LANDSCAPE INDICATORS OF ECOSYSTEM SERVICE BENEFITS

JAMES BOYD AND LISA WAINGER

Section 404 of the Clean Water Act (CWA) requires mitigation for wetland losses caused by development and other activities. Wetland mitigation can involve direct restoration, enhancement, or preservation or payment into a compensation fund subsequently used for mitigation undertaken by the state or another entity. In some cases, wetland acres are explicitly traded via off-site wetland mitigation projects or mitigation banks (Scodari and Shabman).

Wetland Trading and Compensation Ratios

Regulatory requirements for mitigation trades require regulators to determine how much restoration or compensating preservation is enough to offset permitted wetland losses. Surveys of wetland mitigation banking practice show that bank program administrators rely on relatively vague, function-based compensation ratios (Brady). Recent criticism of the Army Corp of Engineers' evaluation procedures has been based on the Corps' failure to address lost functions (National Research Council). Economic benefits arising from lost ecosystem functions are rarely evaluated. In fact, analysis of lost benefits is not required under the CWA. This is a weakness of current regulations geared toward compensation for ecosystem losses.

Ecosystem exchanges, such as tradable development rights or wetland mitigation trades, require more than good ecological analysis. They require the application of economic principles in order to guarantee that trades preserve what is valuable about ecosystems and thus maximize net social benefits (Boyd, King, and Wainger). Wetlands generate value in numerous ways. They can harbor rare and endangered species, reduce flood damages, improve water quality, and enhance property and recreational area values. Unfortunately, in most cases, regulators are not adequately equipped, financially or technically, to judge the relative value of environmental assets to be exchanged in such markets. Until these challenges are met, badly regulated ecosystem trades may undermine, rather than advance, the achievement of environmental and social welfare objectives (Elliott and Charnley, Rose).

Current regulatory programs do not typically account for lost ecosystem service benefits when assessing compensation. The most common regulatory practice is simply to require an "acre for an acre" of biophysically similar wetland when another is destroyed. At best, biophysical equivalence is evaluated (Ruhl and Gregg). But acre-based or purely functional compensation evaluations fail to account for many of the things that determine the social benefits of a particular ecosystem, such as a site's location in the greater landscape, the importance of local substitutes for and complements to the site, and future risks to the site's ability to provide services. In contrast, econometric analysis, the economist's preferred evaluation method, is difficult and costly and typically does not capture the full range of service benefits at a site. In practice, econometric analysis is rarely, if ever, used in wetland permitting decisions.

Study Goals

This study proposes a middle ground between no analysis of services and econometric analysis, which is not realistic for small-scale permitting applications due to its cost and reliance on specialized expertise. The goal is an evaluation method, applicable by noneconomists using existing data sources, that can identify

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James Boyd is senior fellow at Resources for the Future, Washington, D.C., and Lisa Wainger is research scientist at the University of Maryland Center for Environmental Science.

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likely differences in the social benefits generated by ecosystems. The method involves simple GIS-based indicators of ecosystem service benefits to improve regulatory site evaluation. The ability to monetize benefits—and thus compare sites and services directly using a common metric—is sacrificed by a system of simple indicators, but so too is the cost and complexity of econometric valuation methods.

The Measurement of "Adequate Compensation"

Determining whether compensation is adequate requires a comparison of the ecosystem benefits associated with the lost wetland and the restored, enhanced, or preserved site. To provide a structure for the following analysis, consider the following depiction of the evaluation exercise. If individual services are indexed by i and time periods by t, let $A_t^i(\mathbf{u}_t;\mathbf{v}_t)$ denote the expected value of ecosystem service i in period t, if the site to be destroyed were left undisturbed, and where $\mathbf{u}_t$ is a vector of biophysical functions created by the site and $\mathbf{v}_t$ is a vector of economic, social, and landscape characteristics. Ideally, these losses are considered on a per acre basis. Encroachment, natural hazards, invasive species, and a host of other factors can alter the functional characteristics of the site. Demographic, technological, and other social factors can also change over time in ways that affect the services' value.

