stability rather than deteriorating conditions. Finally, older project data could anchor the right ends of curves that rose above reference ranges or beyond the range of CRAM to levels more reflective of a quasi-stable mature wetland condition.

As this study demonstrated the development and application of curves based on the concepts of Kentula et al. (1992), an appropriate next step would be to expand the application range of this tool to a larger suite of restoration approaches and wetland types. Projects with complex time-zero conditions and those with passive vegetation restoration are candidate categories for curve development. CRAM modules exist for other wetlands in addition to riverine: estuarine (tidal marsh), bar built estuarine, individual vernal pool, vernal pool systems, depressional (pond), and slope wetlands, so similar performance curves could be developed for those wetland types as well.

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Table 1 Sources used to locate stream restoration projects for curve development

Restoration Project Sources	**URL**
CalFish Projects	www.calfish.org
California Coastal Conservancy	scc.ca.gov
California Department of Fish and Game Cal Fed Ecosystem Restoration Program	www.dfg.ca.gov
California State Parks Project Inventory	www.parks.ca.gov
California Wildlife Conservation Board	www.wcb.ca.gov
EcoAtlas (formerly the California Wetland Tracker)	www.ecoatlas.org
National Oceanic and Atmospheric Administration Restoration Atlas	restoration.atlas.noaa.gov
Natural Resource Project Inventory	www.ice.ucdavis.edu
Southern California Wetland Recovery Project	scwrp.org
US Army Corps of Engineers Los Angeles District, Regulatory Division	www.spl.usace.army.mil

Table 2 CRAM attributes, metrics, and sub-metrics. Numbers in parenthesis indicate the range of scores available for each data type (California Wetlands Monitoring Workgroup 2013b)

Attribute	Metric	Submetric
Buffer and Landscape Context (25-100)	Stream Corridor Continuity (3-12)	
	Buffer (6-24)	Percent of AA with Buffer (3-12)
		Average Buffer Width (3-12)
		Buffer Condition (3-12)
Hydrology (25-100)	Water Source (3-12)	
	Channel Stability (3-12)	
	Hydrologic Connectivity (3-12)	
Physical Structure (25-100)	Structural Patch Richness (3-12)	
	Topographic Complexity (3-12)	
Biotic Structure (25-100)	Plant Community Composition (3-12)	Number of Plant Layers (3-12)
		Number of Co-dominant Species (3-12)
		Percent Invasion (3-12)
	Horizontal Interspersion (3-12)	
	Vertical Biotic Structure (3-12)	

Table 3 Performance curve summary: mathematical functions of the curves, regression for curves r-squared values, and the years that curves and upper error band boundaries reached the reference zone if this occurred within 30 years (rounded to the nearest year). CRAM attributes are underlined. Raw reference data were not available. CRAM parent components are underlined and italicized

Curve Metric	Curve Function	R^2	Curve Crosses Reference Mean (year)	Error Envelope Crosses Reference Band (year)
CRAM Index	$y = 60.613x^{0.0542}$	0.848	> 30	27
Hydrology	$y = 73.18x^{0.0523}$	0.531	14	1
Channel Stability	$y = 7.3536x^{0.1163}$	0.544	> 30	1
Hydrologic Connectivity	$y = 8.5922x^{0.145}$	0.869	< 1	0
Physical Structure	$y = 41.499x^{0.0642}$	0.32	> 30	> 30
Structural Patch Richness	$y = -0.068x^2 + 0.711x + 3.2656$	0.099	never	never
Raw Patch Count	$y = 3.9973x^{0.1943}$	0.71	n/a	n/a
Topographic Complexity	$y = -0.1331x^2 + 0.9544x + 5.5039$	0.364	never	1
Biotic Structure	$y = 59.149x^{0.124}$	0.934	7	1
Number of Plant Layers	$y = 7.1872x^{0.1189}$	0.739	> 30	1
Number of Co-dominant Species	$y = -0.1567x^2 + 1.4427x + 3.4344$	0.384	2	11
Raw Co-dominant Species Count	$y = 1.1335x^{0.985}$	0.957	n/a	n/a
Percent Invasion	$y = -0.212x^2 + 2.6412x + 3.6755$	0.826	5	10
Raw Invasive Species Percentage	$y = 0.0272x^2 - 0.3265x + 1.3878$	0.059	n/a	n/a
Raw Invasive Species Count	$y = 0.008x^2 - 0.0923x + 0.3039$	0.281	n/a	n/a
Plant Community Composition	$y = 6.8447x^{0.113}$	0.794	18	0
Horizontal Interspersion	$y = -0.1884x^2 + 2.1533x + 2.7442$	0.621	never	1
Vertical Biotic Structure	$y = 7.2688x^{0.1246}$	0.974	4	0

Fig. 1 Hypothetical performance curve. The restored wetland improves until a time point where it reaches a mature or stable condition. The curve is based on the chronosequence approach, where data from multiple restoration projects of different ages are used to illustrate the development of a hypothetical project. Data that approximate the range of natural or near-natural conditions at minimally disturbed reference wetlands are used to determine whether the curve reaches reference-level performance (figure adapted from Kentula et al. 1992, reprinted with permission)

Fig. 2 Restoration project sites where CRAM assessments were conducted for performance curve development in 2012-2013. All projects were located in coastal-draining watersheds in southern California. Black lines are watershed boundaries

Fig. 3 The performance curve (black line) in the center of the error band (gray lines) illustrates the hypothetical CRAM achievement of a high-performing restored stream. This performance curve was formed using the mathematical function best fit to actual CRAM data from projects 2-10 years old and an estimated data value at time-zero. The reference envelope (shaded gray) is composed of the 95% confidence interval around the mean reference value (dashed line). The curve error band is ± the CRAM index error around the curve

Fig. 4 Hypothetical stream restoration performance curves for CRAM (a) index (●), (b) Hydrology (▲), (c) Physical Structure (■), and (d) Biotic Structure (♦) attributes. Curves were developed with CRAM data from best-performing restoration projects. The curve error band (bounded by gray lines) is ± CRAM error values around the curve. Reference envelopes (shaded gray) are composed of the 95% confidence intervals around mean reference values, indicated by dashed lines

Fig. 5 Performance curves superimposed on CRAM index scores from (a) projects over 10 years old (n = 6), (b) projects from the California central coast (n = 7), (c) ephemerally flowing projects (n = 7), (d) projects partially graded prior to restoration (n = 20). Only 19 partially graded site scores are visible because points overlap in year six where two projects scored 70

