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#### **Integrating Ecology and Economics for Restoration:**

#### **Using Ecological Indicators in Valuation of Ecosystem Services**

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#### Abstract

Because it can uniquely furnish insights into nonuse values for ecosystem services, survey-based Stated Preference (SP) valuation is widely used to estimate the benefits of ecological restoration. SP surveys ask respondents to select among restoration options yielding different ecological outcomes. This review examines the representation of ecological outcomes in SP studies seeking to quantify values for restoration of aquatic ecosystems. To promote the validity of ecological indicators used in SP valuation, we identified four standards: indicators should be measurable, interpretable, applicable, and comprehensive. We reviewed recent SP studies estimating the value of aquatic ecosystem services to assess whether ecological indicators in current use had these desirable properties. More than half of the 54 indicators reviewed were measurable, meaning referable to potentially precise quantification. About one third were interpretable, i.e., presented in a way that facilitates understanding the effects of restoration. About three quarters of the indicators were applicable; SP valuation practitioners typically consult with natural scientists to ensure that indicators represent the effect of stressors on ecological systems, and with focus groups to ensure that indicators have a connection with ecosystem services that contribute to public well-being. While most of the SP studies employed diverse and potentially comprehensive indicators that could capture direct and indirect effects of restoration, and six of twenty studies used indicators that met all standards, shortcomings in the indicators were common. These problems can be rectified with attention to how natural scientists measure change, and to relationships between restoration outcomes and characteristics of fully-restored reference ecosystems.

Keywords: aquatic ecology, choice experiment, nonmarket, stated preference, survey

#### Introduction

Improving the provision of ecosystem services to enhance human welfare is widely recognized as a goal of natural resource policy and management, including ecological restoration (Turner & Daily 2008; US EPA Science Advisory Board 2009). Although many ecologists may be reluctant to see economic valuation of ecosystems play a major role in policy making, quantifying the value of ecosystem services can, at a minimum, help ensure that restoration decisions consider the relevance of ecosystems to human welfare. Nonmarket valuation tools (Freeman 2003) are employed to quantify welfare enhancements when ecosystem service benefits from restoration are provided outside of traditional human markets (as they often are). Nonmarket valuation of ecosystem services entails explicit integration of ecology and economics. Ecological data and models are needed to characterize the condition and/or change in ecological systems that provide human benefits. Economic methods are then employed to define and value resulting services within frameworks that correspond to the norms of benefit cost analysis. The validity of the resulting value estimates depends on employing sound ecological and economic methods and on appropriately integrating these components.

Stated preference (SP) methods are a type of nonmarket valuation frequently used to quantify values associated with ecosystem change (Freeman 2003); these involve analysis of responses to surveys representing scenarios of ecosystem change through ecological indicators. When applied appropriately, these methods allow quantification of total nonmarket benefits (and their components) and tradeoffs provided by ecological restoration. However, when surveys incorporate ambiguous representations of ecosystem change, value estimates will be imprecise or biased, especially when survey respondents have little experience with the ecosystem goods or services in question.

This review examines recent indicators used in SP valuation, focusing on analyses associated with aquatic ecosystem restoration. For context, we first provide background on SP methods and on how ecological changes are represented via indicators. We then suggest a set of standards representing best practices for indicators used in SP studies. We also assess the state of the field by examining indicators used in recent SP studies of aquatic ecosystems. The authors' collaboration, reflected in this review, came about to promote the integration of ecological and economic information for the quantification of ecosystem service values. Here we attempt to identify the properties of indicators that best bring this integration about, and to gauge the extent of the integration in the current literature.

#### The Economic Component: Values and Valuation Methods for Ecosystem Services

Despite their diversity, economic methods for valuing ecosystem services have common characteristics (Freeman 2003). In all methods, values are assessed with respect to well-defined marginal ecological changes, and are quantified using metrics that can be linked to improvements in human welfare (Bockstael et al. 2000; US EPA Science Advisory Board 2009). Within economics, *willingness to pay* (WTP) is the most common measure of value, reflecting the maximum amount of money or some other good or service that an individual would be willing to give up in exchange for more of something else (such as ecosystem restoration). Nonmarket valuation provides a means of measuring WTP for goods and services that are not traded in commercial markets (Freeman 2003).

Nonmarket valuation uses revealed preference (RP) and SP methods. RP methods directly address *use values*, those related to observable uses of resources or ecosystem services. SP methods are applicable to a wider range of ecosystem services and measure total values, including both use and *nonuse values*, those unrelated to observed uses, and including existence

and bequest values (Freeman 2003; Bateman et al. 2011).

