Validation of a Wetlands Rapid Assessment Method: Application of the EPA's Level 1-2-3 Framework for method testing and refinement

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Abstract

Wetland rapid assessments have been gaining popularity for use in a variety of monitoring and assessment applications. Because rapid assessments rely on observable field indicators as surrogates for direct measures of condition, they must be calibrated and validated against independent measures of condition in order to establish their scientific defensibility. In this paper, we present as a case study of this process through the calibration and validation of the California Rapid Assessment Method (CRAM). CRAM was validated in terms of its responsiveness to "good" vs. "poor" wetland condition, its ability to represent a range of conditions, internal redundancy between its component metrics, alternative models to integrate the metrics into overall scores, and in terms of reproducibility of results between independent assessment teams. As is often the case, an independent, concurrently collected measure of condition that directly reflects the same elements as the CRAM attributes was not available. Consequently, we took advantage of data from existing monitoring and assessment programs and demonstrated how they can be used for calibration and validation. Existing assessment data based on avian diversity, benthic macroinvertebrate indices, and plant community composition were used to calibrate CRAM. Results for riverine and estuarine wetlands indicate that CRAM is an effective tool for assessing general wetland condition based on its correspondence with multiple independent assessments of condition. Most CRAM attributes captured a range of wetland conditions. The one exception, Buffer and Landscape Context, was modified based on the calibration analysis to improve its representativeness. Several metric combination models were tested for each CRAM attribute, and in most cases the "neutral" model (i.e., a linear combination of metrics) was comparable to alternative models based on more complex computations. Reproducibility analysis revealed several problematic metrics where ambiguous language or metric construction led to high interteam error rates. Clarification of metric construction and inclusion of additional guidance rectified these problems and improved the overall average error between independent assessment teams to ±5%. This study demonstrated that when calibrated and validated, rapid assessment methods provide a reliable tool for assessing wetland condition. Such tools have potential application for general condition assessments, screening-level evaluations, and assessment of program performance.

Introduction

In recent years, rapid wetland assessment methods have been gaining popularity for use in a range of wetland regulatory, ambient assessment, and management applications (Fennessy *et al.* 2004, Stapanian *et al.* 2004, Breaux *et al.* 2005, Cohen *et al.* 2005, Fennessy *et al.* 2007, Wardrop *et al.* 2007). The need for increased assessment and for program accountability has resulted in expansion of ambient monitoring programs, more rigorous performance monitoring for mitigation and restoration projects, and increased focus on landscape scale and cumulative impact assessment (USEPA 2002a). In recogni-

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tion that an intensive assessment is not always practical or desirable, the US Environmental Protection Agency (USEPA) has proposed a three-tiered approach to monitoring and assessment, termed Level 1-2-3. Under this approach, Level 1 consists of habitat inventories and landscape-scale assessment, Level 2 consists of rapid assessment, and Level 3 consists of intensive assessment (Kentula 2007, USEPA 2002b). Because it is less time consuming and relatively inexpensive, Level 2, or rapid assessment, is emerging as a key element of many monitoring programs.

The intent of all rapid assessment methods (RAMs) is to evaluate the complex ecological condition of a selected ecosystem using a finite set of observable field indicators, and to express the relative condition of a particular site in a manner that informs ecosystem management. RAMs are structured tools combining scientific understanding of process and function with best professional judgment in a consistent, systematic and repeatable manner (Sutula *et al.* 2006). They are based on the assumption that the ecological condition of wetlands will vary along a disturbance gradient, and that the resultant state can be evaluated based on a core set of visible field metrics. These metrics are typically qualitative measures of a specific biological or physical attribute that reflects some element of ecological condition and can be related to key ecosystem functions. Ecosystem functions are processes that occur over time which are difficult to quantify through static measurements. RAMs measure ecological condition, which in turn can be used to imply level of function. Development of RAM metrics involves the application of ecological concepts and best professional judgment translated into a standard set of diagnostic questions with mutually exclusive answers that reflect a range in wetland condition.

Because of their integrative nature and reliance on translating ecological theory into field indicators that reflect wetland condition, it is important that RAMs be calibrated and validated against independent measures of wetland condition in order to establish their scientific defensibility (Sutula *et al.* 2006). The goal of this process is not to maximize correlation between RAM metrics and any single measure of condition, rather the goal is to optimize RAM results against multiple independent measures of condition. In their review of RAMs, Fennessy *et al.* (2004) recommend that the calibration/validation process utilize results from more intensive wetland monitoring activities (i.e., Level 3 assessments). In this way, the assumptions behind the rapid assessment can be tested.

Given the cost and difficulty of collecting or compiling suitable intensive data that represent a gradient of wetland condition, very few RAMs are calibrated or validated, although excellent examples do exist. The Ohio Rapid Assessment Method (ORAM) has been validated against measures of ecological condition based on macroinvertebrate, bird, amphibian, and vascular plant diversity data (Mack 2001, Andreas *et al.* 2004, Micacchion 2004, Stapanian *et al.* 2004). The ORAM validation relied on measures of floral and faunal community structure as surrogates for direct measure of function, which is usually logistically prohibitive to collect. Similarly, Wardrop *et al.* (2007) used a floristic quality index (which measures richness of native plant communities) to validate a RAM for the Juniata watershed in Pennsylvania, USA. These RAM validations assume that if floral and faunal habitats and communities are of good condition, they are supported by wetlands of good condition that are performing key wetland functions. Numerous hydrogeomorphic (HGM) assessment methods have used a similar approach (Hruby *et al.* 1999, Hauer *et al.* 2002, Lee *et al.* 2003, Hill *et al.* 2006), although the HGM assessment typically include a greater emphasis on physical and/or hydrological wetland features than do rapid assessments.

Given the complexity and diversity of wetland function and the inherent simplifications associated with RAMs, there is often no direct, mechanistic relationship between the RAM model and the validation data, hence there is no single "gold standard" measure of wetland condition that can be used for validation. However, decisions regarding modification of metrics or attributes can be made based on a "weight-of-evidence" approach. Weight-of-evidence is the process of combining information from multiple lines of evidence to reach a conclusion about an environmental system or stressor (Linthurst *et al.* 2000, Burton *et al.* 2002). Using multiple lines of evidence to make inferences about environmental condition is well established in ecological risk assessment, environmental toxicology, and contaminant research where judgments about the quality, extent, and congruence of the information in each line of evidence is used to draw overall conclusions (Burton *et al.* 2002, Smith *et al.* 2002). The weight-of-evidence approach is less commonly used for wetland assessment, but examples exist for assessment of stream and riparian communities. Bryce *et al.* (2002) demonstrated the value of using multiple assemblages to assess stream and riparian habitats by comparing indices of biotic integrity based on fish, birds, and macroinvertebrates. Griffith *et al.* (2005) used metrics for fish, macroinvertebrates, and periphyton to create a mixed assemblage index of biotic integrity. These investigators found that, although different indices may agree on the general level of disturbance or condition, indicators differed in their sensitivity to stressors and responded differently to conditions in stream substrate, water column chemistry, or channel and riparian habitat. Consequently, using multiple indicators together provided the most complete and robust understanding of overall stream condition.

The weight-of-evidence approach can also be used to assess RAM performance by comparing RAM scores to indicators of wetland condition derived from multiple, more intensive data sets. In contrast to the weight-of-evidence approach, optimization using only a single measure of condition (e.g., plant community structure or invertebrate communities) may or may not adequately capture the same aspects of wetland condition as the RAM.

The preferred approach for RAM validation is to collect independent measures of condition concurrent with conducting a RAM-based assessment. Although desirable, the collection of new data is often cost- or time-prohibitive. For this reason, relying on existing data sources and applying the weight-of-evidence approach is an attractive alternative. This approach allows for validation of the RAM via exploration of relationships between RAM output and independent measures of condition. These relationships can then be assessed *vis-à-vis* the expectations of a conceptual model that is developed *a priori*.

This study presents the results of validation of the California Rapid Assessment Method (CRAM; Collins *et al.* 2006). "Validation" was defined as the process of documenting relationships between CRAM results and independent measures of condition in order to establish its defensibility as a meaningful and repeatable measure of wetland condition. The validation process provides confidence that CRAM results will consistently reflect expectations based on the conceptual models that guided CRAM development. The overall validation process includes several steps designed to meet the following objectives: 1) assure that the method is producing meaningful results based on a comparison between CRAM scores and independent measures of condition (*evaluation*), 2) make adjustments to the method, where needed, to improve the ability of the RAM to discern differences in wetland condition (*calibration*), and 3) minimize observer bias by assessing repeatability between independent assessment teams and modifying metrics that lead to inconsistencies (*standardization*). The validation process involved evaluating CRAM in terms of its performance with regard to several factors: 1) ***responsiveness***, a measure of the ability of the method to discern good vs. poor condition, 2) ***range and representativeness***, the ability of the method to appropriately capture the distribution of condition states that exists in nature, 3) ***redundancy***, the degree to which multiple metrics measure the same elements of condition, 4) ***integration***, the effect of different means of combining CRAM's component metrics of condition to generate an overall score, and 5) ***reproducibility***, the proportion of total variance attributable to user error. The approach presented for validating CRAM with the aid of existing data sources is applicable to any RAM that follows the general framework recommended by Fennessy *et al.* (2004, 2007) and Wardrop *et al.* (2007).