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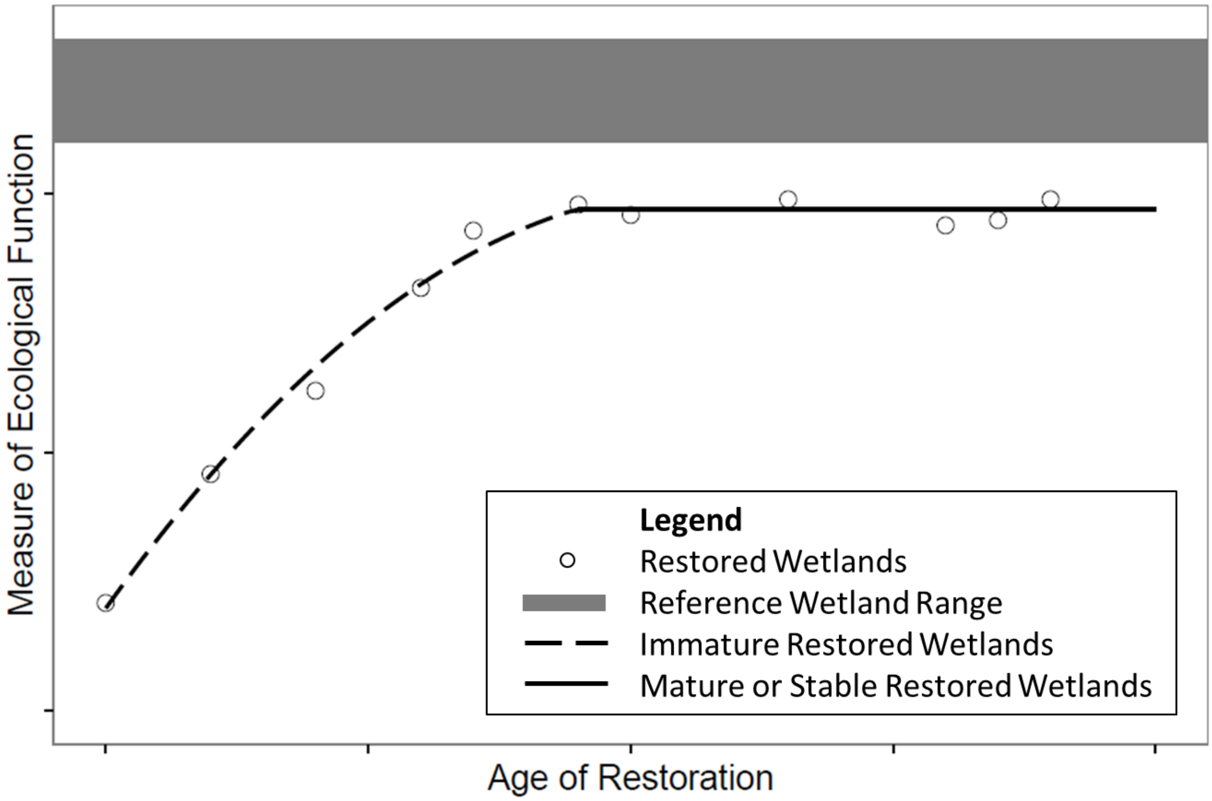
Restoration Project Sources	**URL**
CalFish Projects	www.calfish.org
California Coastal Conservancy	scc.ca.gov
California Department of Fish and Game Cal Fed Ecosystem Restoration Program	www.dfg.ca.gov
California State Parks Project Inventory	www.parks.ca.gov
California Wildlife Conservation Board	www.wcb.ca.gov
EcoAtlas (formerly the California Wetland Tracker)	www.ecoatlas.org
National Oceanic and Atmospheric Administration Restoration Atlas	restoration.atlas.noaa.gov
Natural Resource Project Inventory	www.ice.ucdavis.edu
Southern California Wetland Recovery Project	scwrp.org
US Army Corps of Engineers Los Angeles District, Regulatory Division	www.spl.usace.army.mil

Attribute	**Metric**	**Submetric**
Buffer and Landscape Context (25-100)	Stream Corridor Continuity (3-12)	
	Buffer (6-24)	Percent of AA with Buffer (3-12)
		Average Buffer Width (3-12)
		Buffer Condition (3-12)
Hydrology (25-100)	Water Source (3-12)	
	Channel Stability (3-12)	
	Hydrologic Connectivity (3-12)	
Physical Structure (25-100)	Structural Patch Richness (3-12)	
	Topographic Complexity (3-12)	
Biotic Structure (25-100)	Plant Community Composition (3-12)	Number of Plant Layers (3-12)
		Number of Co-dominant Species (3-12)
		Percent Invasion (3-12)
	Horizontal Interspersion (3-12)	
	Vertical Biotic Structure (3-12)	

Curve Metric	**Curve Function**	**R²**	**Curve Crosses Reference Mean (year)**	**Error Envelope Crosses Reference Band (year)**
CRAM Index	$y = 60.613x^{0.0542}$	0.848	> 30	27
Hydrology	$y = 73.18x^{0.0523}$	0.531	14	1
Channel Stability	$y = 7.3536x^{0.1163}$	0.544	> 30	1
Hydrologic Connectivity	$y = 8.5922x^{0.145}$	0.869	< 1	0
Physical Structure	$y = 41.499x^{0.0642}$	0.32	> 30	> 30
Structural Patch Richness	$y = -0.068x^2 + 0.711x + 3.2656$	0.099	never	never
Raw Patch Count	$y = 3.9973x^{0.1943}$	0.71	n/a	n/a
Topographic Complexity	$y = -0.1331x^2 + 0.9544x + 5.5039$	0.364	never	1
Biotic Structure	$y = 59.149x^{0.124}$	0.934	7	1
Number of Plant Layers	$y = 7.1872x^{0.1189}$	0.739	> 30	1
Number of Co-dominant Species	$y = -0.1567x^2 + 1.4427x + 3.4344$	0.384	2	11
Raw Co-dominant Species Count	$y = 1.1335x^{0.985}$	0.957	n/a	n/a
Percent Invasion	$y = -0.212x^2 + 2.6412x + 3.6755$	0.826	5	10
Raw Invasive Species Percentage	$y = 0.0272x^2 - 0.3265x + 1.3878$	0.059	n/a	n/a
Raw Invasive Species Count	$y = 0.008x^2 - 0.0923x + 0.3039$	0.281	n/a	n/a
Plant Community Composition	$y = 6.8447x^{0.113}$	0.794	18	0
Horizontal Interspersion	$y = -0.1884x^2 + 2.1533x + 2.7442$	0.621	never	1
Vertical Biotic Structure	$y = 7.2688x^{0.1246}$	0.974	4	0

