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Wetlands Division
Washington, D.C. 20460

DEVELOPMENT AND APPLICATION OF FUNCTIONAL RECOVERY TRAJECTORIES FOR WETLAND RESTORATION

2006

DISCLAIMER

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PREPARED BY

Charles V. Klimas
Charles Klimas & Associates
Seattle, WA 98125

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This paper summarizes concepts that build upon the work of many people, beginning with the original authors of the U.S. Fish and Wildlife Service Habitat Evaluation Procedures and continuing with the teams of specialists who have produced many of the regional guidebooks to hydrogeomorphic classification and functional assessment of wetlands (HGM). In particular, Dan Smith (U.S. Army Engineer Research and Development Center), Bill Ainslie (Environmental Protection Agency Region 4), and Tom Roberts (Tennessee Technological University) have been central participants in discussions of how HGM reference data can be applied to projections of future conditions, and Dan Smith was a co-author of the Yazoo Basin HGM Guidebook which included trajectory curves for use in evaluating wetland restoration proposals. Henry Langston (Arkansas State Highway and Transportation Department) suggested the use of the Glaise Creek Mitigation Bank Site as a Case Study and secured the approval of the agency to conduct and publish an analysis of the area. Dr. Langston also participated in collecting the field data from the Glaise Creek site. Dana Klimas, Elizabeth Murray, and Travis Shea helped develop the figures used in this report.

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Introduction

Wetland restoration efforts are being undertaken nationwide for a variety of reasons, including compensatory mitigation in a regulatory context as well as programmatic watershed and ecosystem restoration projects. Typically, a variety of ecological benefits are attributed to these projects, including improvement or maintenance of water quality, wildlife habitat, and ecosystem processes. In most cases, it is infeasible to measure these benefits directly due to costs and the difficulty of separating the direct effects of restoration from natural variability and various unrelated changes occurring in the vicinity or elsewhere in the basin. Instead, the scope and design of mitigation and restoration projects often are based on simple acreage-replacement ratios or theoretical benefits that have little demonstrated applicability to specific site conditions and ecosystem recovery rates. Similarly, monitoring procedures and performance criteria generally are based on simple indicators of whether or not the restoration project establishes and survives as designed. Often, this amounts to little more than determining if planted vegetation maintains some minimal survival rate over the early years of establishment (Streever 1999).

In 2001, the National Academy of Sciences published a review and critique of compensatory mitigation programs and procedures employed to address the requirements of Section 404 of the Clean Water Act. In response, a federal interagency team developed a National Action Plan (2002) that included increased attention to mitigation planning, design, performance monitoring, and adaptive management. That Plan specifically recommended the use of functional assessment approaches to guide and track wetland mitigation project planning and performance..

The principal tools available to assess the functionality of wetlands compare field indicators of ecosystem function against a standard of comparison to produce an index of functional performance. Index values can then be directly compared for pre- and post impact conditions, or multiplied by some measure of area (e.g. acreage) to compare among areas of differing sizes and levels of functional performance. Index-based approaches also can be used to calculate how functionality will improve over time if the values of the indicators can be predicted at intervals as the restored area develops. This requires the development of "recovery trajectories" for the indicators used to construct the functional indices, and particularly for indicators that can be measured periodically to monitor site development and set performance standards.

A major advantage of using functional trajectories in mitigation planning and design is that trajectories can help define and quantify temporal lags in the development of full functionality on mitigation sites. Figure 1 presents a simple example of this concept, where functionality lost within an impact site is offset by restoration of a mitigation site and subsequent maturation of that site over a 100-year project life. In this case, the time required for the mitigation site to achieve a level of function equal to the impact site yields a net functional deficit represented by area A. However, the mitigation site eventually exceeds the impact site in overall functionality (either by virtue of a larger size or higher level of function per unit area), thereby offsetting the temporal lag (area B). Area C represents direct offset of lost function. The net result represented in Figure 1 is a 1:1 replacement of functional loss over a 100-year period of analysis (which is a commonly adopted “life of the project” for mitigation planning).

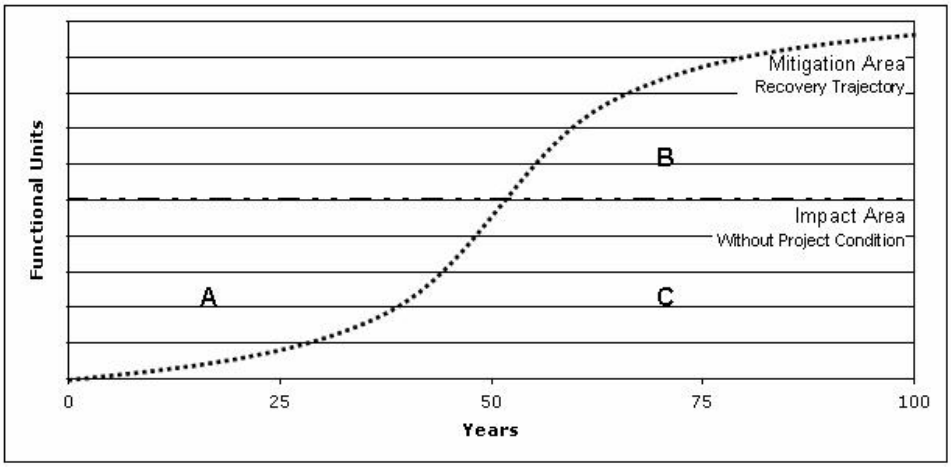

Figure 1. Recovery trajectory analysis illustrating direct 1:1 mitigation of loss of wetland functions ("functional units") over a 100-year period.