Similarly, let $B_t^i(\mathbf{u}_t;\mathbf{v}_t)$ denote the incremental value of the enhanced services provided by each acre of the compensation site. Improvements can arise from a change in the site's functional characteristics $\mathbf{u}$, as when a site is enhanced or restored, or from a landscape context $\mathbf{v}$ that enhances the social value of functional improvements.

At best, conventional regulatory assessments rely on comparison of on-site biophysical functions. Accordingly, regulatory attention tends to be paid exclusively to the vector $\mathbf{u}$. Our study derives indicators of the vector $\mathbf{v}$, to complement the analysis of functions and to more accurately characterize the social value of lost services. If unlimited resources could be devoted to econometric analysis the goal would be to sum and discount over time the A_t^i and B_t^i. Then, the aggregate loss L could be compared to the aggregate compensating gain G. While our approach does not monetize streams of benefits, the basic goal is the same: a comparison of benefits lost to benefits gained.

In practice, it is rare to find compensation sites that yield the same ecological (or economic) gain as the impact site loss. For this reason, trades and compensation typically involve the use of compensation ratios, which convert losses into equivalent gains by adjusting the amount of acreage where compensation occurs. Consider a multi-acre impact site where there is a per acre loss in service value L and a potential compensation site expected to yield a per acre gain G. If $G < L$, an acre-for-acre exchange is inadequate. If total losses are to be compensated by an equivalent gain, then xL must equal yG where x is the number of acres lost and y the number of acres used for compensation. Note that if the per acre loss at the impact site is greater than the per acre gain at the compensation site, then $y > x$.

By describing the vector $\mathbf{v}$, landscape indicators help assess the adequacy of compensation: is the incremental value of services gained at the compensation site adequate to offset the services lost at the impact site? If not, there are economic grounds for denying the trade or seeking additional compensation via the compensation ratio.

Application

To both illustrate and evaluate the ecosystem benefit indicator approach, we evaluated a set of wetland impact sites whose losses were compensated at a mitigation bank in Lee County, Florida.[1] Little Pine Island, the site of the mitigation bank, is a 4670-acre, uninhabited island located just offshore of the southwest Florida mainland near the city of Ft. Myers. The bank developer agreed to restore wetlands on the island in return for the right to sell wetland mitigation credits to permit seekers wishing to develop wetlands elsewhere in the bank's service area. Evaluation of wetland exchanges at LPI involved sophisticated functional assessment, but little in the way of landscape analysis. Our landscape assessment evaluated nine LPI trades, those that fell under federal jurisdiction and were regulated by the U.S. Army Corps of Engineers. The location of each impacted wetland site and LPI is shown in figure 1, along with a sample data layer, the density of private drinking water wells by census blockgroup. To isolate the importance

[1] For a more detailed description of the study see Boyd et al.

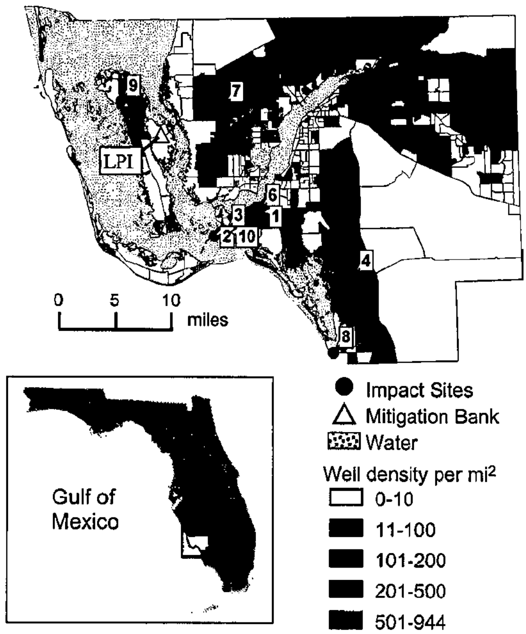

Figure 1. Location of impact sites and mitigation bank with private drinking well density by 1990 census block group

of landscape-related benefit differences, we assumed that gains and losses in wetland functional capacity resulting from each mitigation trade were equal, and that the only potential sources of differences in wetland values were differences in location.[2]

The Data

The majority of GIS data used in the case study were acquired from the Florida Geographic Data Library, a repository of more than 200 spatial data layers for Florida. Additional data were provided by the South Florida Water Management District.