A common SP method is the choice experiment (CE: Adamowicz et al. 1998), in which surveys ask respondents to choose among a set of hypothetical but realistic options, similar to a public referendum presenting several policies. Each option is described by multiple attributes and information on household cost. For example, a marsh restoration program might be defined in terms of effects on land use, hydrology, the abundance of various wildlife species, and required taxes. Survey data consisting of choices over many sets of hypothetical, multi-attribute options enables WTP estimation.

SP methods are widely used, albeit with considerable controversy. Their widespread use is partially attributable to their capacity to furnish unique insights into values for ecosystem services. We do not offer a comprehensive review of the method's advantages and limitations, but focus on one challenging feature of survey design that has a critical effect on the validity of SP-derived value estimates. SP surveys must provide accurate and sufficient information, because respondents can make well-informed choices only when they can understand the influence of ecological changes on their welfare (Bateman et al. 2011). SP surveys must also be succinct and evocative, because of constraints on the quantity and complexity of information that can be effectively communicated (Bateman et al. 2002; Christie et al. 2006).

#### The Ecological Component: Characterizing Change with Indicators

Attention to how natural systems are represented is an important part of SP valuation of ecosystem services. Appropriate representations typically require the grounding of each valuation effort in a conceptual model that includes: 1) stressors, the typically anthropogenic influences that can be affected by management; 2) linkages among system components; and, 3) well-defined and welfare-relevant ecological endpoints, defined as "ecological attributes or

elements. . .that serve as inputs to the production of ecosystem services" (US EPA Science Advisory Board 2009). The relationship of ecological endpoints to goods and services valued by humans varies; some endpoints may themselves be directly valued by humans, while others may serve only as inputs to valued goods and services (Fisher et al. 2008; Bateman et al. 2011). Careful definition and communication of welfare-relevant endpoints is crucial for valid ecosystem service valuation (Christie et al. 2006; Boyd & Banzhaf 2007).

Ecological indicators are measurable ecosystem features that serve as proxies for valued endpoints. Biodiversity, for example, a commonly-invoked endpoint that cannot be directly measured due to its multidimensional nature, is often represented by indicators such as species number (Christie et al. 2006). Multiple functions have been imputed to ecological indicators. Beyond their 'primary role' of reflecting the impact of specific stressors of interest (Niemi & McDonald 2007), indicators also assist in quantifying the degree of current ecological impairment, assessing future effects, and diagnosing stressors (Naweedi 2005). Changes in ecological endpoints can also be summarized using multimetric indices, including widely-used Indices of Biotic Integrity (IBIs), designed to represent "the ability to support a community of organisms having a species composition, diversity and functional organization comparable to that of natural habitat of the region" (Jordan & Smith 2005). IBIs are tailored to a geographic region and (typically aquatic) ecological system, and have been constructed for selected North American estuaries (Deegan et al. 1997) and for streams of eastern (Morgan & Cushman 2005) and western (Mebane et al. 2003) North America. A terrestrial multimetric index is mean species abundance (MSA) of species inhabiting an ecosystem, relative to their abundance in a pristine equivalent (Alkemade et al. 2009).

The development of ecological indicators and indices has been accompanied by close

scrutiny in the ecological literature of their efficacy. Criteria for ecological indicators that are useful in monitoring (e.g., Jackson et al. 2000; Naweedi 2005) include: 1) relevance with respect to endpoints and stressors; 2) feasibility with respect to cost-effective routine data collection; 3) accuracy with respect to sources of uncertainty; and, 4) interpretability with respect to discerning changes making management decisions. Because valid SP valuation requires that respondents accurately understand changes to ecological endpoints, appropriate use of ecological indicators is required to ensure meaningful value estimates. However, the close scrutiny given to indicators within the ecological literature has not been matched in the economics literature, leading to a disparity between indicators considered valid and useful in ecological science and those applied in economic valuation (Johnston et al. In press).

#### **Standards for Ecological Indicators within Stated Preference Valuation**

This section outlines a set of four simple standards for ecological indicators and indices used in SP valuation. In the course of designing our own SP analyses (Johnston et al. In press), we developed these standards by modifying recommendations for indicators used in ecological monitoring programs. The standards do not represent an exhaustive list but serve as minimal requirements enabling SP valuation to (1) provide information necessary and sufficient to elicit well-informed survey responses from non-experts, and (2) provide an accurate representation of ecosystem change resulting from restoration. That is, they are presented as necessary but not sufficient conditions.