Fig1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Legend
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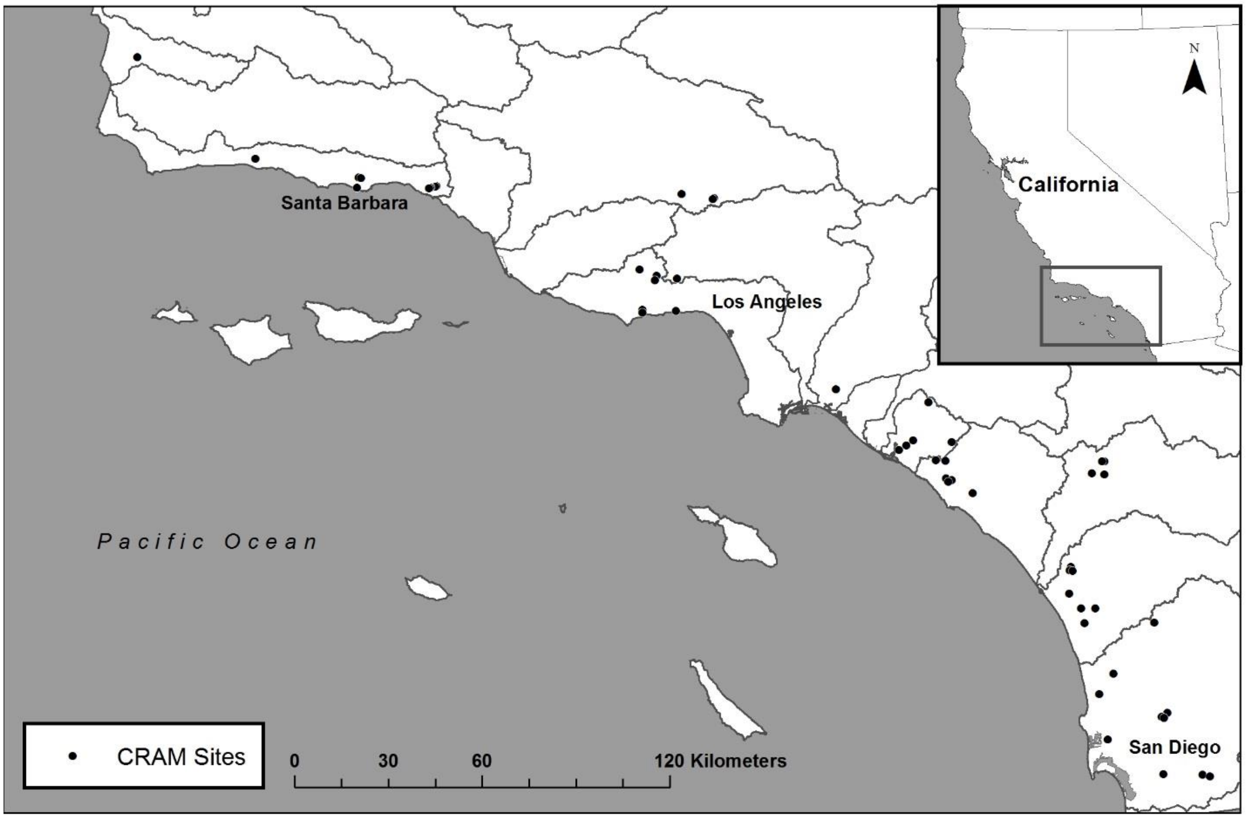
▬ Reference Wetland Range
– – Immature Restored Wetlands
— Mature or Stable Restored Wetlands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California
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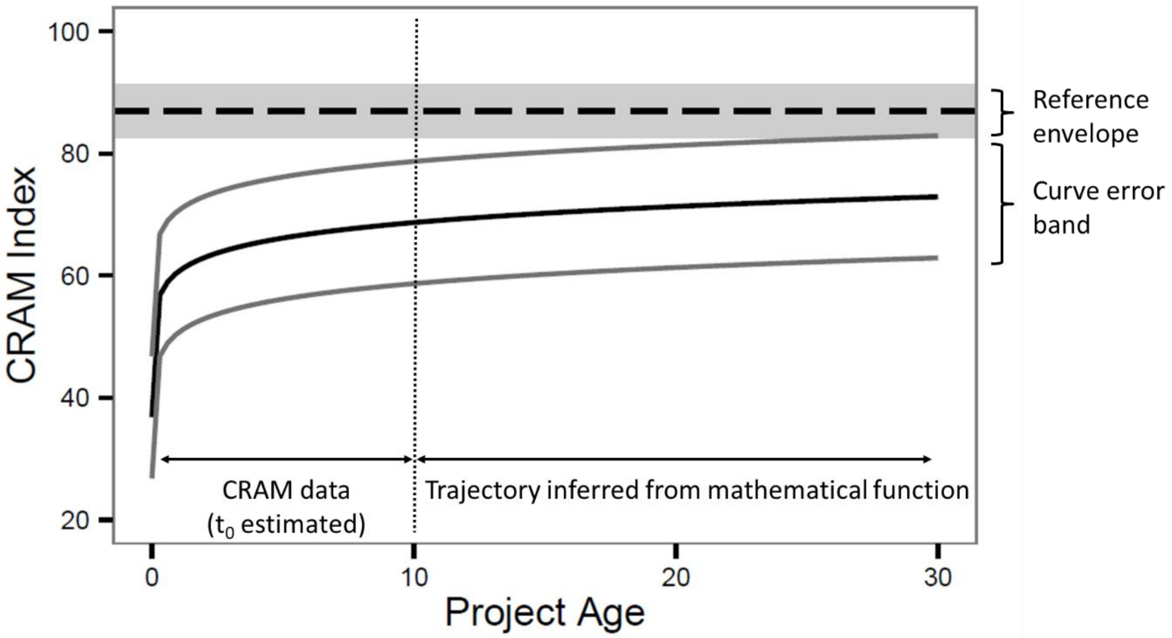
