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Linking Critical Ecological Processes to Landscape Pattern: Implications for USACE Planning and Operations

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) presents a relational database that lists, describes, and links critical ecological processes to their associated landscape metrics and patterns. It is meant to provide a better understanding of the relationships between ecological processes and landscape pattern, which is critical for successful project planning and operations. Such a database is the first of its kind for U.S. Army Corps of Engineers (USACE) project-level assessment of potential impacts and benefits related to ecosystem functions.

BACKGROUND: As agencies move toward more environmentally sustainable paradigms of working with natural processes, understanding the complexities of landscape-level interactions across scales becomes critical. For example, the Engineering with Nature (EWN) initiative of the USACE is focused on designing projects that work with natural processes to create or restore landscapes that utilize natural functions and patterns. In the long term, the EWN effort not only reduces project costs but also increases environmental benefits gained from a project. For these projects to be successful, understanding the quantitative relationship between ecological processes and landscape pattern across temporal and spatial scales is paramount. Landscape pattern is an important driver in ecosystem dynamics and can control system-level functions such as nutrient and sediment cycling, connectivity, biodiversity, carbon sequestration, among others. These patterns are dynamic and evolve naturally over multiple time periods (decades to centuries) as a result of complex, multi-scalar interactions among climatic, ecological, and geomorphological processes. As landscape pattern changes, ecological processes can be altered and in turn affect or change the functions of the ecosystem. Currently, the links among process, pattern, and function remain ambiguous, making management and design of ecosystem-level projects difficult.

Recent advances in remote sensing and Geographic Information Systems (GIS) have led to increased capability for quantifying landscape pattern, through the use of landscape metrics, which is essential for relating spatial patterns to ecological processes (Reif and Swannack 2014). Landscape metrics provide a system-level, quantitative summary of the landscape structure and various processes at both landscape and ecosystem level (McGarigal et al. 2012). Further, these metrics can be correlated with ecological processes, such as biodiversity or sediment cycling, which can provide USACE planners and operations personnel with the ability to quantify the impacts and benefits their projects may have on the ecosystem of interest.

METHODS:

Ecological Process and Landscape Metric Identification. In order to lay the foundation for establishing links related to critical ecological processes, a number of review papers focusing on linking landscape measures to ecological processes published within the last decade were consulted (Reif and Swannack 2014; Uuemaa et al. 2009). In addition, literature searches were compiled using ISI Web of Science (Web of Knowledge) using these terms: "ecolog*", "process*", landscape, and model. The search, limited to the most recent 2 years (2012, 2013), identified 75 references. For each reference, it was determined whether an ecological process was described, and the following information was compiled (as available):

- name of ecological process,
- temporal and spatial scale of process measured within the study,
- metric used to measure the process, and
- habitat in which the study was conducted (e.g., salt marsh, riparian corridor).

Each specific ecological process was assigned to one of 23 broad categories (e.g., Nitrogen Cycle, Water Cycle, Primary Production). In addition, ecological processes were categorized using the United Nations Environment Programme (UNEP) Millennium Assessment designations for ecosystem services: Supporting, Provisioning, Regulating, or Cultural (UNEP 2005a; UNEP 2005b). While this system of goods and services categorization provides a good starting point, it can lead to problems of double counting when benefits are assessed (Tazik et al. 2013). Current USACE efforts to incorporate ecosystem goods and services into environmental planning also involve the process of developing a new classification scheme; the nomenclature proposed in the database will be updated once a new scheme is identified (Murray et al. 2013; Tazik et al. 2013).