Methods

Overview of CRAM

The overall goal of CRAM is to provide a rapid, scientifically defensible, and repeatable assessment method that can be used routinely for wetland monitoring and assessment. CRAM consists of assessing wetlands with respect to four overarching "attributes": Buffer/Landscape Context, Hydrology, Physical Structure, and Biotic Structure. Within each of these attributes are a number of "metrics" that address more specific aspects of wetland condition (Table 1). Each of the metrics is assigned a numeric score based on either narrative or schematic descriptions of condition, or thresholds across continuous values. Metric descriptions are based on characteristics of wetlands observed across a range of reference conditions (per Smith *et al.* 1995), such that the highest score for each metric represents the theoretical optimum condition obtainable for the wetland feature being evaluated for a given wetland type in California. Although wetlands perform a suite of functions, CRAM is designed to assess condition based on the capacity of a wetland to support characteristic native flora and fauna. In other words, hydrology and physical structure are assessed based

Table 1. CRAM attributes and metrics from the pre-calibration version of CRAM. AA = assessment area.

Attributes		Metrics
Buffer and Landscape Context		Connectivity
		% AA with Buffer
		Avg. Width of Buffer
		Buffer Condition
Hydrology		Water Source
		Hydroperiod
		Hydrologic Connectivity
Structure	*Physical*	Physical Patch Richness
		Topographic Complexity
	Biotic	Organic Matter Accumulation
		Biotic Patch Richness
		Vertical Biotic Structure
		Interspersion and Zonation
		% Non-native Plant Species
		Native Plant Species Richness

on their contribution to supporting plant and animal habitat rather than on the ability of the wetland to provide services such as flood attenuation or water quality improvement. The underlying assumption of CRAM is that "living resource support" function is a common management endpoint, is easily discernable, and integrates the contributions of physical, chemical, and biotic interactions within a wetland. The relationship between habitat and physical and biological processes has been demonstrated for a variety of taxa including fish, amphibians, and invertebrates (Talmage *et al.* 2002, Baber *et al.* 2004) and is the basis for numerous other condition assessment methods (Ladson *et al.* 1999, Ode *et al.* 2005, Davies and Jackson 2006). It was also demonstrated by Stevenson and Hauer (2002) who report a strong relationship between conclusions based on indices of biotic integrity (IBIs) and HGM functional assessments. The selection of metrics and attributes in CRAM reflects the underlying assumption that such relationships exist. For this reason, CRAM was validated using Level 3 data that reflect capacity to provide the living-resource support function.

CRAM is applicable to wetlands (including riverine wetlands and their associated in-stream and riparian habitats) throughout California. The general approach and metric categories are consistent across wetland types that roughly correspond to the classes articulated by Cowardin *et al.* (1979), but the specific narratives used to score each metric are customized, as needed, for the characteristics of the specific wetland type being assessed. Metric scores are aggregated up to the level of attributes as well as into a single overall score via simple arithmetic relationships. Categories have been developed based on implied equivalence in the sense that the incremental increase in condition associated with moving from one category to the next higher category is the same across attributes. A detailed description of the method is provided in the CRAM manual (Collins *et al.* 2006).

Conceptual Approach to RAM Validation

The performance of CRAM was evaluated by comparing CRAM scores to field data on biotic community structure, which are believed to be indicative of the level of ecosystem function. Because these data integrate over time and through space in ways analogous to the CRAM attributes, the evaluation and adjustment of CRAM took place largely at the attribute level. Changes to metrics and to combination algorithms were made to improve relationships between CRAM attributes (as opposed to metrics) and independent measures of condition and to provide for more consistency between independent assessment teams (i.e., to improve standardization).

Selection of Validation Data Sets

Existing data sets were screened for suitability for use in validation. In addition to providing an independent measure of ecological condition, the data sets needed to meet the following criteria:

- The data set should have statewide coverage to allow for validation to the same data sources across the study area.
- The data set should represent a range of conditions across a gradient of disturbance.
- The site locations of the surveys should be accessible to the CRAM assessment crews.
- The data should be reflective of defined element(s) of wetland function (i.e., living resources support) that can be related to specific attributes of the rapid assessment method. For example, richness of riparian bird species is anticipated to correlate positively with the Biotic Structure attribute, as well as with the CRAM overall score, but is not necessarily expected to correlate with some of the other attributes, such as stream

channel Physical Structure. This criterion facilitated meaningful comparisons of the RAM scores to functionally comparable, intensive (Level 3) data (see Table 2 for an example of these relationships).

• The data should be readily available and include metadata describing the original purpose and objectives for the data set, sampling methods and location, procedures for data collection, and analysis. Quality control information should accompany the data set or be available through consultation with the data authors.

• The authors of the data set should be available for consultation about such issues as missing data, filling data gaps, the meaning of zero counts, interpretation of outlier data points, and limitations on interpretation of the data set, including the degree to which the data can be extrapolated to sites for which data do not exist.

• The data set should be scientifically credible and clear of any controversy about its validity, integrity, and ownership; and it should not be currently withheld from distribution because of legal or proprietary concerns.

• Consistent data collection and analysis methods and quality assurance procedures should apply to the entire data set.

• The data should be recently collected so that they reflect existing field conditions. For the purposes of CRAM validation, "recently collected" means that data were not older than three years old. It is assumed that this period is an acceptable interval within which to expect only negligible changes in condition at the site, assuming no major impacts (anthropogenic or natural) have occurred (e.g., major flood, fire, change in land use practices). Sites where major impacts are known to have occurred during the intervening time period should be excluded.

Table 2. Expected correlations between CRAM attributes and Level 3 data metrics. The nature of expected relationships (i.e., positive or negative) is indicated by "+" and "–" signs.

Level 3 Data Metric	Definition	Overall CRAM Score	Buffer/ Landscape	Hydrology	Physical Structure	Biotic Structure
BMI IBI	Benthic macroinvertebrate Index of Biotic Integrity for riverine wetlands	+	+	+	+	+
MAPS 1	Species richness of all birds	+				
MAPS 2	Species richness of riparian-associated species	+				+
MAPS 3	Species richness of non-riparian-associated species		+			
MAPS 4	Reproductive index (ratio of young to adults) for all species	+				
MAPS 5	Reproductive index (ratio of young to adults) for riparian-associated species	+				+
MAPS 6	Reproductive index (ratio of young to adults) for non-riparian-associated species		+			
EMAP 1	Relative percent cover of non-native plants across the marsh plain	-	-	-		-
EMAP 2	Relative percent cover of invasive plants across the marsh plain	-	-			-
EMAP 3	The total number of native plant species found along transects across the marsh plain	+		+	+	+
EMAP 4	Relative percent cover of non-native plants along the backshore border of the assessment area (AA)		-			-
EMAP 5	The total number of plant species (native plus non-native) found along transects across the marsh plain	+		+	+	+

Three sources of Level 3 data were identified for use in validation of CRAM: 1) Riparian bird capture data from the Monitoring Avian Productivity and Survivorship Program (MAPS), 2) Benthic macroinvertebrate data from the statewide bioassessment database, and 3) Plant community composition data from a recent USEPA assessment under the Environmental Monitoring and Assessment Program (EMAP) West Coast Pilot. Each of these data sets is described in more detail below.

The MAPS Program is a nationwide effort, overseen by the Institute for Bird Populations (IBP), that collects annual data on bird populations during the breeding season using a constant-effort, mist net approach at fixed-site locations (IBP 2006). A detailed description of the MAPS program objectives and approach can be found at http://www.birdpop.org/maps.htm. MAPS data provide species-specific information about trends in demographics, productivity, survival rates, and rates of recruitment into the adult populations. MAPS data on diversity of bird species from captures in riparian sites during the 2003 breeding season were used for CRAM validation of riverine wetlands. The six MAPS metrics used for the validation are described in detail in Table 2. Studies from other regions of the country have shown that riparian birds are a sensitive indicator of stream condition (O'Connell *et al.* 2000, Croonquist and Brooks 1991, Flather *et al.* 1992). Brooks *et al.* (1991) suggest that avian communities have the ability to integrate watershed and stream disturbances that can only be indirectly inferred from the response of aquatic indicators. Similarly, Bryce *et al.* (2002) reported that bird indices of biotic integrity integrated the effects of watershed and stream channel disturbance on the riparian ecosystem. These relationships between bird communities and riparian condition strongly reflect the conceptual relationships embodied in CRAM.

Throughout California, efforts are underway to collect bioassessment data in wadeable streams for use in a variety of programs. Data collected include information about benthic macroinvertebrate (BMI) species diversity and abundance. These data can be used to calculate an IBI (Ode *et al.* 2005). The results of bioassessment provide information about water quality and instream benthic habitat condition resulting from perturbations such as contamination, hydromodification, and sedimentation from upstream sources (Resh and Jackson 1993). IBI scores from bioassessment data collected by the California Department of Fish and Game (CDFG) in 2003 using the California Stream Bioassessment Procedure (Harrington 1999) were used for CRAM validation. A detailed description of CDFG bioassessment objectives and approaches can be found at http://www.dfg.ca.gov/abl/Field/datacollection.asp. Macroinvertebrates have long been used as measures of condition because they exhibit graded responses to stream hydrology, substrate, physical condition, and pollutants and other stressors (Metcalfe 1989, Barbour *et al.* 1999). As with birds, invertebrate indices attempt to measure analogous aspects of condition and are therefore appropriate for use in CRAM validation.