120 Kilometers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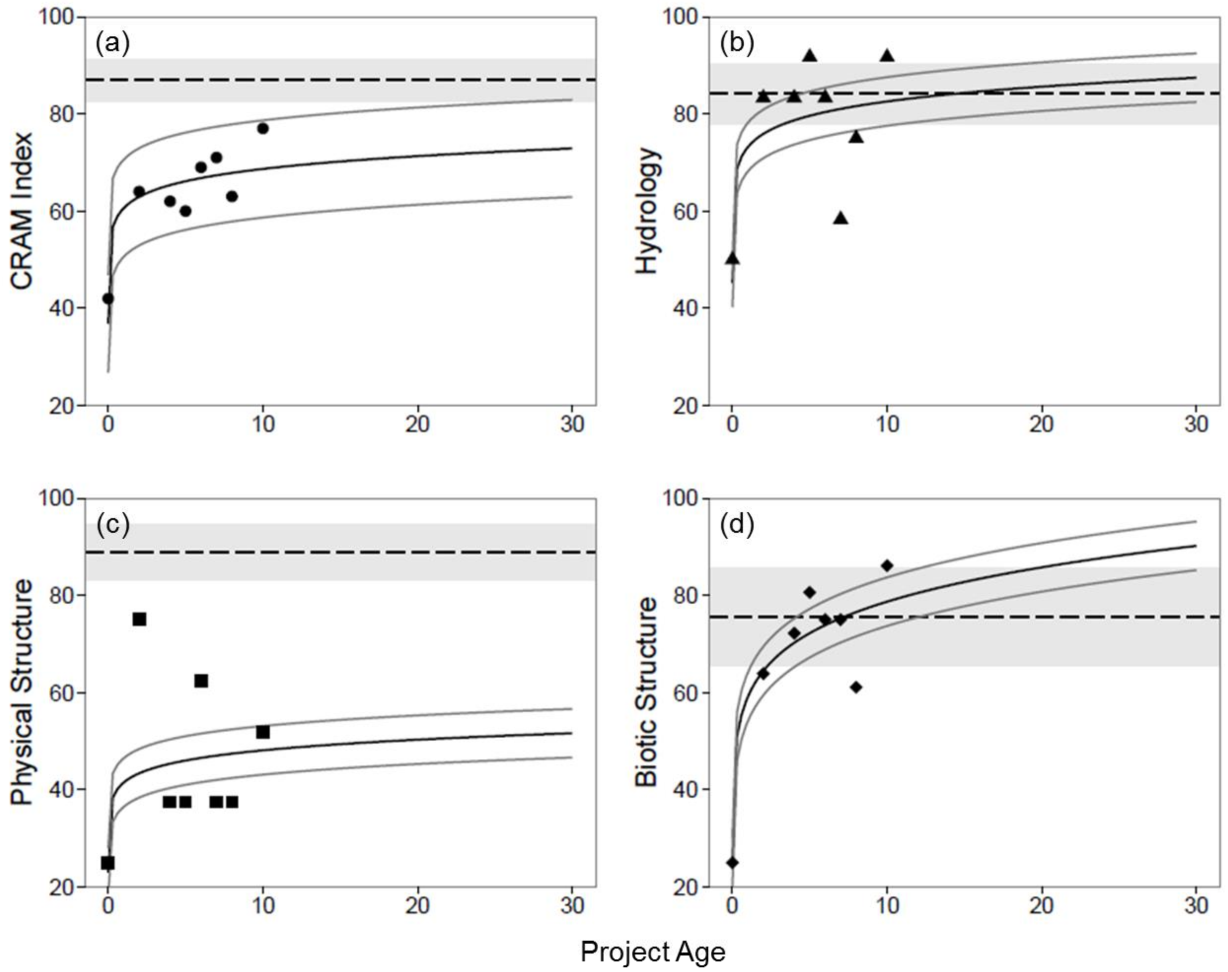
Reference envelope
Curve error band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Physical Structure
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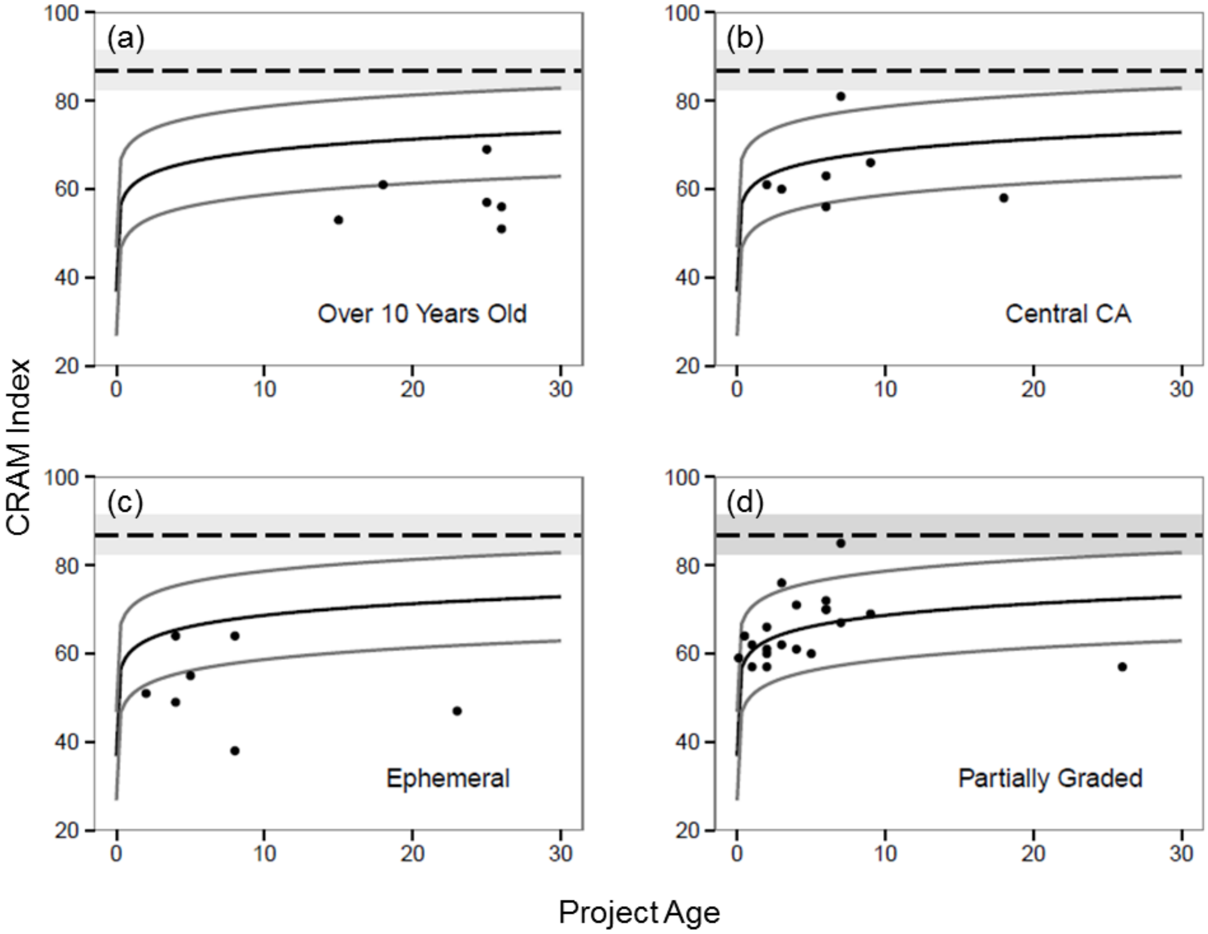
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Over 10 Years Old
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APPENDIX A: Performance Curve Study Sites