Using the same library of literature, associated landscape metrics were identified, including metrics identified in the software program FRAGSTATS v.4, which is a commonly used program for computing landscape metrics to map corresponding patterns (McGarigal et al. 2012). For convenience, metrics were also categorized according to attributes following standard designations (e.g., those used in FRAGSTATS such as area/density/edge, shape, connectivity, etc.). A landscape pattern designation was also assigned to each metric. Landscape pattern designations describe a pattern of the spatial configuration of the landscape, such as habitat fragmentation or habitat connectivity (i.e., spatial continuity of a habitat type across a landscape (Turner et al. 2001)). Landscape metrics, in contrast, describe the quantitative method in which a pattern is measured. As Kupfer (2012) describes, "Landscape metrics are quantitative indices that describe compositional and spatial aspects of landscapes based on data from maps, remotely sensed images and GIS coverages." As such, there can be multiple landscape metrics associated with a particular type of landscape pattern. For example, landscape diversity can be measured using landscape metrics such as Shannon Diversity Index, Simpson's Diversity Index, and Simpson's Evenness index, among others. These indices measure landscape richness or evenness by quantifying the proportion of the landscape in terms of the number of habitat or land cover classes (McGarigal et al. 2012).

Developing Relational Database and Establishing Linkages. In order to identify, organize, and quantify linkages between ecological processes and landscape metrics and patterns, a relational database was developed. Table 1 defines the fields that were selected to organize and describe the processes, patterns, and metrics similar to those identified in Uuemaa et al. (2009). Conceptually, the database describes the following: 1) ecological processes, 2) relevant landscape patterns and metrics, 3) specific studies, and 4) linkage of patterns, processes, and studies (Figure 1). Fields were selected to allow for queries of multiple levels of specificity with respect to ecological processes and landscape patterns. Each pattern and process can be defined using broad terms as well as specific ones, as listed in Table 1. In addition, each ecological process is linked to at least one specific case study.

Table 1. Description of fields in the relational database (Figure 1).

Table	Field	Description
Landscape Pattern Table	Pattern Type	Name of landscape pattern in question (descriptive).
	Pattern Metric	Specific approach used to quantify landscape pattern (alpha-numeric).
	Metric Category	One of 4 types of landscape pattern (Spatial Point, Linear Network, Surface, Categorical Map).
	Broad Metric Type	One of 12 categories describing broad aspects of landscape pattern developed from Fragstats software (descriptive); links to Ecological Process Table.
Ecological Process Table	Broad Ecological Process	One of 23 broad categories referring to groups of ecosystem processes (descriptive; see Table 3).
	Ecological Process Name	Name of specific ecological process (descriptive); links to Study Table.
	Ecosystem Goods & Services Category (UNEP)	One of 4 categories identifying type of ecosystem service provided by process (regulating, supporting, provisioning, cultural). Categories developed by UNEP through the Millenium Ecosystem Assessment (UNEP 2005a,b).
	Process Category	One of 5 overarching ecological process categories (biogeochemical cycling, community dynamics, energy flows, water cycle, other).
	Spatial Scale (process)	Spatial scale(s) encompassed by ecological process of interest (descriptive and numeric when possible).
	Broad Metric Type	One of 12 categories describing broad aspects of landscape pattern developed from Fragstats software (descriptive); links to Ecological Process Table.
Study Table	Study ID	Unique study identifier (numeric).
	Ecological Process Name	Name of specific ecological process (descriptive); links to Ecological Process Table.
	Temporal Scale (Study)	Time scale of analysis used in study (numeric).
	Spatial Scale (Study)	Spatial scale of analysis used in study (numeric).
	Study metric	Specific approach used to measure process in study (numeric).
	Habitat	Habitat in which study was conducted (descriptive).

In order to identify potential linkages or links that have been studied, detailed literature searches that cross each landscape metric with each ecological process were conducted. As a first order analysis, a broad set of searches was conducted by using 23 broad ecological process categories and 12 broad landscape metrics. These 12 broad landscape metrics were categorized according to standard designations used in FRAGSTATS (e.g., area/density/edge, shape, connectivity, etc.) (McGarigal et al. 2012). For each of the broad ecological process categories, a literature review was completed using the following databases within ISI Web of Knowledge: Web of Science, BIOSIS Previews, Zoological Record, and Journal Citation Reports. The process title was used as a key word in the search, followed by a subset search according to each broad landscape metric. Wildcard designations (*) were used in searches in which multiple word endings were appropriate (e.g., cycling, cycle, cycles). Links were identified as positive (existing or potentially existing) if at least one reference within each search described a relationship or tested whether the relationship existed. Links were identified as negative (nonexistent or not yet tested) when a search did not produce results, or the results that were produced did not use the terms appropriately.