Standard #1: measurability. Indicators used within survey scenarios should have a clearly stated relationship to ecological data or model results; they should consist of measures that are, at a minimum, empirically quantifiable. If ordinal categories (e.g., high, low) are used, the empirical basis for these categories should be specified. Multimetric indices, where used, should

be composed of a set of measurable indicators such as species number, abundance, and disease prevalence. This standard helps allay a common concern that SP surveys present ecological information in ways that cannot be traced back to quantifiable measures, and are thus inaccurate or lack meaning.

Standard #2: interpretability. The different possible values for indicators should be understood similarly by respondents and scientists. Indicator measurability is a necessary but not sufficient condition for interpretability. Interpretability of measurable indicators is enhanced by scaling and presenting indicators such that respondents can identify baselines (i.e., status quo), reference conditions (i.e., the best possible level in an undisturbed system), and changes in both relative and cardinal units where applicable. The ecological context represented by reference conditions is important because it enables respondents to better comprehend policy scope (Heberlein et al. 2005); this is particularly important for ecosystem services, with which respondents often have limited experience and understanding (Bateman et al. 2011).

Standard #3: applicability. Indicators in SP surveys should be germane to the restoration project. Developing such indicators requires a conceptual model of the natural system, so that indicators represent well-determined relationships between stressors and ecological endpoints. Furthermore, these endpoints must be linked to specific effects (i.e., changes in ecosystem services) over which respondents have preferences, as revealed by qualitative research methods such as focus groups and cognitive interviews (Powe 2007). This specificity helps prevent situations in which indicators are only indirectly related to respondent values, in which case respondents might make speculative inferences regarding omitted but relevant attributes (Carson 1998). For example, respondents might care about the abundance of migratory fish largely because of a perceived effect on a commercial fishery and local employment, even if there is

little potential for such an effect. Sacrificing ecological applicability reduces the usefulness of SP data to inform decisions on restoration policy.

Standard #4: comprehensiveness. As noted above, incomplete description of relevant effects can encourage speculation; respondents might fail to understand or appreciate fully the ecological importance of certain species or processes, and hence estimated economic values will not reflect the full impact of ecological changes (US EPA Science Advisory Board 2009). This is likely to be a concern for nonuse values or values stemming from regulating or supporting ecosystem services that are not readily perceptible and that influence respondents' welfare only indirectly (e.g., nutrient recycling provided by dung beetles: Nichols et al. 2008). Comprehensive specification of effects includes the direct effect(s) of proposed policies on targeted species or habitats (e.g., an increase in wetland area as a result of hydrological restoration) as well as indirect effects on ecosystem attributes or human uses that occur as consequences of the primary effects or as consequences of other indirect effects (e.g., changes in vegetation as a response to hydrological changes, colonization by animal species requiring wetland flora for habitat or food, etc.). The inclusion of ecological changes at multiple causal levels provides a basis for distinguishing between value for improvements in specific elements of the ecological system and that for overall ecosystem condition.

#### **Prior Stated Preference Studies Estimating Values for Aquatic Ecosystem Change**

To assess the extent to which ecological indicators in use had the minimum properties described by our standards, we reviewed recent SP studies that estimated the value of aquatic ecosystem services. We located roughly 700 studies in Web of Science (Thomson Reuters, New York NY), using search terms for economic methods (e.g. contingent valuation) combined with terms for aquatic systems (e.g. lake), in papers published in 2006 or later. We culled those that

did not pertain to valuation of aquatic ecosystem services or changes, did not use indicators, or were not readily available, yielding a final set of 21 papers to review; Fenichel et al (2009) and Hoehn et al (2010) used the same survey and are treated here as one study. The papers reported 54 ecological indicators (Table 1; details in supplementary document). Although this is a small subset of the subject literature, the criteria we used were meant to furnish a representative view of ecological indicators used in current SP studies.

The indicators in recent SP studies can be grouped according to ecological endpoints they represent. The largest group consists of 14 indicators representing biodiversity (e.g., "number of fish species", Do & Bennett 2009). Indicators also commonly represented habitat quantity (n = 11, e.g., "wetland area", Birol & Cox 2007) or habitat quality (n = 9, e.g. "water clarity", Kerr & Sharp 2008). Seven indicators explicitly represented habitat functions ("erosion control", Kataria 2009). Other indicators represented aesthetics (e.g., "litter and sewage", Hanley et al. 2006b), human health ("risk of injury or illness", McIntosh et al. 2010), productivity (e.g., "Number of salmon passing fish ladder", Håkansson 2009), and recreation (e.g., "Suitability for playing in the river", Nakatani et al. 2007). Several studies incorporated indices of ecological integrity similar to IBIs (Hanley et al. 2006a; Martin-Ortega et al. 2011).

