Development and application of landscape-level indicators of freshwater wetland condition

Thomas E. Kutcher
NRS 534 Fragmented Landscapes
April 29, 2013

In this past decade, the United States Environmental Protection Agency (EPA) has been requiring states to develop methods to support reporting on wetland condition under the Clean Water Act. This has posed a challenge to state scientists and managers because wetland condition is conceptually vague and difficult to evaluate. To provide guidance, EPA developed and recommended a three level approach to wetland assessment and monitoring that employs landscape (level 1), rapid (level 2), and intensive (level 3) assessment methods. In many states, early methods development has focused on rapid and intensive assessments, even though landscape measures have been widely shown to strongly indicate water quality conditions in open surface waters, and can be automated to generate such measures over a broad area, quickly and inexpensively, via remote sensing.

Perhaps the main concern with remotely-sensed assessment is reliability, or accuracy in explaining environmental conditions over ecological noise. The effectiveness of landscape assessment can be tested empirically using correlation analysis against known-effective, existing rapid or intensive measures of wetland condition, but those measures have also been poorly-developed. Another likely obstacle to the development of landscape assessment methods is the interdisciplinary nature of the task. Developing landscape measures that will indicate wetland condition requires considerable ecological knowledge in both wetland and landscape sciences, and proficiency in operating geographic information systems (GIS). Although landscape processes have been considered in wetland ecology since its inception, modern landscape ecological theories and tools have only recently been applied to the science.

Early efforts venturing into this interdisciplinary realm focused on proportional composition of land cover classes from categorical vector data. Brooks et al (2004) applied a simple landscape metric based on the percent of forested cover within a fixed 1-km radius of a wetland. The authors applied the intuitive assumption that wetlands will be disturbed in direct proportion to the amount of disturbance in the surrounding landscape. While this assumption is sound, no substantial validation of the effectiveness this metric was offered. In contrast, the Landscape Development Intensity Index (LDI), developed by Brown and Vivas (2005), is based on the relative proportions of a broad range of land cover classes, and was tested rigorously by the authors. Each cover class is assigned a coefficient related to land use intensity, and the LDI is generated by weighting the coefficients by proportional areal cover. Although perhaps not as straightforward as the % Forest metric, the proportional weighting of land use intensity clearly increases the capacity for more precise characterizations of the surrounding
landscape, over forested area alone. Brown and Vivas found that the LDI explains a meaningful proportion of environmental variability in wetlands. Rigorous landscape analysis additionally revealed other important information about landscape assessment. Specifically, the study suggests that the predictive power of landscape assessment is largely a function of patch composition, is dependent on spatial extent, and is not significantly influenced by patch configuration within any tested scale.

In subsequent years, no studies have successfully improved upon the LDI model. In an analysis testing the LDI in concert with rapid and intensive assessment methods in Ohio wetlands, Mack (2006) failed to duplicate the originally-demonstrated predictive power of the LDI when he modified the spatial extent to 1 km (following Brooks et al. 2004). Reiss (2006), on the other hand, put such faith in the original LDI as to apply it as a reference gradient in the development and calibration of an intensive plant-based biological assessment method. Reiss made no attempts to modify the metric. Later, Stein et al. (2009) applied the LDI as an independent measure in an inter-validation of a level 1-2-3 wetland assessment program for the State of California. This study investigated whether the LDI could be improved by applying it to upstream contributing waters. But again, Stein et al. found that LDI is indeed more depended upon patch composition than on configuration, and they could not improve on the simple area-weighted model recommended by Brown and Vivas (2006).

Remaining ever-faithful to their simple % Forest metric, Robert Brooks and his colleagues at Penn State presented a pair of studies analyzing variants of this metric in a special issue of Wetlands (Hychka et al. 2007, Wardrop et al. 2007). In the first article Hychka et al. attempt to improve upon the original metric by using it as the basis for multi-metric landscape models to be tested against an independent floristic biological indicator. But, the authors only report on whether significant improvement of predictive power is achieved and not on the coefficient of correlation (i.e. the predictive power) for any model. A vague table suggests that few of the metrics more than modestly correlated (r > 0.50) with floristic bioindicator, so my confidence in their combined effectiveness is accordingly low. Additionally, the improved model requires analysis of land cover patches within multiple buffer configurations and scales, which may be cumbersome to operationalize. In a separate, but related study, Wardrop et al. (2007) use the same floristic indicator to designate five categories of condition and apply them to calibrate their unimproved % Forest index among those designations; this implies a bold assumption of improbably-high precision in reflecting wetland condition for both of the measures. It further assumes strong agreement between the two measures, which was not explicitly reported by Hitchka (2007).