The USEPA EMAP-Estuaries West Coast Pilot conducted a probability-based ambient assessment of intertidal wetlands in Washington, Oregon, and California in 2002 (Sutula *et al.* 2001). As an intensification of this survey, comprehensive plant community composition data were collected in southern California and the San Francisco Bay area. Resources providing a description of the EMAP-Estuaries West Coast Pilot objectives and approaches can be found at http://www.epa.gov/region09/water/wemap/. Assessment of plant community composition at these locations involved collecting point-intercept data along a series of transects oriented in a stratified manner designed to cover a variety of elevation gradients and geomorphic features throughout the coastal marsh plain. These data provide information about the species richness, diversity, and relative percent cover. Five metrics were calculated from the EMAP data for use in CRAM validation, and are described in detail in Table 2. Other studies have shown that many ecological services, including avian support (Stralberg *et al.* 2006) and small mammals support (Shellhammer 2000) depend on vegetation structure as assessed by the EMAP intensification survey. To that degree that CRAM scores reflect vegetation structure, they should also reflect these other ecological services.

Validation Analysis

Of the six wetland classes covered by CRAM, the riverine and estuarine classes were selected as the priority for calibration and validation based on current assessment needs and availability of appropriate Level 3 data. Validation of the remaining CRAM wetland classes (depressional wetlands, vernal pools, seeps and springs, lake and lagoon fringe wetlands) will occur in the future. Three regional field teams used CRAM to assess the condition of 95 riverine sites. Of these, 54 had benthic macroinvertebrate data, and 41 had MAPS bird data. For estuaries, assessments were conducted at 38 sites, all of which had EMAP vegetation data (Figure 1). CRAM Assessment Area (AA) sizes ranged from 0.13 - 74 ha for estuarine wetlands and 0.04 - 25 ha for riverine wetlands. These ranges were influenced by locations where Level 3 data were collected and the need for coincident AAs. At each site, CRAM AAs were identified that corresponded to the area where the Level 3 data had been collected. A CRAM assessment was conducted for each site and the results were used in combination with the existing intensive (Level 3) data to conduct the following validation analyses, which are adapted from analyses used by others to test indices of biotic integrity (Whittier *et al.* 2007).

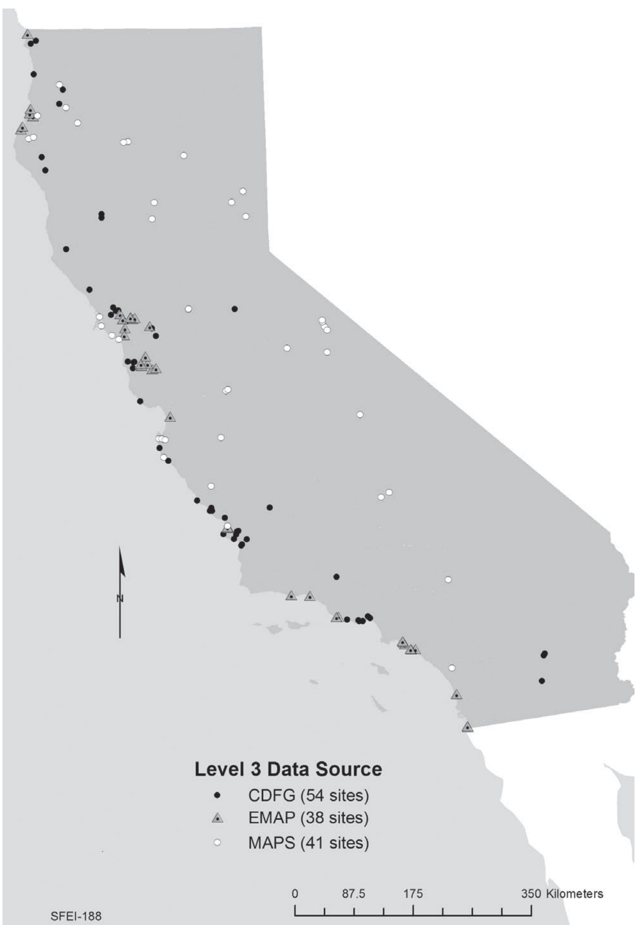

Figure 1. CRAM calibration sites. Data source codes are as follows: CDFG = California Department of Fish and Game; EMAP = Environmental Monitoring and Assessment Program (of the US Environmental Protection Agency); MAPS = Monitoring Avian Productivity and Survivorship program (of the Institute for Bird Populations).

Responsiveness is a measure of the ability of the method to discern good vs. poor condition. Responsiveness was tested in two ways. First, correlation (using Spearman's ρ) and simple regression analyses were used to characterize the relationship between Level 3 data and CRAM overall, attribute, and metric scores. Analyses were conducted using SAS Institute statistical software, and significance was determined using at a level of 0.05. Consistent patterns of correlations between CRAM metrics or attributes and multiple Level 3 variables, in the expected directions, were interpreted as indicating responsiveness. Where the relationship between attribute scores and Level 3 data differed from expected based on the CRAM conceptual model, modifications were explored to improve the relationship. Modifications included changes to metric scaling, weighting, or metric combination rules and were based on the ecological models underlying CRAM, informed by the correlation analysis. The metrics within each attribute were also investigated for consistency of response to varying condition. Divergent metrics were modified (or in some cases eliminated or combined with other metrics) to improve overall method performance.

The second test of the ability of CRAM to reflect overall condition was based on investigation of the relationship between CRAM scores and the Landscape Development Index (LDI; Brown and Vivas 2005), which is a (Level 1) landscape measure of human disturbance. The LDI analysis was conducted using land use data from the 2001 National Land Cover Database (http://www.epa.gov/mrlc/nlcd-2001.html) and the energy values as published by Brown and Vivas (2005). Correlations between CRAM attribute and overall scores and LDIs were used as an additional measure of CRAM responsiveness to condition along a gradient of stress. Relationships were tested against human disturbance at various spatial scales, including within a 200-m buffer, a 500-m upstream area (for riverine wetlands), the upstream drainage area, and the entire watershed.

Range and representativeness is a measure of the ability of the method to appropriately capture the distribution of condition states that exists in nature. The distributions of scores for metrics and attributes were graphed and compared against the normal distribution as well as distributions of the Level 3 data types. There were *a priori* assumptions about distributions of the Level 3 data, based on the goals of the studies for which the data were collected. For instance, for the EMAP vegetation data, scores were not expected to be normally distributed, but rather representative of the range of conditions in the region because the samples were selected at random (i.e., "probabilistically") from all possible locales within the study region. The distributions of scores from validation sites were also compared to the distribution of scores at "reference standard" sites (i.e., known good condition sites, based on studies independent of CRAM and the Level 3 data sets; Ambrose *et al.* 2006). Metrics and attributes that were severely skewed relative to expectations were modified to improve their distribution. Modifications typically entailed adjusting the metric categories by redefining the thresholds between scores within a metric. All modifications were informed by both the distribution of the data and the underlying conceptual models that govern CRAM.

Redundancy assesses the degree to which multiple metrics measure the same elements of condition. High redundancy between specific metrics constitutes implicit weighting of that aspect of the wetland and should be taken into consideration in the course of interpreting CRAM results. Redundancy was measured in two ways. First a correlation matrix, using Spearman's ρ and α level 0.05, was generated to investigate relationships between metrics. Second, a Principal Components Analysis (PCA) was conducted using the individual CRAM metric scores. Correlations were tested for BMI IBI scores both on the first principle component (PC1) of the PCA, which represents the metrics that most influence variability in CRAM scores, and on the CRAM overall score, to test for fidelity of the results across hierarchical levels of CRAM. All analyses were conducted using SAS Institute statistical software. Redundant metrics were not necessarily eliminated, but were acknowledged to improve the transparency of the method, to inform combination rule development, and to aid in interpretation of results.

Integration measures the effect of different metric combination rules on attribute scores. Between one and four potential combination rules were constructed for each attribute based on conceptual model(s) of how the metrics relate to each other to represent the component of condition being assessed by each attribute (Table 3). In all cases, a simple arithmetic mean of metric scores was included as the neutral model with which to compare any alternative combination models. Alternatives to the neutral model consisted of more mathematically complex combinations of metrics based on assumed mechanistic relationships. Combination rules were tested by correlating the resultant attribute scores against the appropriate Level 3 data. Alternatives to the neutral model were selected only if they were mechanistically justified and either provided stronger correlations between attribute scores and Level 3 data or helped meet other validation objectives (i.e., range, responsiveness). All combination rules were tested with Level 3 data to ensure that score calculation processes did not undermine other validation objectives, such as responsiveness.

Reproducibility is a measure of the proportion of total variance attributable to user error. It is a reflection of the precision of CRAM results. Numerous duplicate CRAM assessments were completed by teams of wetland scientists trained in the use of CRAM, to determine the sampling error of the method in terms of multiple potential sources: 1) within-team variability (the same team conducted two CRAM assessments of the same AA within a month), 2) between-team variability (two teams completed a CRAM assessment within the same AA within a month), 3) among-region variability (CRAM teams from each of the regions evaluated the same AA within a month), and 4) temporal variability (the same team returned to conduct a second CRAM assessment four to five months later).