More than half of the indicators (n = 30; Table 1) were measurable, in that they were referable to potentially precise quantification. Indicators of diversity often varied over precise values for species number (e.g., "2 protected bird species" Luisetti et al. 2011), and habitat quantity (e.g., "60% of surface area is open water", Birol et al. 2006). However, the choice set for some diversity indicators comprised ordinal categories whose meaning was not clear (e.g., "mostly desirable fish species with many walleye", Christie & Azevedo 2009). Habitat quality indicators, often presented in categories, were measurable when the categories were distinct

classes (e.g., wooded wetland or marsh, Hoehn et al. 2010), or when the meaning of ordinal categories was spelled out (e.g., "an 'excellent' rating meant that the wetland habitat supported 'these species in better than average numbers...[so] a casual observer is very likely to see a variety of these species'" Hoehn et al. 2010). In contrast, some habitat quality indicators were not measurable (e.g., the choice set for "condition of waterholes' ranged from "poor" to "good", Zander & Straton 2010). Few multimetric indicators were measurable; they typically lacked units, and alternative outcomes were described in poorly-defined ordinal categories (see discussion in Christie et al. 2006). For instance, the choice set in Bateman et al. (2006) includes "plants and wildlife" in an ordinal scale ("plant growth, insects, birds and animal life limited", "more plants would grow, waterfowl can use river", up to "increase in plants and wildlife, possible for otters to survive").

About one third of the indicators were interpretable (Table 1). Interpretability is a more stringent condition than measurability; indicators need to both have a measurable basis and also be expressed in a way that facilitates understanding the effects of restoration among non-expert respondents. Even studies that use measureable indices may fail to represent the potential scope of restoration. In a choice set example presented in Do and Bennett (2009), the number of fish species varied from 40 (baseline or status quo) to 50 or 70 under alternative restoration options. The interpretation of this change depends on how 70 species compares to the reference condition for this system. In contrast, the choice set for an indicator of species abundance in Milon & Scrogin (2006) spells out the quantitative basis, baseline and reference conditions (e.g., "wetland dependent species such as wading birds and alligators" at "20% of historic, predrainage population levels"). Recent studies reflect an appreciation for the value of making reference and baseline conditions clear; eight indicators that were not measurable nonetheless had choice sets

that clearly represented both reference and baseline conditions, and another 19 represented baseline conditions without a reference condition.

Most of the indicators (n=40; Table 1) were economically and ecologically applicable. Economic applicability entails having some demonstrated connection between the indicator and public well-being. Preparation of SP surveys commonly involves work with focus groups to ensure such a connection (Powe 2007), and we interpreted statements of focus group work in the description of a study's method as evidence for economic applicability of the indicators. Ecological applicability entails having at least an implicit relationship among stressors, indicators, and ecological endpoints. To help ensure ecological applicability, it is crucial to consult with natural scientists (e.g. "Significant wetland management attributes pertaining to [the wetland] were identified in consultation with ecologists and hydrologists [and economists]. Three focus groups were then conducted .....to determine the final attributes and their levels that are important to the public, as well as the vocabulary and language to be used in the survey" Birol et al. 2006). Applicability may have been sacrificed in some studies in an effort to simplify survey representations of ecological consequences. For example, Hanley et al. (2006b p. 186) state, "none of these attributes are necessarily consistent with what an ecologist would choose in terms of either indicators of the ecological health of a waterbody, or underlying factors driving changes in ecological status." We interpreted statements of collaboration with ecologists in the description of a study's method as evidence for ecological applicability of its indicators. Otherwise, we classified applicability as unclear. We did not use consultation with regulators, stakeholders or government officials as evidence of ecological applicability, given the unclear contribution of such consultations to the ecological content of indicators. Finally, indicators defined solely in terms of suitability of resources for human use, with no underlying ecological

detail or justification, were also considered to have unclear ecological applicability.

Consistency with our fourth standard, that indicators should furnish a comprehensive depiction of ecological effects of restoration, is difficult to judge conclusively.

Comprehensiveness cannot be assessed one indicator at a time because it is a feature of entire SP scenarios. A minimum condition for comprehensiveness is including multiple indicators that together can represent direct and indirect responses to restoration. Three studies provided only one indicator (Tseng & Chen 2008; Del Saz-Salazar et al. 2009; Håkansson 2009). The indicators presented in most of the studies (n = 12) potentially captured direct and indirect responses to restoration. Four studies omitted indicators that could capture the direct effect of restoration (e.g., changes in flooded area in response to dyke removal, Do & Bennett 2009).