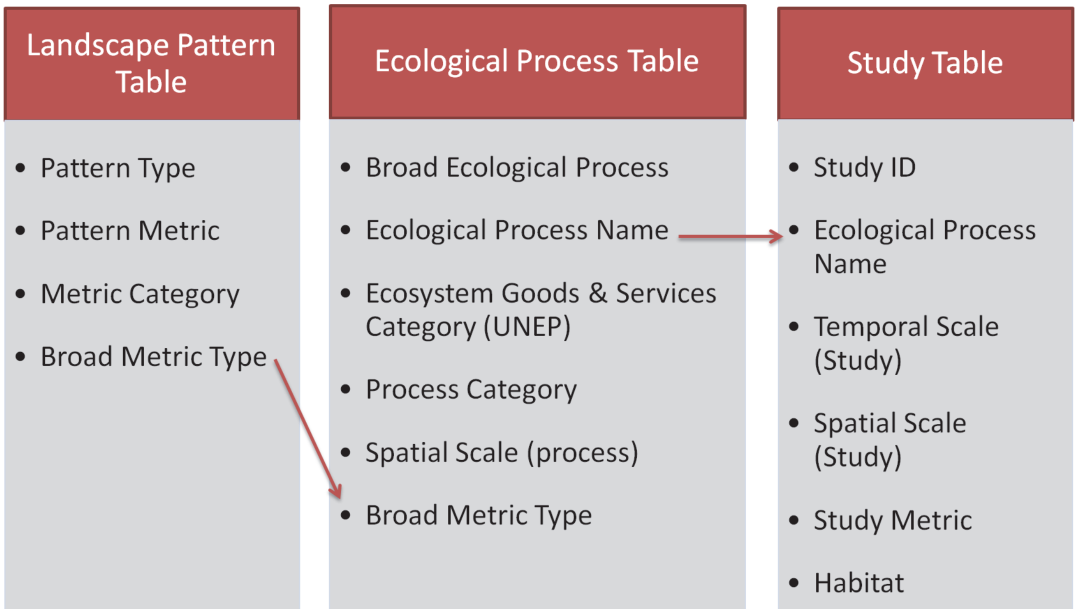

Figure 1. Conceptual schematic of relational database. Arrows represent fields that link one table to another.

Following the broad-based analysis described above, a detailed analysis using specific landscape metrics was completed. Within the 12 broad landscape metric categories, 74 specific landscape metrics were identified. As with the broad landscape metrics, the specific metrics are also standard in FRAGSTATS (e.g., patch area, patch perimeter, edge density). Examples of specific metrics and how they relate to broad landscape metrics are listed in Table 2. For these specific analyses, the same methodology was applied, but the searches were limited to the key words describing the specific ecological process crossed with each of the 74 different specific landscape metrics. Positive and negative link designations were determined following the same criteria as discussed above.

Table 2. Example of relationship between broad and specific landscape metrics. In total, 12 broad and 74 specific metrics were used to develop the relational database.

Broad Landscape Metric Type	Specific Pattern Metric	Description
Connectivity How landscape facilitates or impedes movement across resource patches.	Patch Cohesion Index Connectance Index Traversability Index	Measures of structural, potential, and realized connectivity through quantification of physical connectedness of patch types and joining between patches.
Contrast Magnitude of difference between adjacent patch types with respect to one or more ecological attributes.	Edge Contrast Index Contrast-Weighted Edge Density Total Edge Contrast Index Edge Contrast Index Distribution	Measures of the magnitude of contrast along a patch perimeter and edge per unit area at individual patch level as well as groups of patch type.

RESULTS AND DISCUSSION: Out of 75 references dealing with ecological processes and landscape patterns, 31 studies were identified, containing 68 specific ecological processes that were measured or modeled. These 68 processes were assigned to 23 broad ecological categories that are directly relevant to USACE projects (Table 3). Details of specific studies were collected in a Study Table that is part of the relational database (Figures 1 and 2).