Few attempts to produce landscape-level measures of wetland condition beyond the % Forest and LDI metrics have been published. Weller et al. (2007) used an inferential data-mining approach and regression tree analysis to patch together models using landscape variables that correlated with a field-based wetland condition index. The authors found that various landscape measures can explain multiple separate functions
in two particular wetland classification types. But, the models generally require analysis of multiple datasets at varying scales, complicating their use. Mita et al. (2007) also used an inferential approach to test the effects of spatial pattern on wetland condition. Specifically, they developed various models, generated from 10 metrics derived from FRAGSTATS, against a plant-based bioindicator. Mita et al. standardized spatial extent by testing all models within a 300-m radius of the wetland centroids. Findings of this study support earlier indications that patch composition is more important than configuration at a given scale.

Most recently, Rooney et al. (2012) presented a true landscape-ecological analysis of the influence of spatial extent on the effectiveness of landscape-level wetland assessment measures. These authors used metrics from categorical land cover data and road density to develop parsimonious models that best explain the variability of previously-validated floristic and songbird bioindicators at spatial scales ranging from 100m to 3000m. Many of their most-predictive models include road density, and urban and agricultural land covers. Additionally, % cover of forest (see Brooks et al.) was (understandably) a contributing variable in the best-fit predictive model for the songbird bioindicator. The most predictive spatial scale for floristic integrity was the 100-m buffer, whereas the most predictive scale for the bird index was 500 m. Additional findings indicate that more complex models clearly outperform simple models at most spatial scales. This study provides straightforward and useful new information about the landscape assessment of wetland condition, and strongly supports previous findings that patch composition and spatial scale are important factors to consider.

The science of assessing wetland condition from the landscape scale has clearly advanced in the last decade, since Brooks et al. (2004) introduced their % Forested metric. But, with few researchers actively participating in this fraction of wetland-landscape science, we are just beginning to understand the mechanisms that link landscapes to wetland condition. Identifying gaps in this effort will likely continue to be an iterative process. However, important principles in ecology and methods development can be induced from the studies presented here.

Several ecological principles have risen to the top in this past decade and can be summarized as follows:

1. Wetland condition is clearly a function of the composition of land use / land cover patches. Every study cited supports this hypothesis.
2. The predictive power of landscape assessment depends on the spatial extent of the analysis. More proximate extents (e.g. 100 m) generally outperform broader extents (e.g. 1 km), but the specific scale may depend on the specific ecological function of wetland condition being considered (e.g. plant versus songbird species composition in Rooney et al. 2012).
3. Patch configuration within a given spatial extent is less important than composition. Multiple studies demonstrated this outcome, whether explicitly

4. Metrics that incorporate multiple functional landscape variables outperform simple models based on a single landscape variable. Hychka et al. (2007) improved the % Forest metric (Brooks et al. 2004) by adding other landscape metrics. Rooney et al. (2012) demonstrated directly that three to five-metric models outperformed the best-fit single-category model at every spatial extent. And, the multi-category LDI has been a popular and effective landscape assessment measure for multiple applications.

Study design and details are important when developing and testing landscape indicators; lessons demonstrated in these studies can be summarized as follow:

1. It is critically important that the measure (metric or index) against-which a landscape index is developed and tested is ecologically sound in representing general wetland condition, i.e. it must act as a trusted independent variable in analysis. Many types of rapid and biological indicators were used in these studies, and while some were objective and validated a priori, others were certainly no better tested or based on more ecologically sound theory than the dependent model.