Our analysis is based on 40 GIS coverages containing demographic, real estate, physical, biological, land use, infrastructure, and planning data. From these coverages sixty-six indicators were calculated, all related to the provision of service benefits. The indicator calculations take several forms: the *distance* between two points or areas; the *presence* of a certain feature, or the *number* of features within an area; the *percentage* of an area that has a particular characteristic; and the *connectivity* of a certain feature with other landscape features. The area chosen for a specific indicator calculation may be a physical feature, such as a watershed or a floodplain, or it may be a constructed feature, such as a 1/2-mile radius around a point or larger area.[3]

Choice and Organization of the Indicators

Our analysis focused on four wetland services: improved drinking water supply, flood damage avoided, enhanced aquatic recreation, and the provision of open space, aesthetic, and existence benefits. For each of these four services we sought indicators motivated by the following valuation concepts.

Primary demand. Ecosystem functions yield beneficial services only when there is demand for services. Demand for services arises when the ecosystem provides an amenity or helps avoid a disamentity. For an amenity (e.g., aesthetic enjoyment) to be provided, proximity to populations that benefit is a necessary condition for demand.[4] For a disamenity to be avoided there has to be such a disamenity (e.g., flood risks or water contamination) and a population that benefits.

Scarcity. Because scarcity increases the value of a service, indicators of scarcity and the availability of substitutes are important to an analysis of benefits. Scarcity indicators relate to the local prevalence of other wetlands. Substitutability indicators measure the abundance of other natural land uses that can provide similar services to those generated by wetlands.

Complementary inputs. Some services can be enjoyed only if accompanied by complementary landscape characteristics or infrastructure. This is particularly important for recreation, where access is a key determinant of the ability to enjoy the service.

Risks and changed conditions. A site's value is largely a function of the benefits it will generate in the future. Future benefits depend on risks to the biophysical functions

[2] Formally, this means that we hold constant the vector **u**, a significant simplifying assumption. It assumes away the difficulty or cost of guaranteeing biophysically effective restoration, although we recognize this as an important issue (National Research Council, Brown and Veneman).

[3] Boundaries are needed to define the likely users of a service, areas in which access to a service is possible, and the area over which services might be scarce or have substitutes. We use different spatial scales for different services and data types: the local neighborhood, watershed, floodplain, or county.

[4] The only exception is the existence value of species, where demand does not depend on proximity.

Table 1. Primary Demand

Site	Crop and Pasture Land in Vicinity (%)	Impervious Landcover in Vicinity (%)	Distance to Nearest CAFO	Watershed in Crop and Pastureland (%)	Watershed Impervious Groundcover (%)
1	36	23	8.9	13	14
2	0	14	10.5	24	6
3	0	4	10.3	13	14
4	27	2	4.2	24	6
6	25	30	9.0	13	14
7	0	8	2.6	4	10
8	0	11	3.3	24	6
9	36	3	7.0	3	4
10	0	3	10.5	13	14
LPI	0	0	2.5	0	0

provided by the site and changes in demographic conditions.

Income and equity. Distributional concerns may be important in the analysis of trades. Movement of sites toward, or away from, socio-economically disadvantaged sites is relatively easy to detect with GIS analysis.

In our larger study, we derive twenty different sets of indicators, a set for each of the five valuation categories and each of the four services. Each of the indicator sets is applied to the bank site and its associated impact sites in order to assess the extent to which service benefits are lost (or gained) by the transfer of wetland acres to the bank.

A Service Analysis—Improved Drinking Water Quality and Abundance

Here we present a small sample of indicators related to one service: improved drinking water quality and abundance to illustrate the choice, organization, and interpretation of landscape benefit indicators.

Primary demand. Several conditions are necessary for a site to create drinking water benefits. A necessary condition is that the site be hydrologically connected to an aquifer used for drinking water.[5] Assuming that condition is satisfied, a wetland's ability to increase recharge and purify incoming water becomes increasingly valuable as more and more people use the water for drinking and as the water entering the wetland becomes more and more polluted. Accordingly, primary demand indicators take two general forms: indicators of land uses likely to generate drinking water contamination and indicators of local demand for well-drawn water (see table 1).