Sampling error from each identified source was estimated using a simple tally system that recorded the magnitude of discrepancy between paired assessments. For paired metric scores that differed by one metric category, the difference was enumerated as one (1) discrepancy. If scores for a metric differed by two categories, the discrepancy was enumerated as two (2). The metric discrepancies were summed for each attribute and then expressed as a percentage of total possible differences (i.e., the number of differences that would have occurred if every metric differed by the maximum possible categories) to provide an estimate of error. Sampling error rates were used as a guide to determine when adjustments were necessary to address ambiguity within metrics. In general, adjustments were made when error rates exceeded 10%, or where systematic errors occurred.

Results

Responsiveness

CRAM overall scores were significantly correlated with several of the Level 3 variables in ways

Table 3. Combination rules tested for each CRAM attribute.

Buffer and Landscape Context	
	[% W/Buffer + Avg Width + Buffer Condition + Connectivity] / 3
	[(% W/Buffer * Avg Width * Condition)1/3 + Connectivity] / 2
Hydrology	
	[Water Source + Hydroperiod + Connectivity] / 3
	[Water Source * ((Hydroperiod + Connectivity) / 2)]
Physical Structure	
	(Patch Richness + Topographic Complexity) / 2
Biotic Structure	
	[Organic Accumulation + Patch Richness + Vertical Structure + Interspersion + Native spp. + % Invasives] / 6
	[Organic Accumulation + Patch Richness + Vertical Structure + Interspersion + Native spp.) / 5 * % Invasives]
	[(Organic Accumulation + Patch Richness + Vertical Structure + Interspersion + Native spp.) / 5 * % invasives)]
	[(Organic Accumulation + Patch Richness + (% Invasives * Vertical Structure * Interspersion) 1/3 + (Native spp. * % Invasives)] / 4
	[(Organic Accumulation + Patch Richness + Vertical Structure + Interspersion) + (Native spp. * % Invasives)] / 5

that were consistent with the CRAM conceptual model. For riverine wetlands, CRAM overall scores were strongly significantly correlated with BMI IBI scores (Spearman's $\rho = 0.6419$, $P < 0.0001$; Figure 2a) and were negatively correlated with the relative percent cover of non-native plants in estuarine wetlands (EMAP 4: Spearman's $\rho = -0.3586$, $p = 0.0373$; Figure 2b). In addition, positive relationships were observed between CRAM overall score and some MAPS-derived measures of wetland function in terms of avian support in riverine wetlands (e.g., MAPS 1: Spearman's $\rho = 0.3025$, $p = 0.0545$; Figure 2c).

Individual CRAM attribute and metric scores were also correlated with elements of the Level 3 data sets that represent analogous aspects of wetland condition (Table 2). There were significant positive correlations between CRAM scores and multiple measures of benthic invertebrate community structure and avian diversity at both the attribute level (Table 4) and the metric level (Table 5). Correlations with the MAPS data were stronger at the attribute level than at the overall score level, particularly between avian richness (MAPS 1 and MAPS 2) and CRAM biotic structure, which reflect similar aspects of condition (Figure 3). The one exception to the positive correlations was the significant negative correlation between the CRAM physical structure attribute and the MAPS metric measuring the reproductive ratio of non-riparian birds (MAPS 6). BMI scores correlated strongly and positively with all CRAM attributes for riverine wetlands. For estuaries, the strongest correlations with Level 3 data at the attribute level were for Buffer and Landscape Context and Biotic Structure, the latter of which correlated with a number of the EMAP vegetation metrics. The positive relationships with EMAP 1 and EMAP 2 were unexpected, as these are measures of the relative representation of non-native and invasive plant species, respectively, on the marsh plain. No significant relationships were observed between any Level 3 estuarine data and the Hydrology or Physical Structure attributes.

The strength of correlations at the metric level varied from metric to metric, but in general, the pattern observed for most metrics was consistent with those observed at the attribute level (Table 5). At least one Level 3 metric correlated significantly, and in the expected direction, for every riverine metric with the exception of Hydroperiod, although its relationship to BMI IBI scores was nearly significant (Spearman's $\rho = 0.1968$, $p = 0.0686$). For many of the riverine metrics, there were significant correlations not only with multiple metrics, but also correlations with metrics from two distinct data sets (i.e., both MAPS and the BMI IBI). For estuaries, the expected significant correlations between metrics and Level 3 data were observed for over half the metrics. There were only two relationships that ran contrary to expectations: the significant positive relationships between the Water Source CRAM metric and the EMAP 1 and EMAP 2 metrics (which reflects the relative percent cover of non-native and invasive plant species in estuarine AAs).

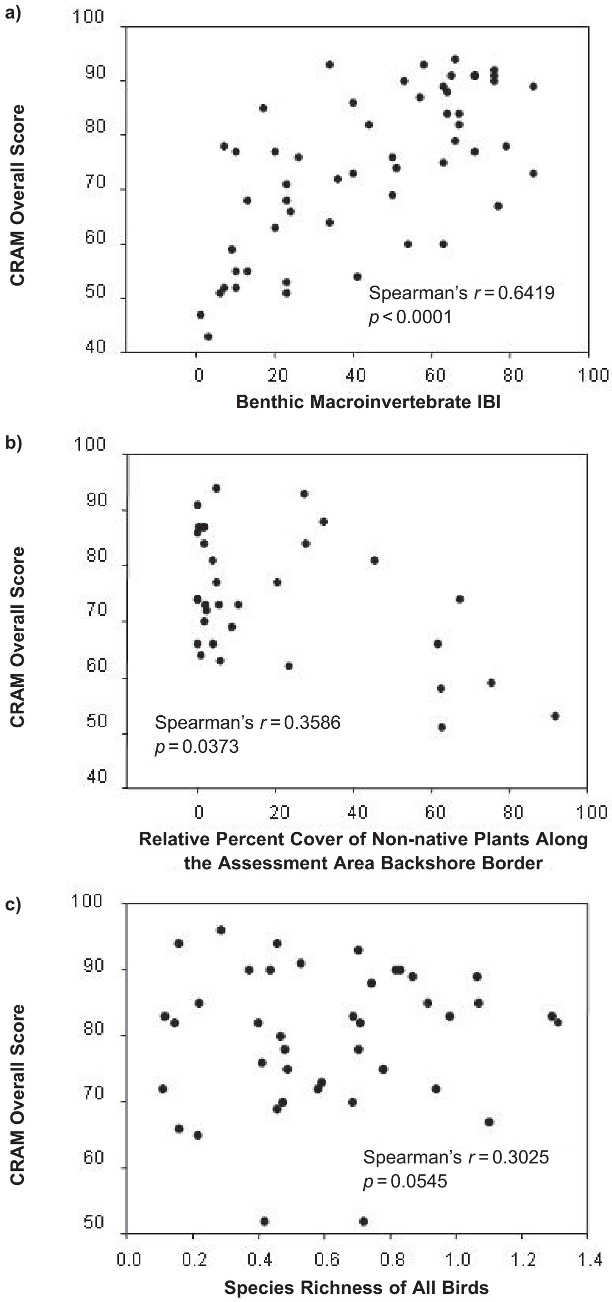

Figure 2. Relationships between CRAM overall score and benthic macroinvertebrate Index of Biotic Integrity scores for riverine wetlands (a), bird species richness in riverine wetlands, MAPS1 (b), and the relative percent cover of non-native plant species along the backshore of estuarine wetlands, EMAP4 (c).

There were consistent, significant negative correlations between LDI scores and CRAM overall and attribute scores. These relationships were apparent at varying spatial scales ranging from buffers of varying widths around the wetland up to the entire contributing catchment (Table 6). As the index of human disturbance increased, the CRAM scores decreased. For riverine wetlands, relationships were strongest for the Buffer and Landscape Context and Biotic Structure attributes, regardless of the spatial scale investigated. For estuarine wetlands, relationships were strongest for the Buffer and Landscape Context and Hydrology attributes, while the relationships with the Physical Structure and Biotic Structure attributes were not significant at the $\alpha = 0.05$ level.

Table 4. Relationships between CRAM attributes and Level 3 metrics. Correlations are presented in terms of Spearman's ρ. All relationships that are significant at the $\alpha = 0.05$ level are shown. Level 3 metrics are as defined in Table 2.