Has the use of ecological indicators in SP analyses improved over time? The collaboration of the authors was stimulated by the perception that ecological considerations had been poorly integrated into SP surveys. Nonetheless, some recent papers (especially Hoehn et al. 2010; Pattison et al. 2011) employed an especially comprehensive set of indicators that each fully met the recommended standards, suggesting that the field is increasingly incorporating best practices. Moreover, there are an increasing number of publications in the valuation literature that discuss the quantification and representation of various ecological effects (e.g., biodiversity, Christie et al. 2006), implying greater awareness of such concerns. Unfortunately, the limited 6-year scope of the papers examined in this review does not permit a powerful test of temporal change.

In summary, our evaluation revealed wide variation in the presentation of ecological information within SP surveys. Six of twenty studies used indicators that met all of the standards. It is encouraging that nearly all of the SP studies took care to ensure ecological and

economic applicability, and that the indicators used represented diverse and potentially comprehensive responses to restoration. However, we found rather widespread shortcomings with respect to the use of indicators that are explicitly quantifiable, and that are interpretable with respect to both unrestored and fully-restored conditions. Estimated values for restoration are likely to lack precision and accuracy as a result. It is important to note that our evaluation of ecological indicators used in an SP study is not intended as a comment on a study's overall quality, which can have many facets that are not considered in this limited review. Furthermore, our judgment of whether an indicator met the standards was based on entirely on what was presented in the published account, which may well have omitted information that would have changed our interpretation.

#### **Concluding Remarks**

Measurements of the conditions of ecological systems that are useful in designing and monitoring restoration projects are also useful in assessing the public costs and benefits of such projects. Indicators can play an important role in restoration and other forms of management; restoration projects, which are designed to ameliorate the effects of one or more ecosystem stressors, must at least implicitly conceive of how the success of the restoration would be judged. There is a robust literature providing guidance on ecological indicators for resource managers that stresses the importance of accurate and comprehensive quantification of ecosystem state. In this paper, we have argued that the properties of well-conceived indicators that make them useful in the design and monitoring of restoration are precisely the same as those needed in valuation of restoration's public benefits. Incorporating information about the value of ecological effects is critical for making sound decisions about public policies that impact the environment. SP surveys are now a commonly used method for estimating these values. The validity of resulting

value estimates is conditional on an accurate representation of ecosystem change.

Our informal review of recent SP surveys focusing on aquatic restoration indicates mixed results. On the positive side, most of the studies we examined maintained a focus on ecological indicators that were relevant to restoration efforts. On the negative side, many of these indicators do not meet minimal standards for measurability or interpretability. This paper develops an initial set of standards designed to help ensure, in combination with other best practices, that SP-derived value estimates can be linked unambiguously to meaningful and measurable indicators.

As ecology and economics are undergoing a more thorough integration, the strengths and limitations of different approaches to valuation are of increasing interest. Some ecologists and economists regard the estimates provided by survey-based methods as less repeatable, less generalizable and in greater need of validation than those yielded by other approaches. It is well beyond the scope of this paper to compare and contrast the methods that are presently brought to bear on the valuation problem. In lieu of a broad critique, we emphasize that the SP method is distinct from other methods in several respects that recommend its use in restoration planning: these include its ability to quantify nonuse values and its direct approach to public attitudes. In a broader context than is represented in this review, valuation for project planning entails a dialogue among technical experts, chief stakeholders and other citizens, and the representation of ecological change as reflected in indicators plays a role in each part of this dialogue. The development and implementation of schemes that formally link multiple stages in project planning should prove fruitful (see Sijtsma et al. 2011 for one promising example). Our review also suggests that SP valuation, despite the controversies surrounding its use, has provided a platform for more widespread collaboration and dialogue among ecologists and economists. It is

hoped that this paper will further promote such interactions.

We conclude by pointing to valuation challenges that must be addressed in order to more fully integrate ecology and economics. One challenge will be to assess whether well-crafted indicators reflect a rich sense of the value of natural systems. It will be interesting to map out where surveys succeed in providing sufficient background for respondents to make informed choices about indirect benefits; this will be especially challenging for supporting ecosystem services. Other issues that will require careful attention are the degree to which results of analyses can be generalized from one restoration project to another in a different time and place, and the degree to which results can be scaled up to values arising from national and global environmental policy (Sijtsma et al. 2011).

#### **Implications for Practice**

- Insofar as ecological restoration seeks to enhance the delivery of ecosystem services, it entails valuation of these services. Stated preference valuation can quantify explicitly nonuse nonmarket values that are prominent in ecosystem service valuation.
- Integration of ecological and economic considerations in valuation efforts requires ongoing collaboration rather than time-limited consultation. Ecologists must play a role at all stages of formulation, design and execution of valuation projects.
- Valid estimates of value for ecosystem services require ecosystem indicators that are
  developed with attention to data and models, and are quantitative, interpretable,
  applicable and comprehensive. This is true of all approaches to valuation.
- Stated-preference approaches to valuation frequently use ecosystem indicators that are
  not likely to yield valid estimates of value. With care, it is possible to design surveys
  using indicators that comprehensively characterize ecosystem services in a fashion
  understandable to respondents.