2. While an inductive approach to problem solving can provide a good deal of useful empirical information, data-mining through every conceivable landscape metric is seldom successful. Variables specific to the study sample, unrelated to wetland condition, or redundant with other measures will too-often confound the relevant mechanisms. And while regression tree and PCI analysis can increase parsimony by reducing redundancy, the resulting measures can sometimes be hard to explain or cumbersome to operate in a GIS. Using landscape and wetland ecological theory to inform model development may be the best method to ensure effectiveness.

3. More work can be done. Rooney et al. (2012) have recently demonstrated that the LDI is not the singular or ultimate answer to landscape assessment for wetlands, and that the ideal spatial extent may vary with the specific question of concern. More practical studies like this need to be conducted to improve our understanding of the processes by which changes in landscape condition influence wetland condition.
Brooks et al. present and demonstrate a simple landscape-level (Level 1) approach to assessing wetland condition using remote-sensing. The approach applies categorical land use data and GIS to quantify the proportion of forested cover within a 1-km polygon surrounding wetland centroids. This proportion is used as a landscape index of wetland condition and averaged per watershed to act as a landscape metric of watershed-wide wetland condition. While I don’t doubt that the integrity of the surrounding landscape influences wetland condition, the authors offer no evidence that their metric is indeed a viable indicator. Rather, they base the paper on an unsupported assertion that land-use patterns “are usually correlated with landscape and wetland condition”, citing two papers that look at bird communities in uplands and sedimentation in wetlands, respectively. Although they refer to conducting a finer-scale, ground-based (Level 2) assessment for some of the wetlands in their study, the authors offer no analysis of inter-method correlation, but instead state that closeness in the scores from the landscape and ground-based assessments for one of the seven watersheds assessed suggests their method’s viability. Weakening their case further, their ground-based metric included the landscape metric as a component. The authors conclude that their method has sufficient rigor to be used as a planning tool.


Brown and Vivas present an excellent analysis of their new Landscape Development Intensity index (LDI), designed to indicate the ecological condition of landscapes and patches, including isolated wetlands. The LDI uses categorical land use/land cover data and GIS to generate an index of development intensity based on the relative amount of unrecoverable energy (emergy) expended by the various land uses. The LDI applies an emergy coefficient to each of 27 LULC categories and the index is generated by calculating the average of the coefficients, weighted by the proportionality of their associated categories within an area of concern. For wetlands, the authors recommend using a fixed 100-m buffer surrounding the wetland as an indicator of condition, based on analyses showing no difference in LDI scores among this size and larger areas (200m and 500m), and no difference within 100-m using distance-weighted versus simple area-weighted models. The authors then demonstrate strong, highly-significant correlations between the LDI and an in-wetland rapid assessment index, and with nitrogen and phosphorus concentrations in the receiving wetlands. The emergy coefficients are based on theoretic energetics, rather than more straightforward functional-ecological principles, and both coefficients and land use categories are assigned more finely than
seems necessary. However, the results are compelling and the LDI seems to work well as presented.


Working with Brooks and Wardrop (see Brooks et al. 2004; Wardrop et al. 2007), Hychka diverges drastically from the simple landscape assessment approach employed by her colleagues. Brooks (2004) originally used the % forest cover within a fixed 1-km radius as an indicator of wetland condition, based on largely untested assumptions. Using the % forest metric as a starting point, Hychka rigorously develops and tests 47 landscape metrics against a number of in-wetland measures, including the Floristic Quality Assessment Index (FQAI), exotic species cover, and physical measures, at two concentric buffer scales and three upstream scales. Landscape metrics were run through a screening process that selected metrics by correlation with singular and combined in-wetland metrics, lack of redundancy, and contribution of new information. Hychka concludes that the original % Forest metric could be improved by adding additional landscape information, but offers no sense of how strong the resulting associations are. A weakness of this approach is that the resulting best-fit model may be complex and cumbersome to execute in GIS because it combines metrics from various datasets at varying buffer scales, including stream buffers and upstream contributing watersheds, for each wetland. Additionally, some of the in-wetland metrics, against which the models were tested, were not clearly relevant indicators of wetland condition; the metrics that correlated best with landscape measures were FQAI and % exotic species, predictably. I suspect that a landscape model fit against only those two metrics would be a more relevant indicator of general wetland condition than models fit against the total combined in-wetland measures. However, this study provides a good deal of useful information on the spatial-functional mechanisms that drive the associations between landscape and wetland condition.