CRAM Attribute	Wetland Class	Level 3 Metric	ρ	Prob>|ρ|
Buffer and Landscape Context	Estuarine	EMAP 4	-0.3516	0.0415
	Riverine	BMI IBI	0.4325	<0.0001
		MAPS 3	0.4739	0.0018
Hydrology	Riverine	BMI IBI	0.4644	<0.0001
Physical Structure	Riverine	BMI IBI	0.2612	0.0116
		MAPS 6	-0.3434	0.0348
Biotic Structure	Estuarine	EMAP 1	-0.3375	0.0383
		EMAP 2	-0.3684	0.0228
		EMAP 3	0.5017	0.0013
	Riverine	BMI IBI	0.3242	0.0008
		MAPS 1	0.3421	0.0286
		MAPS 2	0.3275	0.0366

Range and Representativeness

For riverine wetlands, CRAM Biotic Structure attribute scores were normally distributed (Shapiro-Wilk's (W) = 0.971393, p = 0.1889), and Physical Structure attribute scores approached normality (W = 0.904900, p <0.0001; Figure 4a). For estuarine wetlands both the Buffer/Landscape Connectivity and Biotic Structure attributes were nearly normally distributed (W = 0.938501, p = 0.0498 and W = 0.934092, p = 0.0350, respectively; Figure 4b). These distributions are consistent with the distributions based on various Level 3 indicators, suggesting that the distribution in CRAM scores is representative of the actual range of condition at the validation sites. In contrast, the Hydrology attribute scores were positively skewed for both wetland classes (W = 0.863466, p <0.0001 for riverine and W = 0.849722, p = 0.0001 for estuarine; Figures 4a and b). Buffer and Landscape Context was also highly skewed for riverine (W = 0.821937, p <0.0001; Figure 4a). Further investigation revealed that the compo-

Table 5. Relationships between CRAM metrics and Level 3 metrics. Correlations are presented in terms of Spearman's ρ. All relationships that are significant at the α = 0.05 level are shown. AA = assessment area. Level 3 metrics are as defined in Table 2.

Attribute	CRAM Metric	Wetland Class	Level 3 Metric	ρ	Prob>|ρ|
Buffer and Landscape Context	Connectivity	Riverine	BMI IBI	0.355	0.0013
			MAPS 3	0.3458	0.0268
	% of AA with Buffer	Riverine	BMI IBI	0.278	0.0127
	Average Buffer Width	Estuarine	EMAP 4	-0.4993	0.0026
		Riverine	BMI IBI	0.4514	<0.0001
	Buffer Condition	Estuarine	EMAP 4	-0.5606	0.0006
		Riverine	BMI IBI	0.4395	<0.0001
			MAPS 3	0.4094	0.0079
			MAPS 6	-0.3885	0.0159
Hydrology	Water Source	Estuarine	EMAP 1	0.3283	0.0442
			EMAP 2	0.4636	0.0034
		Riverine	BMI IBI	0.5672	<0.0001
			MAPS 3	0.4552	0.0028
	Hydrologic Connectivity	Estuarine	EMAP 1	-0.4158	0.0094
			EMAP 4	-0.4639	0.0057
		Riverine	BMI IBI	0.4472	0.0005
Physical Structure	Physical Patch Richness	Riverine	MAPS 6	-0.3657	0.0239
	Topographic Complexity	Riverine	BMI IBI	0.3227	0.003
Biotic Structure	Organic Matter Accumulation	Estuarine	EMAP 1	-0.3663	0.0237
			EMAP 2	-0.5044	0.0012
		Riverine	BMI IBI	0.4074	0.0001
			MAPS 4	0.3087	0.0496
			MAPS 5	0.3196	0.0416
	Biotic Patch Richness	Riverine	MAPS 1	0.419	0.0064
			MAPS 2	0.4813	0.0014
	Vertical Biotic Structure	Estuarine	EMAP 3	0.3364	0.0389
	Interspersion/ Zonation	Estuarine	EMAP 3	0.513	0.001
			EMAP 5	0.428	0.0073
		Riverine	BMI IBI	0.2531	0.0163
	% Non-native Plant Species	Estuarine	EMAP 1	-0.4618	0.0035
			EMAP 2	-0.3833	0.0175
		Riverine	BMI IBI	0.4011	0.0001
			MAPS 3	0.3397	0.0298
	Native Plant Species Richness	Estuarine	EMAP 1	-0.3831	0.0176
			EMAP 2	-0.4157	0.0094
			EMAP 3	0.4608	0.0036
		Riverine	BMI IBI	0.2172	0.0386
			MAPS 1	0.3153	0.0447
			MAPS 2	0.4252	0.0056

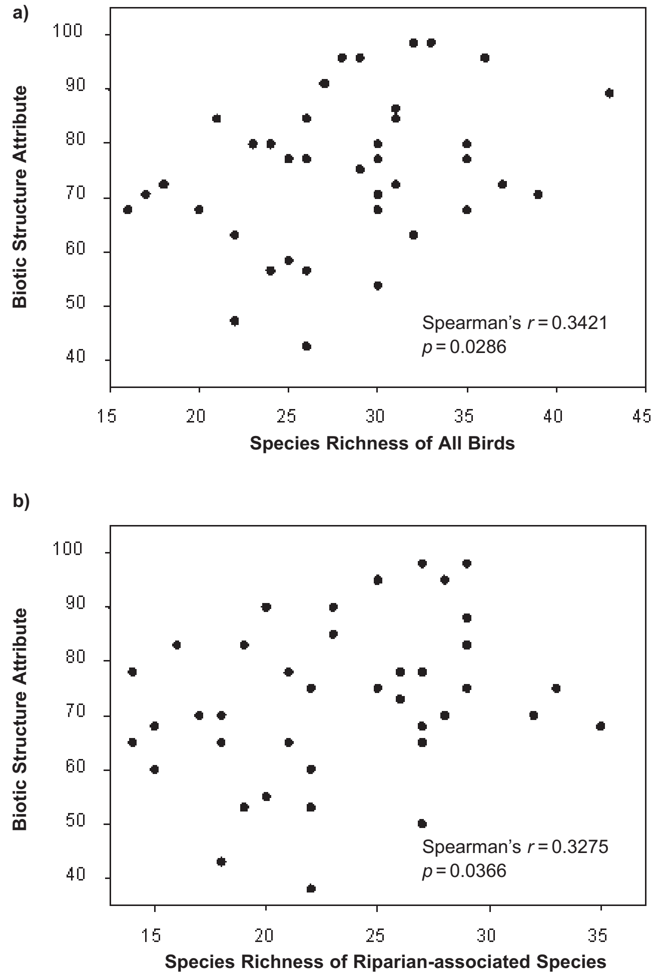

Figure 3. Relationship between CRAM Biotic Structure attribute score and measures of overall bird species richness, MAPS1 (a); and riparian-dependent bird species richness, MAPS2 (b).

nent metrics of the Buffer and Landscape Context attributes were also positively skewed. Similarly, the Hydroperiod metric was positively skewed, resulting in the shift of the distribution of the Hydrology attribute scores (to which the Hydroperiod metric contributes).

Redundancy

Correlation among metrics within an attribute was generally high, particularly for the Buffer and Landscape Context and Physical and Biotic Structure attributes (Table 7). Although not unexpected, such correlations can result in implicit weighting of certain wetland features by "double counting" them via several metrics. Results of the PCA indicate that the level of redundancy inherent in CRAM does not obscure the overarching patterns of wetland condition. Both overall CRAM scores and BMI IBI scores were positively correlated with the PC1 of the PCA (Spearman's $\rho = 0.9703$, $p < 0.0001$ and $\rho = 0.6465$, $p < 0.0001$, respectively), and with each other ($\rho = 0.6419$, $p < 0.0001$). Figure 5 shows an example of results that are indicative of all the PCA correlations. Eigenvalues and factor loadings for the PCA are provided in Table 8. The results indicate fidelity across hierarchical levels of CRAM and suggest that the manner in which CRAM metrics are combined into attributes, and attributes combined into overall scores, captures the overall variance in wetland condition.

Table 6. Correlations between CRAM attribute and overall scores and the Landscape Development Index (LDI). Correlation coefficients are shown for riverine and estuarine wetlands at various spatial scales. All coefficients shown are significant at the ρ value noted. NS = not significant.

	Riverine				Estuarine			
	200 m Buffer	ρ value	500 m Upstream	ρ value	Watershed	ρ value	200 m Buffer	ρ value
Overall CRAM	-0.594	0.01	-0.586	0.01	-0.358	0.01	-0.332	0.05
Buffer and Landscape Context	-0.648	0.01	-0.530	0.01	-0.404	0.01	-0.407	0.01
Hydrology	-0.249	0.01	-0.266	0.01	-0.227	0.05	-0.427	0.01
Physical Structure	-0.304	0.01	-0.287	0.01	-0.251	0.01	NS	
Biotic Structure	-0.465	0.01	-0.483	0.01	-0.262	0.01	NS	

Integration

For all CRAM attributes, there were no significant differences between the neutral metric combination model (i.e., an arithmetic mean) and the more complex mechanistic models in terms of their relationship with Level 3 data. An example of the relationships between Level 3 data and various combination rules for the Hydrology attribute is provided in Figure 6. The differences between Hydrology Attribute scores generated by the neutral model for combining the CRAM Metrics and the alternative model were calculated, then the percent difference between models on the neutral model scores was regressed. The regression tested the null hypothesis that the slope of the relationship between percent difference between models and the neutral model scores is 0. The failure to reject the null hypothesis indicates the two models behave similarly across a range of CRAM scores. Similar results were observed for all other attribute combination rules tested. Because there were no differences in combination rules, the neutral model was selected to ease the use and interpretation of CRAM by a broad range of practitioners.