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Table 1. Summary of indicator analysis. For each of 21 studies (2 of which use the same SP dataset and are thus combined in a row), entries in the table include the number of ecological indicators, followed by the number of indicators that we regard as measurable and interpretable, and whether the indicators were applicable (Y: yes; U: unclear) and comprehensive (Y: yes; N: no) according to our criteria. Judgment of whether an indicator met the standards was based on entirely on what was presented in the published account, which may have omitted information that would have changed our interpretation.

N(indicators)	N(measurable)	N(interpretable)	Applicable	Comprehensive	Reference
3	1	3	U	Y	Bateman et al. 2006
2	1	0	Y	Y	Birol et al. 2006
1	0	0	U	N	Hanley et al. 2006a
3	0	0	U	Y	Hanley et al. 2006b
2	2	2	Y	Y	Milon & Scrogin 2006
3	3	1	U	Y	Birol & Cox 2007
2	1	1	U	Y	Nakatani et al. 2007
5	2	5	Y	Y	Kerr & Sharp 2008
1	1	1	Y	N	Tseng & Chen 2008
					Christie & Azevedo
4	3	0	Y	N	2009
					Del Saz-Salazar et al.
1	0	0	U	N	2009
3	3	0	Y	N	Do & Bennett 2009
					Fenichel et al. 2009;
3	3	3	Y	Y	Hoehn et al. 2010
1	1	0	Y	N	Håkansson 2009
4	1	0	Y	Y	Kataria 2009

4	0	0	Y	Y	McIntosh et al. 2010
3	1	3	Y	Y	Zander & Straton 2010
2	2	1	Y	Y	Luisetti et al. 2011
					Martin-Ortega et al.
1	0	1	Y	Y	2011
6	6	6	Y	Y	Pattison et al. 2011

Ecological indicators in recent stated preference valuation analyses of aquatic ecosystem services. Each indicator is represented on a separate row, except where noted. Some indicator descriptions are simplified for clarity of presentation. To more fully describe each indicator, the table provides: 1) one or more welfare-relevant ecological endpoints for each indicator (see text for distinction between endpoints and indicators); 2) lower and upper limits (as lower / upper) to the range of indicator values, omitting intermediate values if any for conciseness. Each indicator is scored according to whether it meets three guidelines: measurable if field workers could unambiguously score its value (yes/no), interpretable if both baseline and reference values were clear (yes/no), and applicable if the published account reported both consultation with ecologists and focus groups as a basis for indicator development (yes/unclear). To illustrate the comprehensiveness of indicators used in a particular study, the table also provides the environmental stressors that the restoration project reported in the study was designed to ameliorate, and whether the indicator reflected a direct or indirect effect of the restoration.

Bioindicator description	Ecological endpoint(s)	Range of values	Measurable	Interpretable	Applicable	Stressor	Direct / indirect effect	Reference
		No fish /						
		game fish						
Fish species		plus				Adverse water		
number	Biodiversity	salmonids	Yes	Yes	Unclear	quality	Indirect	Bateman et al. 2006

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Plant growth,	Biodiversity							
insects, birds	and	Limited /				Adverse water		
and wildlife	productivity	Increase	No	Yes	Unclear	quality	Indirect	Bateman et al. 2006
Boating and		Unsuitable /				Adverse water		
swimming	Recreation	suitable	No	Yes	Unclear	quality	Direct	Bateman et al. 2006
Species								
number and								
abundance,		Decrease /						
habitat		10%		Reference		Adverse water		
diversity and		increase		value		quality and		
size	Biodiversity	from current	No	omitted	Yes	quantity	Indirect	Birol et al. 2006
				Reference		Adverse water		
Open water	Habitat			value		quality and		
surface area	quantity	< 20% / 60%	Yes	omitted	Yes	quantity	Direct	Birol et al. 2006