Table 3. The 23 broad ecological categories for use in assessing project-level impacts and benefits established in the relational database.

Broad Ecological Process	Description
Animal Behavior	Behavioral processes of organisms in relation to landscape pattern.
Animal Dispersal and Population Movement	Dispersal and movement of animal populations, including threatened and endangered species. Organism flows across spatial heterogeneity, movement due to soundscape.
Biodiversity	Biodiversity patterns and dynamics including the following: species diversity and response to environmental change, species turnover saturation, and biodiversity loss.
Biomass	Flow of biomass across spatial heterogeneity, change in biomass in relation to environmental parameters.
Canopy Attribute(s)	Forest canopy attributes affected by landscape change including defoliation.
Carbon Cycling	Organic material (dissolved and particulate carbon) flux, and total soil C changes in response to landscape change.
Community Attribute(s)	Attributes including community nestedness/ patterns of species composition, commmunity abundance, community acoustic diversity, community assembly and succession.
Community Interaction	Species interactions such as the following: competition, predation, and conspecific attraction.
Disturbance	Dynamics of environmental disturbance at various spatial and temporal scales.
Energy Flow	Energy flows across spatial heterogeneity.
Food Web	Ecosystem shifts and subsequent food web shifts due to changes in animal or plant abundance/mortality or animal interactions and food availability.
Heterogeneity	Temporal, spatial, and environmental heterogeneity (dynamic habitat patches).
Invasion	Bioinvasion dynamics (at various spatial scales) including invasion spread due to landscape and environmental change.
Mortality	Mortality rates of plants, trees, and animals.
Nitrogen Cycling	Nitrogen mineralization, total soil N, extractable N, and N retention.
Nutrient Cycling	Ecosystem shifts in nutrients, nutrient return due to litter fall, and nutrient flux in response to disturbance (hurricanes), nutrient retention, and flux across biogeographic boundaries.
Phosphorus Cycling	Soil phosphorus concentration flux, phosphorus release and consequent influence on plant community succession.
Plant Dispersal and Population Movement	Plant or seed dispersal and population movement across heterogeneous landscapes (specialists vs. generalist responses) and plant pollination.
Population Attributes	Population abundance (relative to land use and ecological traits), population survival probability, population distribution probability, and acclimation potential.
Population Growth	Growth rate (e.g., fish stock growth rate including recruitment, survival, and growth).
Primary Production	Measures of productivity, ecosystem shifts in primary production, and above-ground net primary production (ANPP).
Sediment Cycling	Sediment flux.
Water Cycle	Water flux, water flow regulation, water clarity, quality, depth, and relation to habitat suitability.

Landscape Pattern

Pattern Type	Pattern Metric	Metric Category	Broad Metric Type
Habitat Fragmentation	Clumpiness Index	Categorical Map Pattern, Surface Pattern	Contagion/ Interspersion
Landscape Configuration	Patch Area	Categorical Map Pattern, Linear Network Pattern	Area/Density/Edge

Ecological Process

Broad Process	Process Name	Ecosystem Goods & Services Category (UNEP)	Process Category	Spatial Scale	Broad Metric Type
Biodiversity	Species Richness	Supporting/Provisioning	Community Dynamics	Local - Global	Contagion/ Interspersion
Sediment Cycling	Sediment Flux	Supporting/ Regulating	Other	Local - Global	Area/Density/Edge

Study

Study ID	Process Name	Temporal Scale	Spatial Scale	Study Metric	Habitat
3	Species Richness	1 week	30 Km^2	Shannon's Diversity Index	River
8	Sediment Flux	Daily tidal cycles	14,500 Km^2	$VS=\int_{tlow}^{thigh} CsQdt$	Salt Marsh

Figure 2. Example of relational database, tables, and links.