Developed land uses with a high proportion of impervious surfaces and agriculture, particularly confined animal feeding operations (CAFOs), are likely sources of water quality problems due to runoff. The first three indicators characterize these conditions locally, within a 1/2 mile radius of the site.[6] Additional indicators describe conditions at a larger, watershed scale.

Potential sources of water contamination are a necessary, but not sufficient condition for there to be drinking water quality benefits. The water must also be used for drinking, or at least commercial or agricultural use. Aggregate demand for drinking water improvements is a function of the number of persons drawing water from aquifers fed by surface waters improved by a wetland site. The first three indicators in table 2 describe the number of wells within a 1/2-mile radius of the sites. While aquifers may be recharged by wetlands located throughout the aquifer's recharge zone, wetlands in close proximity to wells are likely to be particularly valuable as a means of preventing local drawdown and contamination (U.S. Corps of Engineers).[7]

Permitted wells include agricultural and industrial wells. Because public drinking supply

[5] Except for Little Pine Island, all of the sites in the case study satisfy this basic condition. The fact that LPI does not is a strong indicator that mitigation has not replaced lost drinking water quality benefits.

[6] All subsequent vicinity calculations are based on a circular neighborhood with 1/2-mile radius.

[7] Drawdown refers to lowered water tables that occur in the vicinity of a well when pumping rates exceed the rate at which water can flow in from the surrounding aquifer.

Table 2. Primary Demand and Scarcity

Site	Permitted Wells	Vulnerable Public Wells	Private Well Density	Wetland in Vicinity (%)	Watershed in Wetland (%)	Watershed Nonagr. Natural Land Use (%)
1	9	0	16.9	0	8	20
2	1	0	0	65	36	60
3	1	0	0	87	8	20
4	11	1	33.0	17	36	60
6	16	0	153.6	0	8	20
7	0	0	22.2	0	16	37
8	0	0	60.1	60	36	60
9	40	0	4.4	0	34	72
10	2	0	0	85	8	20
LPI	17	0	0	78	91	100

wells require good water quality and serve many people, we isolate the number of these wells in the second drinking water benefits indicator. A further refinement is to count only public supply wells that are "vulnerable," defined as those drawn from relatively shallow aquifers (shallow aquifers being more susceptible to contamination). Information on the number of private drinking wells is available from the census and is summarized in the third indicator. The density of such wells is depicted in figure 1.

Scarcity. The indicators already described depict threats to water quality and the number of persons demanding drinking water. Sites, such as site 6, which score relatively high on these dimensions, are likely to be valuable. But before arriving at such a conclusion, it is important to explore the degree to which wetland functions are scarce in the site's vicinity. If nearby wetlands are abundant, the loss of one wetland may not lead to a significant loss of water quality benefits. If wetlands are scarce, the service lost with the wetland will tend to be more valuable.

The last three indicators in table 2 describe functional scarcity. At different scales, the percentage of local vicinity and its watershed that is wetland describes the scarcity of wetland functions. The nonagricultural, natural land-use indicator describes landcover that can act as a substitute for certain wetland functions, such as groundwater recharge (U.S. Corps of Engineers).

Risks and changed conditions. A site's benefits are also a function of future demand conditions and risks to the site's biophysical functions.

Wetlands can be degraded over time through a variety of natural processes. For example, exotic species invasions can significantly degrade the functions normally associated with wetlands. Invasion by woody exotic species (melaleuca, Brazilian pepper, Australian pine) can lower the water table and potentially allow saltwater intrusion. All else being equal, the closer and denser such communities are, the more likely it is that they will propagate onto a site. The first two indicators in table 3 describe the proximity of exotic communities and thus index the risk of exotic invasion. Other risks include the risk of flooding due to hurricanes and future sea-level rise. Low-elevation sites, and particularly low-elevation coastal sites, are more vulnerable.

County planning data speak to the likelihood of changes in economic, demographic, and cultural conditions that can alter the sites' benefits.