Mack JJ (2006) Landscape as a predictor of wetland condition: an evaluation of the Landscape Development Index (LDI) with a large reference wetland dataset from Ohio. Environmental Monitoring and Assessment 120:221-241

In this paper, John Mack tests the Landscape Development Intensity index (LDI, see Brown and Vivas 2005) against various finer-scale assessment metrics across 166 wetlands of various types. Mack chose to ignore the LDI authors’ validated recommendations of using a fixed 100-m buffer surrounding the wetlands, and instead chose to use a 1-km buffer in which to run the LDI model. Mack adapted the LDI to utilize available categories from Ohio LULC datasets. Index results were run against the Ohio Rapid Assessment Method (ORAM) and variants of a vegetation indicator of biological integrity (VIBI), all of which were developed by Mack. Mack found modest significant correlations between the LDI and the VIBI for forested and emergent wetlands, but not for shrub wetlands. He also found a significant, but weak, non-linear
relationship between the LDI and ORAM. Mack’s modest results must be considered in the context of certain confounding factors. Foremost, the ORAM model strongly weights wetland attributes that do not necessarily measure condition, such as diversity, wetness, size, uniqueness, and social value. And his VIBI, which was developed and calibrated against ORAM, heavily weights richness, which confounds condition assessment due to area-species covariance and intermediate disturbance (non-monotonic) effects. Additionally, Mack concedes that he may have had better results if he had used a smaller buffer area, citing the LDI authors. I suspect that the effectiveness of the LDI as a wetland indicator was underrepresented in this study due to these oversights by the author.


Mita et al. present a unique study focusing on the development and testing of a landscape indicator of wetland condition based on spatial pattern. Using categorical data and GIS, the authors develop landscape models using 10 spatial-pattern metrics derived from FRAGSTATS. Models are tested, within a 300-m radius of each of 73 wetland centroids, against a plant-based IBI. Of these ten metrics, only two showed potential as indicators of condition, these were Core Percent Land of grassland and Largest Patch Index of grassland. These results clearly indicate that the proportion of natural grasslands was the most influential landscape factor in the model, suggesting that wetland condition is more sensitive to landscape composition than to configuration. This and other useful information is partly undermined by the authors’ questionable claim of demonstrating a strong connection between wetland condition and landscape pattern, and by their over-analysis of straightforward data, results, and concepts.


Reiss used the LDI (see Brown and Vivas 2004) to develop and calibrate a multi-metric vegetation index (IBI) for Florida. The LDI was developed as a landscape model that could provide a coarse, indirect indication of wetland condition when applied to a surrounding buffer. Applying the LDI as the reference measure against which a more rigorous measure is calibrated is inconsistent with the general multi-level approach to indicator development, which generally considers biological indices to be the most reliable measures of condition. A better approach to this study would have been to assess the vegetation metrics comprising the IBI, separately, as independent measures of condition, based on their inherent ecological principles. Indeed, the FQAI and (proportion of) exotic species, both components of the IBI, have been empirically tested and validated on their own independent merits as effective indicators of wetland condition. Both of these were shown here to strongly correlate with the LDI nearly as well as the full vegetation IBI. And, as a result of their inter-calibration, the multi-metric
IBI cannot be applied as an independent and supporting measure to the LDI. Further, other measures incorporated in the IBI are redundant with the FQAI and exotic species. Specifically, the metrics tolerant species and sensitive species are inverse variants of the same measure that is the basis of the FQAI model (conservatism, or species sensitivity to disturbance); and native species is the approximate inverse of exotic species. In spite of these deficiencies, this study is loaded with useful information, and it bolsters my confidence in the LDI, FQAI, and % exotic species as indicators of wetland condition.