Geographic coordinates of select sites not included due to requests from restoration practitioners or land managers.

(*) indicates sites where, due to limited project information, restoration year was estimated as the Clean Water Act § 404 permit year.

(†) indicates high-performing sites used for curve development.

Site	Latitude	Longitude	Watershed	Hydrologic Regime	AA Entirely Graded	Year Restored	Site Considerations
Southern California Restoration Projects							
San Antonio Creek Site 1	37.77681	-120.49756	San Antonio Creek	perennial	yes	2010	Compensatory mitigation
San Antonio Creek Site 3†	34.77991	-120.50688	San Antonio Creek	perennial	yes	2010	Compensatory mitigation
SCHR 5			Santa Barbara Channel	intermittent	no	2011	Arizona crossing removed for improved fish passage; irrigated; had not seen regular flow since restoration
SCHR 6			Santa Barbara Channel	perennial	no	2011	Arizona crossing and concrete apron removed to improve fish passage
Upper Las Positas Creek	34.43325	-119.73519	Santa Barbara Channel	ephemeral	yes	2010	City project; in golf course; reach in low-order headwater of Las Positas Creek; appearance similar to vegetated swale
Mission Creek SB	34.43214	-119.72687	Santa Barbara Channel	intermittent	no	2012	Project to improve fish passage; channel dry with construction occurring directly downstream of AA at time of visit

SCHR 4			Santa Barbara Channel	intermittent	no	2012	Removed fish passage barrier
SCHR 3			Santa Barbara Channel	intermittent	no	2010	Removed concrete box culverts to improve fish passage
SCHR 2			Santa Barbara Channel	intermittent	no	2010	Arizona crossing and concrete apron removed for improved fish passage
Mesa Creek (Arroyo Burro)	34.40490	-119.73994	Santa Barbara Channel	perennial	yes	2006	City project
SCHR 1			Santa Barbara Channel	intermittent	no	2010	Restored to improve fish passage
SCHR 7			Santa Barbara Channel	intermittent	no	2010	Removed fish passage barrier
Pico Creek†	34.37824	-118.61166	Santa Clara River	intermittent	yes	2005	Mitigation bank
Whitney Canyon	34.36561	-118.49792	Santa Clara River	intermittent	yes	2010	Mitigation bank; project managers noted difficulty with dryness; sprayed area with water truck; floodplain not planted beyond berm along channel
Elsemere Canyon	34.36249	-118.50202	Santa Clara River	intermittent	no	2009	Mitigation bank; no water flowing when assessed
Medea Creek	34.16298	-118.76118	Santa Monica Bay	perennial	yes	1994	Restored by housing developer to remove non-permitted gunnite channel; urban flow input
Las Virgenes Creek-Agoura Rd†	34.14440	-118.70125	Santa Monica Bay	perennial	yes	2007	City project; concrete channel bottom removed; urban flow input; floodplain sandwiched by shopping and business centers

Dry Canyon Creek	34.13564	-118.63187	Los Angeles River	intermittent	yes	2007	Non-profit land trust project; concrete lining, rock retaining wall, large debris, and culvert removed from channel
Las Virgenes Creek-Lost Hills	34.13131	-118.70748	Santa Monica Bay	perennial	yes	1997	City project; urban flow input
Solstice Creek-AC2 to AC3	34.04570	-118.75356	Santa Monica Bay	perennial	no	2005	Project removed barriers to fish passage
Las Flores Creek†	34.04145	-118.63759	Santa Monica Bay	intermittent	yes	2008	City project; riprap banks and concrete structures removed; landslides common occurrence in area (large landslide next to project)
Solstice Creek-D1 to D3	34.03813	-118.75211	Santa Monica Bay	perennial	no	2005	Project removed barriers to fish passage
El Dorado Nature Center	33.80737	-118.08752	San Gabriel River	perennial	yes	2010	Nature center created stream; urban flow input
Peters Canyon Wash Mitigation*	33.76469	-117.77029	Newport Bay	intermittent	yes	1987	Compensatory mitigation, urban flow input; formerly irrigated
Pacific Commerce / Mason Regional Park*	33.65627	-117.82522	Newport Bay	perennial	yes	1988	Compensatory mitigation; urban flow input; formerly irrigated
Serrano Creek	33.64835	-117.69308	Newport Bay	perennial	yes	2002	County restoration project co-funded by county flood control district, city, local non-profit, et al.; urban flow input
Bison/Berkeley Mitigation*	33.64140	-117.84937	Newport Bay	ephemeral	yes	1990	Compensatory mitigation; dry at time of visit
Big Canyon Country Club	33.62918	-117.87398	Newport Bay	perennial	yes	2006	Compensatory mitigation; urban flow input; in golf course

El Toro Rd *	33.59655	-117.74805	Aliso Creek	perennial	no	1987	Compensatory mitigation (Tentative Tract project); urban flow input; site sided by highway and housing development
Dairy Fork	33.59415	-117.71555	Aliso Creek	perennial	yes	1987	Compensatory mitigation; urban flow input
Murrieta 2			Santa Margarita River	ephemeral	yes	2008	Compensatory mitigation; channel showed no dynamic characteristics; rip-rap grade control structures every ~100m along project
St. Martha's Mitigation	33.58006	-117.17602	Santa Margarita River	perennial	yes	2004	Compensatory mitigation; urban flow and groundwater input; assessed in winter; evidence of camp-style fire in AA
Murrieta 1			Santa Margarita River	perennial	yes	2006	Compensatory mitigation; urban flow input; flood channel adjacent to AA not cleared of vegetation; vector control performed in area
WetCat West/Country Village Mitigation*	33.54399	-117.71582	Aliso Creek	perennial	yes	1988	Compensatory mitigation; urban flow input; channel sandwiched between hillslope and sidewalk/road
Arboretum Mitigation	33.54247	-117.17068	Santa Margarita River	intermittent	yes	2002	Compensatory mitigation; urban flow input; assessed in winter; part of AA impacted by road expansion since 2012 assessment
Sulphur Creek-Crown Royale Area	33.53907	-117.69650	Aliso Creek	perennial	yes	2006	City project; urban flow input