Figure 2 provides an example of the relational database, showing sample details for two ecological processes, Biodiversity and Sediment Cycling. The figure illustrates not only how the tables themselves are linked by way of common fields but also the relationship between ecological processes, patterns, and metrics. To describe the relationships in Figure 2, the Landscape Pattern Table is linked to the Ecological Process Table via the Broad Metric Type field, allowing queries to include both landscape pattern and ecological process and providing the critical capability to link the two. In this case, habitat fragmentation, a landscape pattern type, can be measured by the clumpiness index, a landscape metric. The clumpiness index falls into the contagion/interspersion Broad Metric Type and is linked by this field to the Ecological Process Table. As such, habitat fragmentation is linked to the broad ecological process of biodiversity via the contagion/interspersion entry in the Broad Metric Type field. Continuing with this example, ecological processes are linked to individual studies (i.e., references to studies in recent literature) via the Process Name field which is found in both the Ecological Process Table and the Study Table. In this case, species richness is included as a specific process name that falls within the broad process of biodiversity. The Process Name field is likewise used to link with the Study Table, which provides linkages or examples, to specific studies that focus on species richness (in this example, the study occurred in a riverine habitat). Results indicate that the broad process of biodiversity is tied to all 12 Broad Metric Types (also shown in Figure 3), encompassing 48 of 74 specific metrics, such as core area, contiguity index, and effective mesh size in addition to the clumpiness index highlighted in Figure 2.

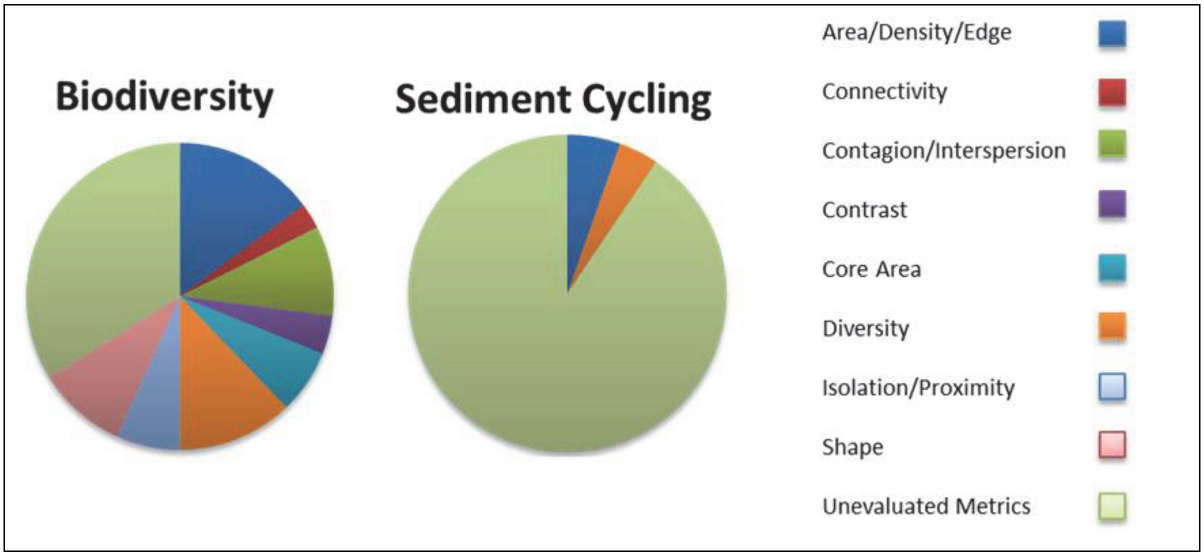

Figure 3. Distribution of broad landscape metrics that have been evaluated or described in current literature to characterize Biodiversity and Sediment Cycling. Links were identified using detailed queries of ecological process and 74 specific landscape metrics; results are displayed as the proportion of metrics within broad landscape category (some related metrics, such as area, density, and edge, are grouped in this example). Note that Biodiversity has considerably more linked landscape metrics described in the literature than Sediment Cycling.

Using broad categories to define both landscape metrics and ecological processes resulted in 288 possible linkages. Results indicate that 186, or ~65%, of those linkages have been evaluated or addressed in the relevant literature to date. This shows that there are clear differences in the extent to which linkages have been studied, depending on the ecological process of interest. For example, linkages can be expected between every aspect of Biodiversity and broad landscape metrics, while few linkages have been explored between Sediment Cycling and the same landscape metrics (Figure 3).