Reproducibility

The average error in overall CRAM results following repeated independent assessment ranged from 7 to 23% prior to modifications in the method protocols and support materials. Error rates were lowest within a single assessment team (7 to 11%) and higher when a site was assessed by two different teams (9 to 23%). Investigation of error by attribute revealed the most likely causes of discrepancy between individual assessments. The highest error rates among different regions were in the Physical and Biotic Structure attributes. Further investigation of specific metrics revealed that for riverine wetlands, the majority of error was due to three metrics: Hydroperiod, Vertical Biotic Structure, and Percent Non-native Plant Species (which were also problematic for estuarine wetlands). Comparison of assessments conducted months apart resulted in a 25% error rate for the Biotic Structure attribute compared to an error of 7% when assessments were conducted only weeks apart. This suggests that seasonal differences in plant communities may contribute to variability in this attribute.

To address initial reproducibility problems, CRAM was modified to reduce ambiguous language in the metric descriptions and additional guidance was provided for metrics subject to high error rates. For several metrics (Native Plant Species Richness, Percent Invasive Plant Species, and Vertical Biotic Structure) the basic evaluation method was simplified or changed. Reproducibility of the revised estuarine CRAM was re-evaluated in 2007 in preparation for its use in a statewide ambient survey. The average attribute error between independent assessment teams ranged from 6 to 12% and average error in overall CRAM score was 5% for estuaries and 7% for riverine wetlands (Table 9). More importantly, the error rate in previously problematic metrics was substantially reduced. For several of the metrics related to plant community compositions, a substantial simplification of the metrics dramatically improved reproducibility, yet still provided adequate ability to discern biotic condition. For example, the original error rates for the Vertical Biotic Structure and Percent Non-native Plant Species metrics were

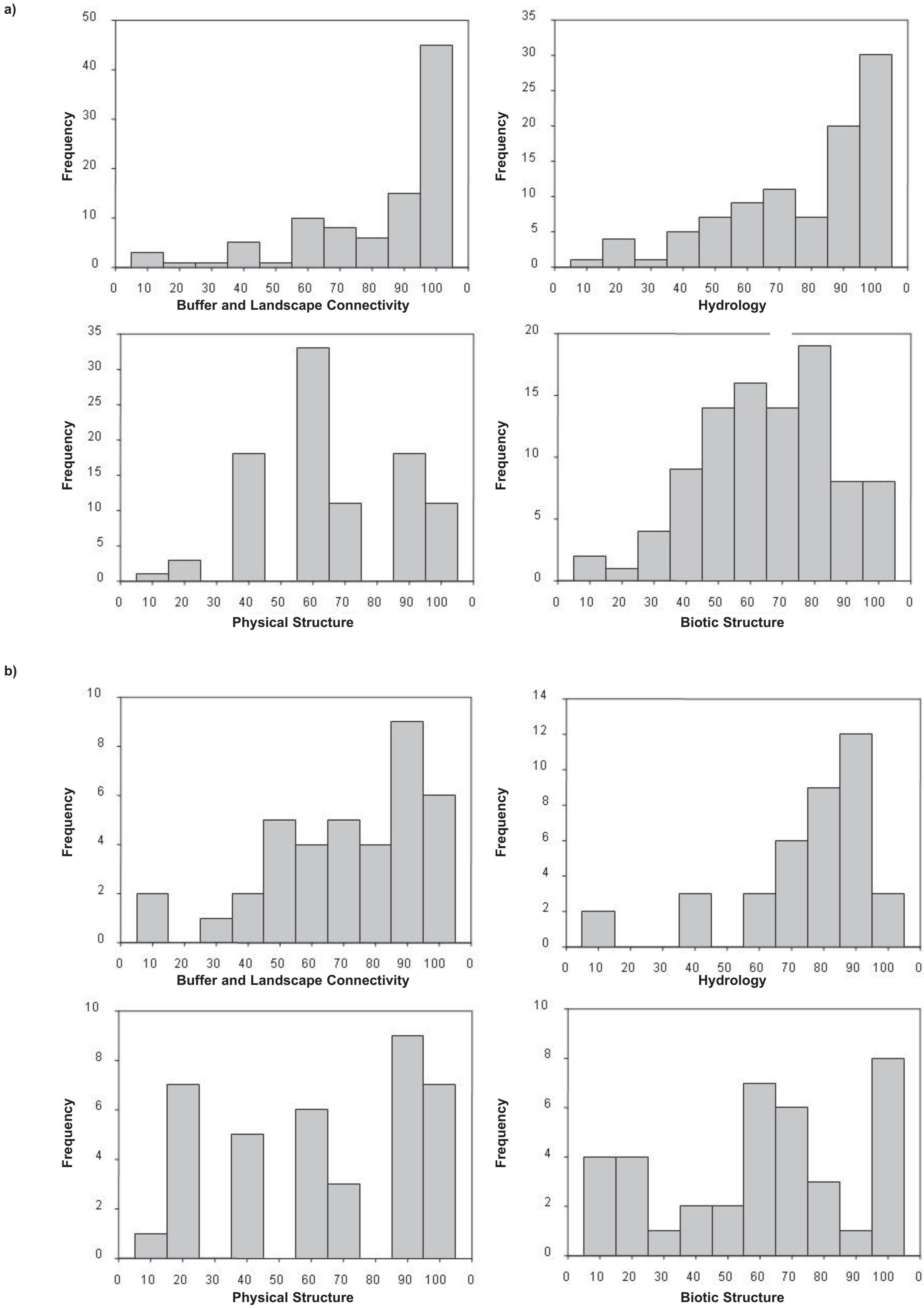

Figure 4. Distributions of CRAM attribute scores for riverine wetlands (a) and estuarine wetlands (b).

Table 7. **Correlations between CRAM metrics. AA = assessment area.Spearman's ρ values are shown for all CRAM metric combinations pairwise. Asterisks indicate the level of significance associated with each ρ, where * = 0.05, ** = 0.01, and *** = 0.001. Highlighted boxes indicate groupings of metrics that belong to the same CRAM attribute.**

CRAM Metric	Landscape Connectivity	% of AA* with Buffer	Avg. Buffer Width	Buffer Condition	Water Source	Hydroperiod	Hydrologic Connectivity	Physical Patch Richness	Topographic Complexity	Organic Matter Accumulation	Biotic Patch Richness	Vertical Biotic Structure	Interspersion/ Zonation	% Non-native Plant Species
% of AA* with Buffer	0.2821***													
Avg. Buffer Width	0.3105***	0.4398***												
Buffer Condition	0.3400***	0.4654***	0.6121***											
Water Source	0.3488***	0.3105***	0.4207***	0.3921***										
Hydroperiod	0.0664	0.2299**	0.2859***	0.2996***	0.2230**									
Hydrologic Connectivity	0.2017*	0.3701***	0.4750***	0.4812***	0.3431***	0.2535**								
Physical Patch Richness	0.1374	0.2128*	0.2268**	0.2441**	0.1263	0.2317**	0.2393**							
Topographic Complexity	0.2123*	0.1491	0.1860*	0.2935***	0.3069***	0.3486***	0.2904**	0.5103***						
Organic Matter Accumulation	0.1016	0.3342***	0.1427	0.3075***	0.1226	0.1588	0.2723**	0.1782*	0.3237***					
Biotic Patch Richness	0.0015	-0.0054	-0.0327	0.0455	-0.0725	0.0957	0.0166	0.1878*	0.2546**	0.3101***				
Vertical Biotic Structure	0.0933	0.1608	0.0458	0.0899	0.1121	0.0192	0.0547	-0.0737	0.1319	0.2987***	0.2265**			
Interspersion/Zonation	0.1185	0.2123*	0.169	0.3009***	0.1745*	0.4043***	0.3238***	0.4194***	0.4579***	0.4706***	0.3708***	0.2016*		
% Non-native Plant Species	0.1714*	0.2626**	0.14	0.3432***	0.1293	-0.0141	0.2305*	0.0682	0.2482**	0.4066***	0.0719	0.2535**	0.276**	
Native Plant Species Richness	0.0499	0.2001*	-0.0381	0.2298**	-0.0532	0.0808	0.0271	0.1019	0.2129*	0.3894***	0.4402***	0.4212***	0.4181***	0.4230***

26 and 28%, respectively. Following the modifications made during the validation process, these error rates were reduced to 11 and 8%, respectively. As a result of the modifications described above the overall error rates met the pre-determined objectives of less than 10% error between assessment teams.

Discussion

The analyses presented in this paper demonstrate how existing data can be used to evaluate, refine, and standardize RAMs using a weight of evidence approach. CRAM attributes generally corresponded well to multiple independent measures of biologic condition: BMI IBIs, MAPS, and LDIs. These results validate the underlying conceptual models of CRAM and provide scientific defensibility for methodology that will be important for future regulatory and management applications.

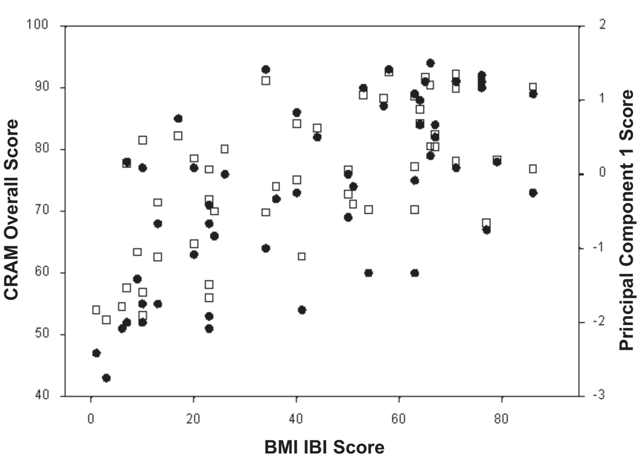

Figure 5. Relationship between CRAM overall score and principal component scores derived from a model with all CRAM metrics loaded. Solid black circles correspond to CRAM Overall Score as calculated per the CRAM protocol, and open squares correspond to Principal Component 1 Scores.