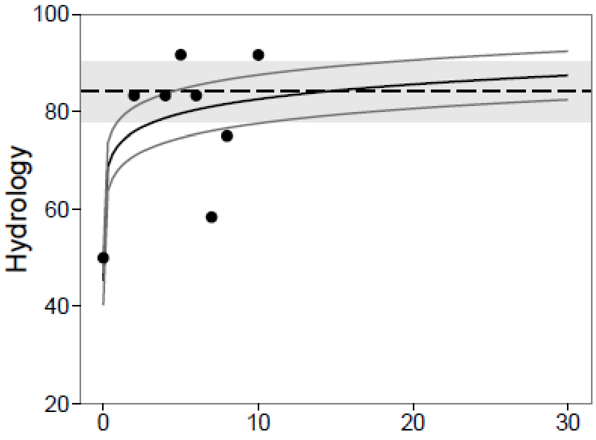
Sulphur Creek-Army Corps of Engineers	33.53429	-117.70715	Aliso Creek	perennial	no	2008	City project; urban flow input
Whispering Hills Mitigation	33.49982	-117.62405	Aliso Creek	ephemeral	yes	2007	Compensatory mitigation; AA part large, highly engineered project
Wilmont Mitigation	33.27811	-117.29455	San Luis Rey	intermittent	no	2007	Compensatory mitigation; urban flow input; low, broad floodplain/highwater-difficult to identify thalweg; old willows suggest channel not graded during restoration
Morro Hills West Parcel	33.26990	-117.29768	San Luis Rey	ephemeral	no	2004	Compensatory mitigation
Morro Hills East Parcel	33.26732	-117.28859	San Luis Rey	ephemeral	no	2004	Compensatory mitigation; in golf course
Rancho del Oro	33.20275	-117.30207	San Luis Rey	perennial	no	2006	Compensatory mitigation; urban flow input
Rosemary's Mountain Quarry	33.15870	-117.26234	San Luis Rey	perennial	no	2009	Compensatory mitigation (Fischer property); urban flow input
Future Elementary School	33.15662	-117.21360	San Luis Rey	intermittent	yes	2007	Compensatory mitigation; urban flow input; major culverts near site; multiple channels in project-assessed primary channel
La Costa†	33.11615	-117.25332	San Luis Rey	perennial	yes	2004	Compensatory mitigation; urban flow input; several crayfish at site; knickpoint downstream of AA
Cloverdale Creek	33.11113	-117.01348	San Diego River	perennial	yes	2006	Compensatory mitigation; much fencing near project; trash/debris from restoration seen at time of visitation

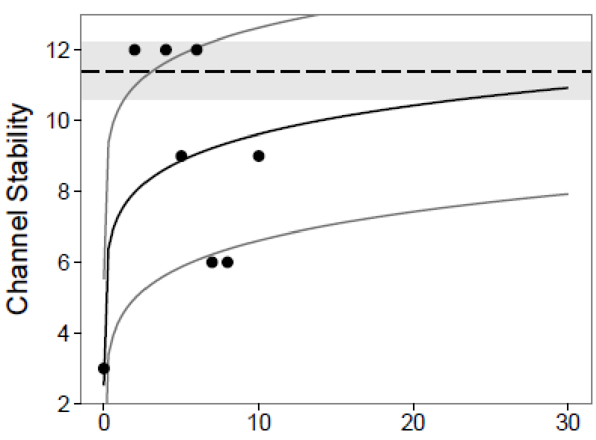
McGonigle Canyon	32.96739	-117.15842	San Diego River	perennial	no	2003	Compensatory mitigation; urban flow input; dense, impenetrable vegetation; homeless encampments nearby in floodplain
Los Peñasquitos	32.90956	-117.20982	San Diego River	perennial	no	2006	Compensatory mitigation (El Cuervo Norte project); urban flow input; assessed one of several channels
Santee Town Center	32.84922	-116.98005	San Diego River	ephemeral	yes	2008	Compensatory mitigation; little/no hydrology; appeared swale-like
Forester Creek DOT	32.83920	-116.99893	San Diego River	perennial	no	2006	Compensatory mitigation for DOT; urban flow input; assessed enhanced area
Forester Creek Improvement	32.83499	-116.99158	San Diego River	perennial	yes	2008	City project; urban flow input; stream deep (non-wade able); recent invasive plant removal prior to CRAM visit
Tecolote-Tecolote Canyon Mitigation	32.77794	-117.18539	San Diego River	perennial	no	2008	Compensatory mitigation; urban flow input
Bonita Meadows[†]	32.67273	-116.99900	San Diego River	perennial	yes	2006	Compensatory mitigation, urban flow input
Jamul Creek	32.66835	-116.86584	San Diego River	perennial	yes	2002	Mitigation bank; project involved grading floodplain adjacent to incised, aggrading channel
Dulzura Creek[†]	32.66273	-116.84097	San Diego River	perennial	yes	2002	Mitigation bank; two burns post-restoration; regular water transfer began 2010

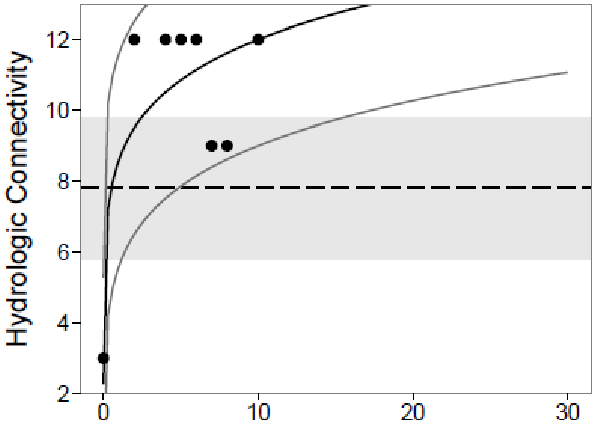
Southern California Reference Sites			
Site	**Latitude**	**Longitude**	**Watershed**
Bear Creek	34.2692	-117.8913	San Gabriel River
San Gabriel River, West Fork	34.2406	-117.8831	San Gabriel River
SMC00476	33.9551	-117.9054	San Gabriel River
SMC00480	33.9823	-117.8157	San Gabriel River
SMC01040	33.8263	-117.7009	Santa Ana River
Little Mill Creek	34.1642	-117.1419	Santa Ana River
South Fork Santa Ana River	34.1328	-116.8429	Santa Ana River
Noble Canyon	32.8641	-116.5085	Tijuana River
SMC01161 (Sandia Creek)	33.4418	-117.2557	Santa Margarita River
SMC00827	34.2724	-119.2502	Ventura River