		Algae only,						
		few animals,						
		smell of						
		rotting						
		vegetation /						
		Increased						
		populations						
Macrophytes,		of plants and						
invertebrates,		animals, no						
fishes and		offensive						
mammals,		smells,		Reference		Adverse river		
odor,	Ecological	improved		value		water quality		
appearance	integrity	appearance	No	omitted	Unclear	and quantity	Indirect	Hanley et al. 2006a
				Reference		Adverse river		
Litter and				value		water quality		
sewage	Aesthetics	Some / none	No	omitted	Unclear	and quantity	Direct	Hanley et al. 2006b

	function:	Few / plenty				Adverse river		
	Habitat							
birds	Biodiversity	birds	No	No	Unclear	and quantity	Indirect	Hanley et al. 2006b
insects and		insects and				water quality		
plants,		water plants,				Adverse river		
fish, water		range of						
Species of		fish, wide						
		and coarse						
		salmonids						
		birds /						
		insects and						
		plants,						
		of water						
		poor range						
		Coarse fish,						

Abundance								
of wetland								
dependent,								
dryland		Percent						
dependent		relative to						
and bay		historical						
dependent		pre-impaired				Adverse		
species	Productivity	values	Yes	Yes	Yes	hydrology	Indirect	Milon & Scrogin 2006
		Percent						
		relative to						
Lake and		historical						
wetland	Habitat	pre-impaired				Adverse		
water values	quantity	values	Yes	Yes	Yes	hydrology	Direct	Milon & Scrogin 2006
Protected				Reference				
bird species				value				
number	Biodiversity	14 / 34	Yes	omitted	Unclear	Habitat loss	Indirect	Birol & Cox 2007
				Reference				
	Habitat			value				
Wetland area	quantity	100 / 347 km	Yes	omitted	Unclear	Habitat loss	Direct	Birol & Cox 2007

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Otter holt	Habitat							
construction	quantity	Yes / no	Yes	Yes	Unclear	Habitat loss	Direct	Birol & Cox 2007
Suitability								
for playing in		Impossible /				Adverse water		
the river	Recreation	possible	No	No	Unclear	quality	Direct	Nakatani et al. 2007
		None / carp,						
		crucians,						
		loaches,						
Fish species		bitterlings,				Adverse water		
number	Biodiversity	killifish	Yes	Yes	Unclear	quality	Indirect	Nakatani et al. 2007
	Habitat							
	function:							
	erosion and					Adverse		
Channel	flood	Straightened				hydrology and		
form	control	/ natural	No	Yes	Unclear	water quality	Direct	Kerr & Sharp 2008

						Adverse		
	Habitat	Muddy /				hydrology and		
Water clarity	quality	clear	No	Yes	Yes	water quality	Indirect	Kerr & Sharp 2008
		Little or				Adverse		
Riparian	Habitat	none /				hydrology and		
vegetation	quality	plentiful	No	Yes	Yes	water quality	Direct	Kerr & Sharp 2008
						Adverse		
Fish species						hydrology and		
number	Biodiversity	1 / 5 species	Yes	Yes	Yes	water quality	Indirect	Kerr & Sharp 2008

						Adverse		
	Habitat					hydrology and		
Fish habitat	quantity	1 / 4 km	Yes	Yes	Yes	water quality	Direct	Kerr & Sharp 2008
Fish		146 / 1612				Climate		
abundance	Productivity	trout	Yes	Yes	Yes	change	Indirect	Tseng & Chen 2008

		Mostly						
		bullhead /						
		mostly						
		desirable						
		species with		Reference				
Fish species		many		value				
number	Biodiversity	walleye	No	omitted	Yes	Eutrophication	Indirect	Christie & Azevedo 2009
		Brown, 1-5		Reference				
Water color	Habitat	inch / blue,		value				
and clarity	quality	5-8 feet	Yes	omitted	Yes	Eutrophication	Indirect	Christie & Azevedo 2009
		Almost		Reference				
Algae	Habitat	constant / 3-		value				
blooms	quality	4 per year	Yes	omitted	Yes	Eutrophication	Indirect	Christie & Azevedo 2009

				Reference				
	Habitat	Always		value				
Lake odor	quality	strong / none	Yes	omitted	Yes	Eutrophication	Indirect	Christie & Azevedo 2009
		Not						
		acceptable						
		for any use /						
	Habitat	safe for				Adverse		
Water quality	quality	drinking	No	No	Unclear	water quality	Direct	Del Saz-Salazar et al. 2009
				Reference				
Fish species		40 / 70		value		Adverse		
number	Biodiversity	species	Yes	omitted	Yes	water quantity	Indirect	Do & Bennett 2009
Area with				Reference				
healthy	Habitat			value		Adverse		
vegetation	quantity	50% / 80%	Yes	omitted	Yes	water quantity	Indirect	Do & Bennett 2009