Evaluation

The results of this analysis show that CRAM is an effective tool for assessing general wetland condition based on field indicators of a wetland's ability to support characteristic flora and fauna. Specifically, CRAM meets key features suggested by Brooks *et al.* (1998) for an acceptable index of ecological integrity, such as the ability to discern biological communities with high integrity, inclusion of metrics with biological, chemical, and physical bases, indicators that are related to specific stressors that can be managed, and protocols that can be rapidly applied. Conclusions about the validity of CRAM are based on its correspondence with previously validated independent measures of condition that reflect biotic integrity in terms of bird and macroinvertebrate indices for riverine wetlands and plant indices for estuarine wetlands. Furthermore, CRAM results were strongly (negatively) correlated with independent measures of landscape disturbance based on the LDI, which has previously been shown to indicate

Table 8. Eigenvectors and factor loadings from a Principal Components Analysis using CRAM metrics.

Eigenvalue:	**5.1733**	**1.9625**	**1.816**	**0.9695**	**0.7225**	**0.6961**	**0.6354**	**0.4917**	**0.4219**	**0.3618**	**0.2994**	**0.1993**	**0.1561**	**0.0947**
Percent of Variance Explained:	36.9524	14.0178	12.9712	6.9249	5.1605	4.972	4.5384	3.5122	3.0136	2.5846	2.1382	1.4233	1.1148	0.6762
Cumulative Percent of Variance Explained:	36.9524	50.9702	63.9414	70.8663	76.0268	80.9988	85.5372	89.0493	92.0629	94.6475	96.7858	98.2091	99.3238	100
Eigenvectors:														
Connectivity	0.23686	-0.27336	0.15378	-0.54279	0.17469	-0.0521	-0.40064	0.29185	-0.25493	-0.06778	0.20137	0.14948	0.35801	0.10652
% Assessment Area (AA) with Buffer	0.2806	-0.38908	0.0199	0.12951	0.11647	-0.16593	0.42297	-0.33321	0.18725	-0.22767	0.01673	0.1337	0.48096	-0.29206
Average Buffer Width	0.33449	-0.29558	-0.10118	0.08552	0.18704	0.2764	-0.02617	0.0634	0.43221	-0.196	-0.16117	0.01972	-0.23176	0.60152
Buffer Condition	0.38321	-0.16806	0.01427	-0.10345	-0.02509	-0.16915	0.05531	0.08784	-0.08185	-0.25586	0.30577	-0.38116	-0.58118	-0.35395
Water Source	0.32462	-0.20238	-0.12241	0.30185	0.011	0.15804	-0.20543	0.37137	0.03769	0.50911	-0.34132	-0.11088	0.09991	-0.3781
Hydroperiod	0.21408	0.18473	-0.3706	0.19037	0.21163	-0.67171	-0.00315	0.06209	0.02292	0.29092	0.25371	0.18775	-0.031	0.2467
Physical Patch Richness	0.24432	0.06248	-0.35759	-0.21493	-0.12415	0.38658	0.54157	0.08348	-0.41693	0.15687	0.067	0.28866	-0.07767	0.07024
Topographic Complexity	0.28374	0.26836	-0.0787	0.22132	-0.5677	0.19649	-0.16781	0.05919	0.17911	-0.12557	0.45364	-0.1492	0.34023	0.08999
Organic Matter Accumulation	0.31007	0.07892	0.17741	0.32747	0.17504	0.08549	-0.19868	-0.48163	-0.58845	0.00136	-0.10599	-0.21116	0.03794	0.21446
Biotic Patch Richness	0.13265	0.48366	0.03727	-0.19538	0.60841	0.31267	0.05397	-0.09539	0.29066	0.14265	0.21715	-0.18404	0.09909	-0.18248
Vertical Biotic Structure	0.04696	0.09984	0.59355	0.42028	0.13941	0.07269	0.1415	0.36604	-0.06632	-0.08497	0.21427	0.45162	-0.13223	-0.0345
Interspersion/Zonation	0.27154	0.40541	-0.19209	-0.07115	-0.04428	-0.059	-0.28302	-0.04704	0.03139	-0.44744	-0.41614	0.423	-0.08617	-0.26737
% Non-native Plant Species	0.2628	-0.01393	0.38231	-0.28952	-0.31197	-0.04925	-0.07361	-0.42527	0.24981	0.47657	0.0033	0.27333	-0.22465	-0.0051
Native Plant Species Richness	0.23725	0.30431	0.33301	-0.1927	-0.13482	-0.29028	0.38112	0.2858	0.00584	-0.02445	-0.41361	-0.35345	0.17223	0.21774

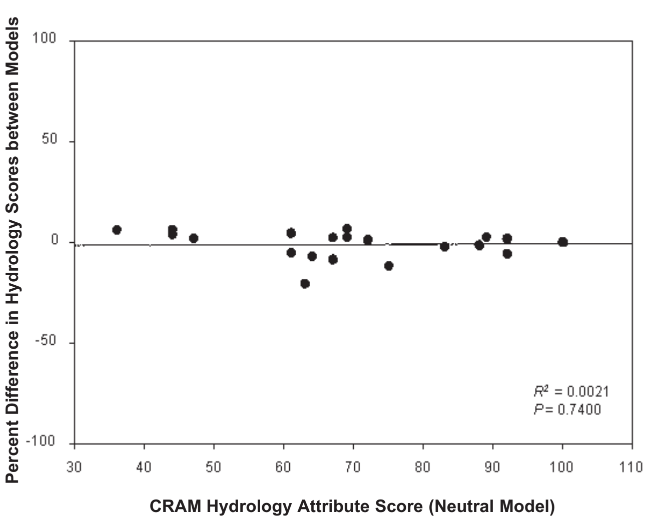

Figure 6. Effect of alternative metric combination rules on Hydrology Attribute score and its relationship to the BMI IBI score (top) and the percent difference in the Hydrology Attribute score based on a "neutral" model for combining CRAM metric scores and an alternative model, regressed against the neutral model scores (bottom). The neutral model consists of averaging the Hydrology metric scores to arrive at the attribute score. For the alternative model, the following formula was used: [Water Source*(Hydroperiod + Connectivity)/2]^1/2.

stress and to correlate with lower wetland condition as measured in both Level 2 (RAM) and Level 3 (intensive) assessments (Brown and Vivas 2005, Mack 2006, Reiss and Brown 2007). Similarly, in their study of wetland compensatory mitigation, Ambrose *et al.* (2006) found that CRAM scores reliably reflected overall condition. Ambrose *et al.* (2006) also conducted CRAM assessments at 47 "reference sites" that represented the best attainable conditions within each wetland class and found that that "reference standard" sites exhibited CRAM scores that were clustered toward the upper end of possible scores.

In aggregate, Level 3 data corroborated overall CRAM performance; however, individual Level 3 measures and CRAM scores were not always significantly correlated. Deviations between CRAM and MAPS and IBI data may result from the fact that CRAM is scaled to a theoretical optimum condition while the MAPS/IBI indices are scaled to the least disturbed condition sampled for these studies (Stoddard *et al.* 2006). However, it should be noted that site selection for the MAPS dataset tended to be skewed toward higher-quality habitat areas. This is because MAPS monitoring sites are selected based on

Table 9. Final error rates for CRAM attributes and overall index scores for riverine and estuarine wetlands. Percentages represent the "between team" error rates following completion of CRAM validation.

Wetland Class	CRAM Attribute % Error				Total % Error
	Landscape Context	Hydrology	Physical Structure	Biotic Structure	
Estuarine	11	8	12	8	5
Riverine	8	6	7	10	7

the specific needs of individual monitoring proponents, and not probabilistically, or in any other objective or systematic way across the region sampled. This may mitigate the aforementioned phenomenon to some degree, but still represents a potential deficiency of the dataset from the standpoint of our purposes. Bird and macroinvertebrate indicators used by MAPS and the BMI IBI can integrate external stressors (water quality, predation intensity, lack of food from adjacent habitats or upstream areas) in ways that CRAM does not. CRAM integrates impacts from upstream and other adjacent areas through landscape and hydrologic connectivity and water source metrics, which reflect a small portion of the overall condition score. However, poor water quality can have a significant impact on benthic macroinvertebrates and potentially bird populations, overwhelming other site-specific condition attributes. Therefore, MAPS and IBI results may respond to specific stressors that make other components of the wetland condition irrelevant. This is illustrated by the fact that the strongest correlations for the MAPs data were with the CRAM biotic structure attribute, while weaker correlations were seen for CRAM attributes that are less closely related to aspects of the riparian community measured by MAPS. MAPS and IBI metrics may also respond to stressors not associated with the wetland being assessed. For example, MAPS data may be confounded by the presence of young migrant birds from other areas that were captured during the mist net surveys or by population effects at overwintering habitat. Nevertheless, the fact that very few sites with high MAPS or IBI scores were found in association with low CRAM scores is a key indication of CRAM's ability to discern condition in a robust manner despite different underlying theoretical assessment models.