The results were refined by exploring the linkages between each ecological process and 74 specific landscape metrics. In total, there were 1,774 potential links between ecological process and landscape metric examined through literature reviews. Each ecological process revealed a unique suite of associated landscape links. For example, as illustrated in Figures 2 and 3, Biodiversity and Sediment Cycling displayed very different linkage profiles. For each ecological process, a maximum of 74 possible links could be identified. Evidence for 49 Biodiversity-landscape links and 7 Sediment Cycle-landscape links was discovered. These correspond to 66% and 9% of total possible links, respectively. These links were established from literature searches respectively comprised of ~174,000 and ~30,000 citations. Through the establishment of such links, planning and operations managers can begin the process of identifying potential ecological processes in their project areas as well as quickly see what patterns and metrics can be used to assess and quantify a particular process of interest. For example, including a broad category to describe the goods and services associated with each ecological process allows for a succinct way to interpret the impact or service a particular process provides. These designations can aid in identifying quantitative measures of goods and services provided by specific USACE projects.

The relational database presented in this Technical Note is designed to be useful throughout a project life cycle, including planning, operations, and post-project monitoring of the project site. As stated in Murray et al. (2013), it is critical to understand and identify problems and opportunities associated with goods and services in the formulation phase, or early in the project planning process in order to be fully informed about the project outcomes. The relational database described in this Technical Note offers a single inventory resource that can be used to help identify potential ecological processes that could be impacted as a result of a project action. Furthermore, a better understanding of the ecological processes in the project planning framework (especially in formulation and evaluation phases) would enable project designs that more comprehensively capture potential system-level benefits (i.e., not just habitat creation). The database not only offers a single resource for identifying potential ecological processes but also provides a capability to link those processes to associated patterns and metrics. These links, although still being studied by the research community, offer a way to assess and quantify project outcomes in the form of potential impacts and benefits. In this light, the database is also useful in the evaluation and accounting phase of the planning process (evaluation of alternative scenarios), whereby associated metrics can be quickly identified and used to help quantify the impacts/benefits each alternative will have on an ecological process. For example, if a project is going to impact biodiversity, then metrics such as habitat patch area, shape, and/or contagion (Figure 2) could be useful for quantifying impacts and benefits of different project alternatives. Likewise, when a beneficial use (BU) project is being considered, this database can provide operations managers with a quantitative-based estimation of the potential benefits they might derive from their projects. For example, if operations managers have an understanding that a BU project will alter the landscape, then they can use this database to determine which ecological processes will be affected. Furthermore, upon project implementation, this database can assist operations and planning personnel with choosing the appropriate metrics for post-project monitoring. USACE is often not involved with post-project monitoring, making it challenging to claim the long-term environmental benefits of ecosystem-scale projects, such as EWN, BU, or ecosystem restoration efforts. This database, however, provides operations and planning personnel with a tool that can quickly identify the appropriate metrics that can be used to monitor the ecological processes of interest.

SUMMARY: Although the purpose of this CHETN is to illustrate how the database alone serves to inform project planning by providing key relationships inherent in ecological processes, it will also serve as the foundation for future landscape modeling efforts. The overall project goal of future efforts is to develop an ecological model that will allow planners to further evaluate the critical processes identified for their project to forecast conditions and evaluate impacts and benefits. This will take the relational database to the next level of tools available for project planning, in which it will serve as the basis for establishing quantitative values and methods to link spatial patterns to ecological processes, and thus, proving it to be essential for the development of landscape evolution models. More specifically, the findings and relationships established in the database will be used to parameterize site-specific landscape evolution models to project how landscape pattern may change as a result of project activities. By including categories at different levels of specificity for both landscape pattern and ecological process, a variety of project development, impact, and forecasting needs can be addressed.

POINTS OF CONTACT: This CHETN is a product of the Navigation Systems (NavSys) Research Program at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Molly Reif (Voice:

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