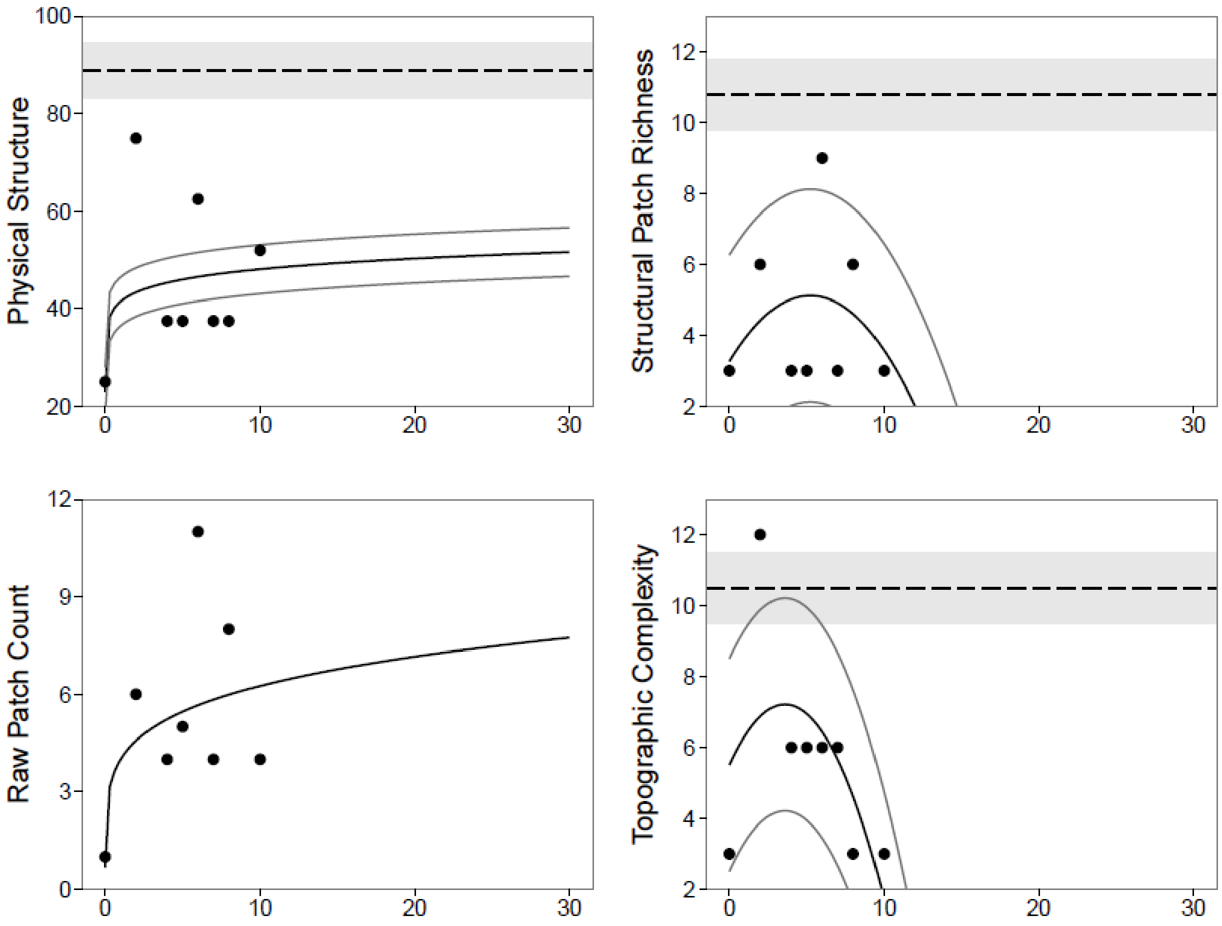
Central Coast Restoration Projects				
Site	**Latitude**	**Longitude**	**Restoration Year**	**Assessment Year**
Lombardi Creek	36.9655	-122.1110	2004	2010
Natividad Creek Restoration	36.69966	-121.608	1995	2013
Queseria Creek Lower	37.0448	-122.2239	2004	2010
Stenner Creek	35.3081	-120.6801	2001	2010
Walters Creek phase 2	35.3466	-120.7558	2005	2008
Walter's Creek Phase I	35.3496	-120.7475	2004	2006
Wilder Creek	36.9675	-122.0808	2000	2007

APPENDIX B: California Rapid Assessment Method (CRAM) Attribute, Metric, Sub-Metric, and Raw Data-based Hypothetical Performance Curves