Rooney et al. present an excellent study analyzing the effectiveness of various landscape-scale wetland assessment metrics in predicting floristic and songbird IBIs at various spatial scales. The authors used categorical land use/land cover data and GIS to develop landscape models, based on the proportions of various combinations of LULC classes and road density, that would best predict previously-validated IBIs at 45 wetlands. Best fit was determined based on lowest AIC and highest coefficient of determination ($r^2$) value at each of seven nested buffer zones ranging from 100m to 3000m. The authors were careful to account for the effects of spatial autocorrelation and multi-collinearity, and even (as an exercise) removed the influence of location (although not applied in the other analyses). A simplified landscape assessment model quantifying the proportion of undisturbed land was also tested for efficacy across the spatial scales for each IBI. Complex models outperformed the simplified model, explaining 70 to 82% of IBI variability; but even the simple (independent) model explained about 60% of IBI variability at the most effective spatial scales. This paper empirically demonstrates the strong associations between wetland condition and surrounding landscape condition that had previously been unclear, and how those associations are dependent upon spatial extent and other spatial variables.


In this excellent paper, Stein et al. test the California Rapid Assessment Method (CRAM) of wetland condition against a number of biological assessment methods and against the LDI. CRAM includes four measures of buffer and landscape condition that were tested against the biological measures. Stein et al. found that individual and combined CRAM landscape measures were modestly correlated with % cover of exotic species, a benthic macroinvertebrate IBI, and species richness of non-riparian species. Additionally, they found modest, significant correlations between CRAM and its various components versus the LDI within a 200-m buffer and within 500-m upstream. The simpler 200-m buffer performed as well or better than the 500-m upstream variant of the LDI. The authors’ use relevant analytical methods, present clear results, and
generate a wealth of useful information. Their paper is well-conceived and well-written and provides an excellent model for index development and testing.


Wardrop et al. apply the proportion of forested cover within a 1-km buffer (sensu Brooks et al. 2004) to a study designed to demonstrate a widely-recommended (by EPA) multi-level protocol for the assessment of wetland condition. Additionally, they use FQAI, a plant community-based indicator, to calibrate the landscape metric and a rapid assessment method. This study comes from the same group as Brooks et al. (2004) and they again fail to clearly support assertions of the effectiveness of their simple landscape metric with empirical or qualitative evidence (but see Hychka et al. 2007, in the same issue of Wetlands). While the authors’ statistical methods are impressively complex, they do not provide clearly useful information. The authors’ calibration of their landscape measure to the FQAI index relies on an assumption that FQAI is adequately precise (i.e. lacking in ecological noise) and comprehensive in indicating wetland condition that it will generate five uniquely meaningful categories into which the distributions of the landscape measure should be allocated (and further assuming that their landscape measure is equally capable of such precision, once redistributed). As with other studies that calibrate one assessment level to another, some of the utility of the three-level approach may be diminished by the interdependence that results from calibration.


Weller et al. used a variety of statistical modeling methods to data-mine landscape variables and generate models that best predict a Functional Condition Index (FCI) of five wetland functions. This inductive approach produces a great deal of useful information on the associations between landscape composition and wetland condition. But, this study is flawed in two ways. Foremost, the FCI, against which all models are measured and developed, is based on best professional judgment of the condition of wetland hydrology, biogeochemistry, plant community, habitat, and landscape. Best professional judgment of such complex functions is a tenuous basis upon which to develop and test highly complex, quantitative landscape models with any degree of confidence. This study would have benefitted greatly from applying one or more of the many, tested, objective measures available (such as a variant of FQAI, see Reiss 2006). Second, the vast array of landscape characteristics that was mined to produce the models contained several variables that were redundant or irrelevant to wetland condition assessment. Landscape indices based on a priori ecological premise (e.g. LDI, see Brown and Vivas 2005), rather than broad empirical association, may serve as more
intuitive and relevant metrics because the mechanisms are theoretically understood. Interestingly, the Brown and Vivas study and the subsequent successful application of the LDI by Reiss (2006) were not cited in this paper. Weller et al. developed models that effectively explained variability in all five of the wetland functions in two hydrogeomorphic categories, but these models mix data types and scales and may be operationally unwieldy. Given that relatively straightforward landscape models had previously been shown to strongly predict wetland condition, this paper complicates an established, clear-cut ecological premise.