Future land-use changes, such as planned, new impervious groundcover, speak to future water quality threats, and hence the benefits of wetland services.

Income and equity. Particularly for drinking water improvements, environmental justice issues may be of concern to decision makers. The income indicator describes median household income within the site's census tract. The race and ethnicity indicator describes the percentage of Black and Hispanic residents in the site's census blockgroup.

Indicator Interpretation

The indicators' purpose is to reveal characteristics of the sites' landscape setting that

Table 3. Risks and Changed Conditions and Income and Equity

Site	Distance to Exotic Community	Exotic Community in Vicinity (%)	Elevation (in feet)	Future Impervious Groundcover in Vicinity (%)	Median Income (in thousands)	Black or Hispanic (%)
1	2.1	0	5–10	35	26	9
2	1.8	0	0–5	0	30	4
3	0.7	0	5–10	0	30	4
4	0.1	8	15–20	0	32	8
6	2.1	0	5–10	29	30	4
7	1.3	0	10–15	0	37	0
8	0.3	1	10–15	0	30	0
9	0.3	2	5–10	0	22	1
10	0.4	1	0–5	0	30	4
LPI	0	18	0–5	0	n/a	n/a

are likely to affect ecosystem service benefits. The importance of landscape in this case study is clear—at least for the evaluation of drinking water benefits. The bank site receives no contaminated runoff from agricultural or developed lands. Moreover, the bank site is unpopulated and hydrologically isolated from wells used for drinking water. Even if there were water quality problems to be mitigated, the site produces no drinking water benefits because of its isolation from groundwater withdrawals.

From a trade and compensation perspective the question is, did the impact sites where wetland functions were lost generate drinking water benefits? The answer for some sites appears to be yes. Consider first landscape-related water quality threats. Here sites 1 and 6 are notable. For both sites, agricultural and developed land uses comprise more than 50% of the sites' immediate vicinity. Thus, nearby land uses are relatively likely producers of contaminated runoff. At the watershed scale, only sites 7 and 9 are in areas where there is relatively little agricultural or developed land use.

In terms of demand for well-drawn water, site 6 is noteworthy, being associated with by far the highest household drinking well density. Site 4 is also noteworthy due to the close proximity of a public water supply well. Site 8 has proximity to drinking water wells, but is a coastal site. This may limit its ability to purify runoff, but coastal sites tend to be well situated to help prevent saltwater intrusion of inland aquifers.

Indicators of future risk highlight threats to LPI's wetland functions and again identify sites 1 and 6 as being particularly desirable. Exotic plant communities already exist on and in close proximity to LPI.[8] In contrast, the nearest exotic infestations to sites 1 and 6 are relatively distant. LPI, being at a low elevation, is at risk from sea level rise as are the coastal impact sites. In terms of future land use, sites 1 and 6 are again distinctive. Planned development means that water quality improvements from these sites are likely to be in even greater demand in the future.

There are no obvious environmental justice implications of the trades. The nearest inhabited area to LPI (Pine Island, location of site 9) is at the low end of the income scale. Thus, the bank area is, if anything, moving wetlands toward lower income areas. Finally, all of the sites are in areas with relatively small minority populations.

To summarize, based on an analysis of our landscape benefit indicators, the LPI mitigation site scores quite poorly in terms of its ability to provide drinking water quality benefits. In contrast, two of the impact sites, 1 and 6, stand out as being particularly beneficial in both current and future development patterns. But all of the impact sites are likely to provide more drinking water benefits than the bank site.

Analysis of Other Services

The larger study included analysis of three additional services, flood protection, improved aquatic recreation, and provision of aesthetic, open space, and existence benefits. The following is a brief summary.

[8] While a performance bond is meant to ensure removal of invasives within the bank site, the difficulty of eradicating invasives suggests the risk of invasive regrowth will persist well into the future.

Flood damage avoided. In the analysis of flood reduction benefits, LPI again scores poorly. Because the island is hydrologically isolated and uninhabited and undeveloped, save for the road bisecting it, it is in a poor landscape position to supply flood-related benefits. For this service the landscape analysis focused on sites' hydrological characteristics, such as whether or not they were located in a floodplain. Also of importance are the density and value of residential, commercial, and industrial properties. Sites upslope of numerous and valuable properties can be expected to provide larger benefits than downslope sites in underdeveloped areas. The location of culturally important sites and infrastructure, such as roads, also played a role in the analysis. Several of the impact sites were in a good position to provide flood-related benefits.