The relationships between Level 3 data, LDI scores, and CRAM scores were less significant for estuarine wetlands than for riverine wetlands. This difference could be due to smaller sample sizes, exaggerated regional differences in estuaries, and a smaller range in condition compared to riverine wetlands. A potential deficiency of the EMAP dataset, from the standpoint of our purposes, is the fact that the data do not capture very high quality sites. This is because much of the California coastline has been degraded, and there are very few estuaries in the state that have not been impacted by anthropogenic activities, particularly in Southern California and the San Francisco Bay area. The influence of regional differences is illustrated by the unexpected positive relationship between the CRAM water source metric and the EMAP metrics that reflect the relative percent cover of non-native and of invasive (which is a subset of non-native) plant species. This relationship likely resulted from the effect of different forcing functions in different regions of California. In northern California, EMAP assessments yielded higher percent cover values for invasive plant species, mainly due to the prevalence of invasive cordgrass in this area. In southern California, invasive species are less of a problem within the tidal marsh plain. However the CRAM water source metric scores are lower in southern California, which tends to have more intense coastal development impacting estuaries. These regional differences in key forcing functions likely led to a spurious relationship between CRAM and some of the EMAP metrics. Another possible explanation for the relatively poor relationships between CRAM and EMAP data is that estuarine plant communities may respond to stressors in a non-linear manner compared to CRAM metrics which were constructed based on a linear response model. Future analysis could employ a different set of statistical approaches to investigate potential nonlinear responses (Bedford and Preston 1988).

Fewer significant relationships between CRAM and LDI for estuarine wetlands (compared to riverine) also reflect the variable response of wetlands to landscape stressors. All riverine CRAM attributes were significantly correlated with LDI. However, LDI relationships were not significant for estuarine Physical and Biological Structure attributes. This is likely because tidal forcing, rather than watershed stressors, largely controls the condition of estuarine wetlands. In addition, many California estuaries tend to be more intensively managed to promote wildlife functions (e.g., via active invasive plant control or treatment of watershed inflow), which further decouples landscape stressor effects from wetland condition. These discrepancies between CRAM validation results for estuarine and riverine wetlands further demonstrate the importance of using multiple validation measures in a weight of evidence approach, and understanding the factors that control each measure of condition or stress.

Calibration

Results were used to modify CRAM to improve its performance and validity. The main changes included providing better support documentation, guidance, and instructions; revising narratives for metric scoring; rescaling metrics; rescoring or re-binning metrics; eliminating or combining metrics; and creating new submetrics (Table 10). The most substantive changes included: 1) rescaling the buffer and hydroperiod metrics to rectify the skewed distribution observed in the validation analysis and to better represent the distribution of scores across the range of condition, 2) restructuring the riverine hydroperiod metric to focus on floodplain geomorphology, 3) combining the physical and biotic structure metrics, and 4) refining the buffer and plant community composition metrics by creating submetrics. The submetric scores represent specific elements of the metrics and are aggregated to metric scores, which are then aggregated to attribute scores. For example, the Percent of AA with Buffer, Average Buffer Width, and Buffer Condition submetrics are combined into a single, multidimensional buffer metric, which is then combined with the landscape connectivity metric to generate an attribute score. This reduces the double counting of the buffer submetrics, as their combined weight is equal to that of the other metric in the Buffer and Landscape Context Attribute. A similar approach was taken for the plant community composition metric, for which submetrics were created to evaluate species richness, percent invasion, and structural complexity (based on number of distinct plant layers present). Correlations between attributes and Level 3 data were re-analyzed following these changes to ensure that the modifications improved CRAM overall performance. This process will continue iteratively to provide for ongoing refinement of CRAM.

Standardization

As with any assessment, CRAM results should be viewed in light of the expected precision of the method. The repeatability analysis allows for bounding of the confidence in CRAM output. From a management perspective, quantification of precision helps decisions makers determine when differences in CRAM scores likely represent a true difference in condition as opposed to being within the expected error of the method. Following the modifications made as a result of this study, CRAM attribute scores should generally be considered precise within ±10%, while overall CRAM scores should be considered precise within ±6%. Higher precision at the overall score level results from the internal redundancies and "smoothing" of variability associated with combining attributes into an overall score. However, as with any multimetric assessment, a specific overall score can result from various combinations of attribute scores, and likewise for attribute scores resulting from various metric combinations. Therefore, CRAM results are best considered at both the overall score and attribute level to provide a more complete understanding of wetland condition.

Implications for Other Calibration/Validation Efforts

This study demonstrates how data from existing monitoring and assessment programs can be used to calibrate RAMs. Ideally, validation would be done against an independent measure of condition that reflects the same elements as the RAM attribute of interest (e.g., Hydrology, Physical Structure). This "gold standard" measure would be independent of confounding factors associated with other elements of condition and would be collected concurrently with the RAM assessments. Obtaining this "gold standard" is difficult due to the challenge of identifying a unique measure of a single element of condition, and the cost associated with creating this new data set. However, multiple indices that reflect condition along a gradient of disturbance can be used to provide a weight-of-evidence approach (Miller *et al.* 2004, DeZwart *et al.* 2006). Use of multiple validation measures is important because a precise match

Table 10. Summary of changes to CRAM based on the calibration analyses.

Metrics	Type of Change					
	Rescored metric based on calibration results	Refined scaling of metrics	Revised wording/clarified narratives	Created separate narratives for a wetland type or sub-type	Added more guidance to definitions and field indicators sections	Added new wetland types: vernal pools and playa
Buffer and Landscape Context						
Landscape Connectivity		X	X	X	X	X
Percent of AA with Buffer			X		X	X
Average Buffer Width		X	X		X	X
Buffer Condition		X	X		X	X
Hydrology						
Water Source			X		X	X
Hydroperiod or Channel Stability		X	X	X	X	X
Hydrologic Connectivity		X	X	X	X	X
Physical Structure						
Structural Patch Richness	X	X	X	X	X	X
Topographic Complexity			X	X	X	X
Biotic Structure						
Organic Material Accumulation	Deleted Metric					
Vertical Biotic Structure	X		X	X	X	
Horizontal Interspersion and Zonation		X		X	X	X
Plant Community:	X	X	X	X	X	X
Number of Plant Layers Present	X	X	X	X	X	X
Number of Co-dominant Species	X	X	X	X	X	X
Percent Invasion	X	X	X	X	X	X

between RAM model output and validation data is not expected due to: 1) the inherent variability in natural systems, 2) different indices integrating different aspects of condition, 3) each index responding to different stressors and forcing functions, and 4) the fact that data are often collected over different spatial and temporal scales. The relationships between individual indices of condition will often be biased in one direction or another because of variable responses to natural environmental gradients and sensitivity to stressors (Hawkins 2006). It is virtually impossible to find response variables affected by a single forcing function or stressor (Karr and Chu 1999). If multiple relationships are concordant and consistent, it is reasonable to assume that the RAM results are accurately reflecting changes in condition relative to stressors on the wetland (Reiss and Brown 2007). The goal of validation should not be to maximize correlation with any one measure of biologic condition, but to optimize the method to achieve reasonable correlations with multiple measures of condition. This approach does not eliminate uncertainty in our conclusions; rather it provides a sound, transparent process for reducing uncertainty by integrating the best scientific information available at the time (Burton *et al.* 2002).

The analysis of CRAM relative to Level 1 or Level 3 data sources does not fit the traditional definition of calibration or validation. The purpose of calibration is to optimize the correspondence between RAM results and quantitative data for wetlands across a gradient of condition within a reference network (Brinson and Rheinhardt 1996) or to generate numeric scaling of metrics or variables (Hruby *et al.* 1999). In contrast, validation uses independent data sources to evaluate the accuracy of a RAM at assessing condition. True validation of assessment models of natural systems is impossible because natural systems are never closed and because model results are always non-unique (Oreskes *et al.*

1994). Furthermore, available Level 3 data sets are themselves indices of wetland condition based on floral and faunal community composition. Assessment models can only be evaluated in relative terms, and based on heuristic evidence from multiple independent measures of condition. Consequently, the overall RAM validation process includes elements that resemble both traditional calibration and validation (Oreskes *et al.* 1994, Janssen and Heuberger 1995). The ability to explain relationships observed in the data with well established ecological principles and understanding of wetland condition can serve to further validate RAM results. As with most biological models, CRAM performance should be continually refined as understanding of wetland condition improves and additional Level 3 data sets become available.

Final Thoughts

It is important to understand the limitations of RAMs. Despite rigorous validation that demonstrates the validity of a method, RAMs are only one tool for wetland monitoring and assessment. They are valuable in that they provide an inexpensive method that can be routinely and rapidly applied in a consistent manner across a range of wetland types. These features make RAMs a valuable and reliable tool for general condition assessments, screening level evaluations, and assessment of program performance. RAMs are not intended to replace intensive Level 3 data or to provide detailed information on specific wetland functions, support or health of particular species or communities, or detailed success of mitigation or restoration projects. When used in combination with Level 1 and Level 3 tools, calibrated RAMs fill a valuable niche in integrated assessment programs.

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