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Raw Patch Count
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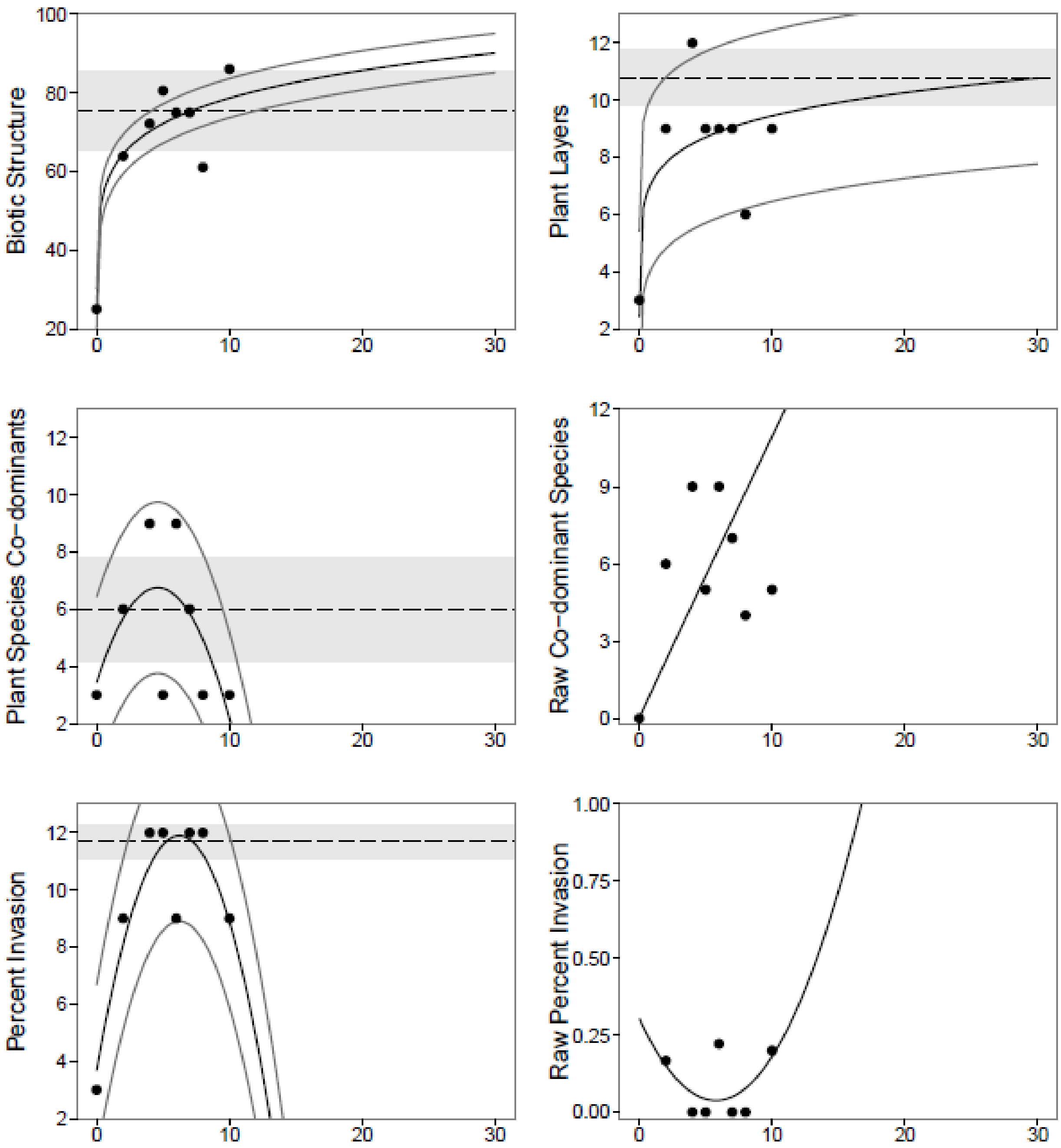
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Raw Co−dominant Species
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Percent Invasion
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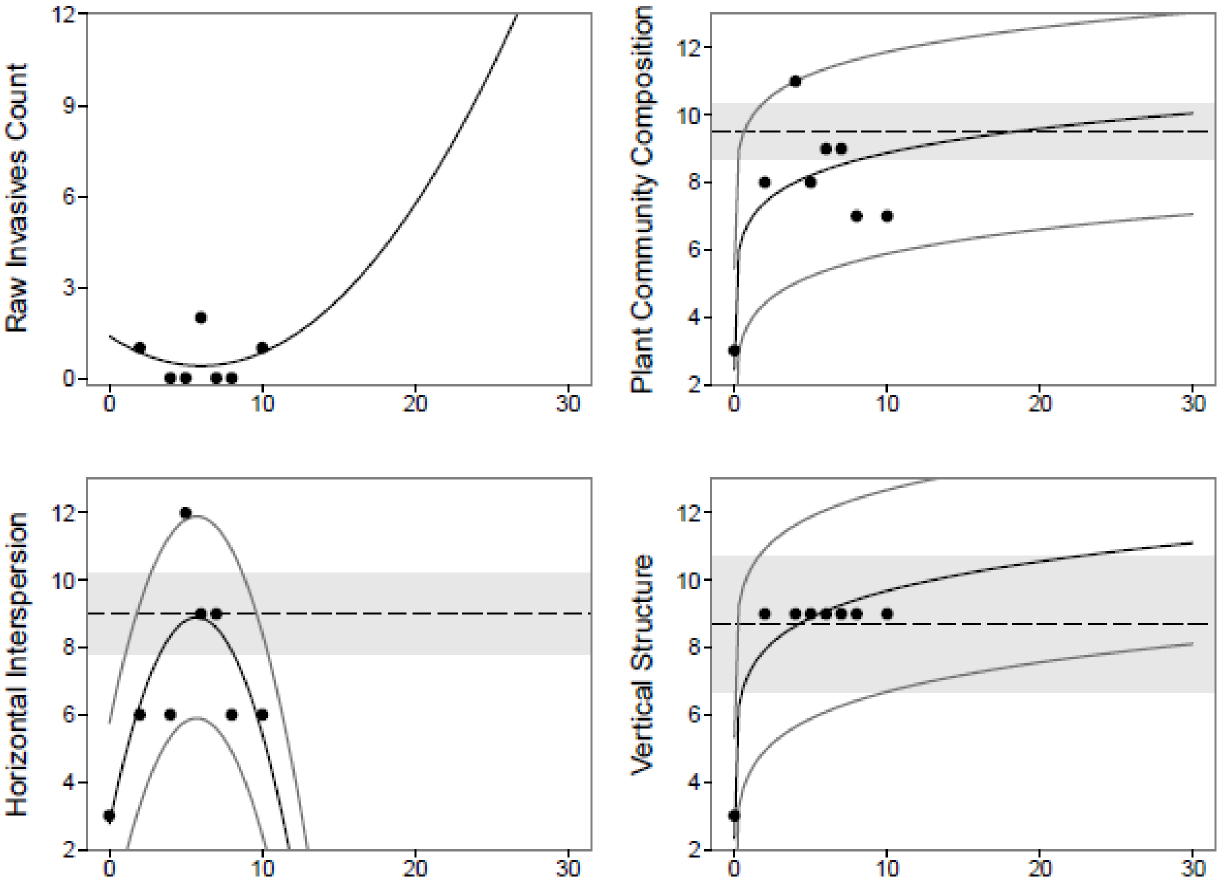
10
8
6
4
2
Raw Percent Invasion
1.00
0.75
0.50
0.25
0.00
0
10
20
30


Raw Invasives Count
12
9
6
3
0
0
10
20
30
Plant Community Composition
12
10
8
6
4
2
0
10
20
30
Horizontal Interspersion
12
10
8
6
4
2
0
10
20
30
Vertical Structure
12
10
8
6
4
2
0
10
20
30