Improved aquatic recreation. As described in the analysis of drinking water improvement, LPI does not score well as a source of surface water quality improvement. Since there is no agriculture and very little development on the island, there is relatively little demand for water quality improvement. Several of the impact sites were found to be much better located in relation to agricultural and development-related runoff problems, and several are in close proximity to both impaired coastal waters and seagrass beds, which are an important component of habitat for aquatic species. Accordingly, those sites are likely to be particularly valuable as providers of water quality benefits.

Provision of open space, aesthetic, and existence benefits. LPI is desirably located relative to rare and threatened species habitat. For this reason, the site can claim relatively high existence-related benefits, at least in relation to the impact sites. Also, because it is an island, there may be fewer man-made, future threats to the site's functions than for the other sites. However, it deserves emphasis that the mitigation bank did not create these characteristics, since the island was public land prior to its development as a mitigation bank. In terms of open-space recreation and aesthetic benefits, the case is less clear. Several of the impact sites are better situated with respect to park-like recreational access points and trails.

LPI's main advantage, based on landscape analysis, is as support for species existence benefits and recreational benefits related to the enjoyment of such species. Those benefits may outweigh LPI's poor performance as a source of drinking water, flood prevention, and aesthetic benefits. The indicators say nothing about the relative importance of these different characteristics, an issue to which we now briefly turn.

Conclusion and Discussion

When numerous indicators are generated, questions arise regarding their aggregation and interpretation. For example, we could have aggregated the multiple sets of service indicators into a single index to aid interpretation. In principle, aggregation of indicators into a summary index can be a boon to decision making. In practice, however, aggregation obscures information contained in a larger set of indicators.

Many aggregation methods depend on statistical meta-analysis to determine the relationship between individual indicators and social benefits derived from existing econometric studies of ecosystem service benefits (Murtaugh). Survey methods can also be used to elicit the value individuals place on the characteristics described by the indicators. Derivation of a relatively precise correspondence between indicators and social benefits requires this kind of methodological effort, an effort complicated by the complexity of the relationships being described.[9]

A weakness of indicator-based methods is that they do not easily allow for the analysis of trade-offs. Without a common metric, such as dollars, it is impossible to say whether a site scoring highly on one measure is better or worse than a site scoring highly on another measure. The ideal approach for comparing the value of different services is to monetize benefits associated with each service. Barring that, there are alternative methods to assess trade-offs, such as multi-attribute utility analysis (Keeney and Raiffa, Saaty). Multi-attribute utility analysis, using indicator data as an input, can quantify the degree to which sites achieve a broader objective in a way that is logically consistent with the values of the decision maker or community.[10]

[9] For example, most indicators will not be linearly or even monotonically related to benefits.

[10] Typically, this kind of analysis relies on expert groups to make technical judgments and working groups or survey methods to assess value judgments (Merkhofer and Keeney).

Notwithstanding these caveats and proposed extensions, landscape analysis can effectively combine economic valuation principles with existing data sources to improve understanding of the relative benefits generated by different ecosystems. Indicators can be used to evaluate the scarcity of ecosystem services in the landscape, the accessibility of sites for recreation and aesthetic enjoyment, future risks to the ecosystem, and the ecosystem's marginal impact on a larger area's provision of ecosystem services.

The study establishes a methodological middle ground between econometric valuation methods and purely biophysical site assessments. While lacking the sophistication of econometric valuation, the method's virtue is its relative simplicity. Relative to most ecosystem evaluations, which typically fail to explore sites' service-related differences, landscape indicators provide a more complete understanding of the portfolio of changes associated with trades. In particular, indicators can help reveal extremely good and extremely poor landscape scenarios for the provision of benefits. The case study, for instance, demonstrates that only a subset of the services lost at the impact sites were provided by the mitigation bank. Ideally, this kind of result should play a role in the regulatory analysis of ecosystem compensation.

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