				Reference				
Number of		150 / 450		value		Adverse		
Sarus cranes	Productivity	birds	Yes	omitted	Yes	water quantity	Indirect	Do & Bennett 2009
	Habitat	Wooded /						Fenichel et al. 2009; Hoehn et
Wetland type	quality	marsh	Yes	Yes	Yes	Habitat loss	Direct	al. 2010
Habitat for a								
taxon or								
guild (e.g.,		Poor (few						
songbirds,		species) /						
wild	Habitat	excellent						
flowers): five	quality /	(variety of						Fenichel et al. 2009; Hoehn et
bioindicators	productivity	species)	Yes	Yes	Yes	Habitat loss	Indirect	al. 2010
	Habitat							Fenichel et al. 2009; Hoehn et
Wetland area	quantity	5 / 16 acres	Yes	Yes	Yes	Habitat loss	Direct	al. 2010
Number of								
salmon				Reference				
passing fish		3000 / 9000		value		Habitat loss or		
ladder	Productivity	fish	Yes	omitted	Yes	fragmentation	Direct	Håkansson 2009

Benthic								
invertebrate		Considerably		Reference				
species		reduced /		value		Altered		
number	Biodiversity	high	No	omitted	Yes	hydrology	Indirect	Kataria 2009
		Eroded						
		beach with						
		reduced /						
		broad beach						
	Habitat	with high						
	function:	plant species		Reference				
Riparian	erosion	richness and		value		Altered		
vegetation	control	biomass	No	omitted	Yes	hydrology	Indirect	Kataria 2009
	Habitat	Not		Reference				
Conditions	quality or	improved /		value		Altered		
for birds	biodiversity	improved	No	omitted	Yes	hydrology	Indirect	Kataria 2009
						Altered		
				Reference		hydrology and		
Fish		0% / 25%		value		habitat		
abundance	Productivity	increase	Yes	omitted	Yes	fragmentation	Direct	Kataria 2009

Water clarity	Aesthetics	Reduced /	No	No	Yes	Invasive species	Direct	McIntosh et al. 2010
	resultes	pro , <b>cu</b>						
Native								
animals and		Reduced /				Invasive		
plants	Biodiversity	not reduced	No	No	Yes	species	Indirect	McIntosh et al. 2010
Risk of								
injury or	Human	Higher / not				Invasive		
illness	health	higher	No	No	Yes	species	Direct	McIntosh et al. 2010
Sport fishing								
and								
swimming		Reduced /				Invasive	Direct,	
opportunities	Recreation	not reduced	No	No	Yes	species	Indirect	McIntosh et al. 2010
						Habitat loss		
Condition of	Habitat					and water		
waterholes	quality	Poor / good		Yes	Yes			Zander & Straton 2010

						Habitat loss		
Fishing	Recreation /					and water		
quality	provisioning	1-star / 4-star	No	Yes	Yes	quality	Indirect	Zander & Straton 2010
		25% less				Habitat loss		
Floodplain	Habitat	than / current				and water		
area	quantity	level	Yes	Yes	Yes	quality	Direct	Zander & Straton 2010
Protected								
bird species								
number	Biodiversity	2/5 species	Yes	Yes	Yes	Habitat loss	Indirect	Luisetti et al. 2011
				Reference				
Area of new	Habitat	25 / 173		value				
marsh	quantity	acres	Yes	omitted	Yes	Habitat loss	Direct	Luisetti et al. 2011
		Loss of						
		many fish						
		birds insects						
Fish, birds,		and most						
wildlife,		vegetation /						
riparian	Ecological	optimal					Direct,	
vegetation	integrity	conditions	No	Yes	Yes	Low flow	Indirect	Martin-Ortega et al. 2011

	Habitat							
	function:	740,000 /						
	carbon	800,000 car						
Carbon	capture and	emissions						
capture	storage	stored	Yes	Yes	Yes	Habitat loss	Indirect	Pattison et al. 2011
	Habitat	6 million /						
	function:	6.8 million						
	erosion	tons not						
Erosion	control	eroded	Yes	Yes	Yes	Habitat loss	Indirect	Pattison et al. 2011
	Habitat	1.1 billion /						
	function:	1.2 billion						
	flood	cubic meters						
Flood control	control	of water	Yes	Yes	Yes	Habitat loss	Indirect	Pattison et al. 2011
	Habitat							
	function:	4500 / 5000						
	water	truck loads						
Water quality	purification	of fertilizer	Yes	Yes	Yes	Habitat loss	Indirect	Pattison et al. 2011
		Percent						
	Habitat	relative to						
Wetland area	quantity	1968 values	Yes	Yes	Yes	Habitat loss	Direct	Pattison et al. 2011

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		1.8 million /	1.8 million /								
		2 million									
Breeding	Habitat	breeding									
ducks	quantity	pairs	Yes	Yes	Yes	Habitat loss	Indirect	Pattison et al. 2011			