Figure 2 illustrates another possible use of trajectory analysis. In this case, areas A, B, and C represent temporal deficit, offset of deficit, and offset of direct losses, respectively, just as they do in Figure 1. However, the length of the temporal deficit has been reduced by increasing the rate of accrual of function on the mitigation site, which can be achieved by accelerating recovery through management, or more commonly, by increasing the overall size of the mitigation area. In this example, the time until the temporal lag (A) is offset by the net gain (B) is approximately 60 years, rather than the 100-year period required in the scenario depicted in Figure 1. Further, in Figure 2, there is an overall net gain (area D) in functionality over the life of the project. There are numerous possible variations on the types of scenarios illustrated in Figures 1 and 2, all of which can be better understood and quantified through the use of trajectory analysis.

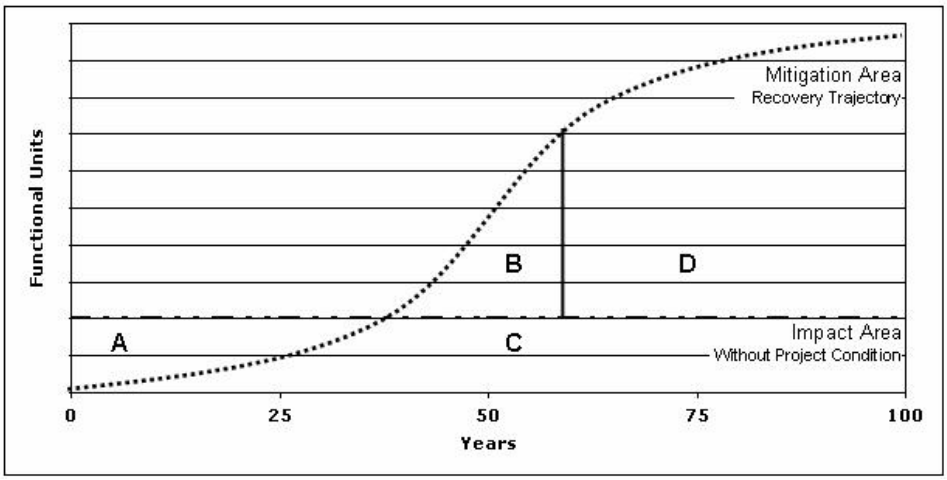

Figure 2. Recovery trajectory analysis of a mitigation site illustrating accelerated offset of temporal loss on an impact site and resultant net gains in functionality over a 100-year period.

One opportunity to collect recovery trajectory data and support the types of analyses illustrated in Figures 1 and 2 is in conjunction with the development of regional guidebooks for assessing wetland functions using the Hydrogeomorphic Approach to wetland assessment (HGM), which requires extensive regional sampling of reference wetlands (Smith et al. 1995). With little additional effort, the HGM reference sampling can include collection of the data needed to construct simple curves (trajectories) that predict change in assessment variable values over time following restoration. This has been done in conjunction with HGM guidebook development in all five of the physiographic regions of Arkansas (Figure 3) as well as the Yazoo Basin Region of Mississippi (Smith and Klimas 2002). The Arkansas Delta Region HGM Guidebook (Klimas et al. 2004) and trajectory curves are used in this document to demonstrate how recovery trajectories are developed and how they can be used in the context of HGM assessments. No other HGM effort has as yet included methods and data to support projections of future conditions on proposed mitigation sites or other restoration projects. This paper is intended to illustrate how future efforts to develop HGM guidebooks can be improved, and to suggest how similar methods can be used to increase the utility of other wetland assessment approaches.

Figure 3. Physiographic regions of Arkansas, which correspond to the areas covered by five HGM Regional Guidebooks and associated recovery trajectories.

Basic Components of the HGM Approach

Recovery trajectories are employed in the context of existing assessment approaches – in this case HGM – therefore a basic understanding of the HGM assessment approach is important to understanding how trajectories are developed and used. The following discussion briefly outlines some relevant concepts incorporated in the Arkansas Delta HGM Guidebook. Persons who wish to learn more about HGM assessment should consult overview documents such as Smith et al. (1995), and Brinson (1995, 1996). Bartoldus (1999) provided a review of other assessment approaches, including some that might be adapted to incorporate recovery trajectories.

The HGM assessment approach incorporates several components. Wetlands are first grouped into regional subclasses based on functional similarities, as represented by hydrogeomorphic setting. Thus, wetlands in isolated depressions function differently than wetlands on river floodplains in various respects. For example, a functional riverine wetland exports organic materials to downstream aquatic systems during floods, whereas a depression that lacks a surface connection to a stream does not perform that function. Therefore, a group of functions can be identified for each regional subclass, and other regional subclasses may not perform those functions, or may perform them to different degrees. Table 1 identifies the regional wetland subclasses and associated wetland functions included in the Arkansas Delta HGM Guidebook.

Table 1. Wetland functions assessed in each of six regional wetland subclasses included in the Arkansas Delta HGM Guidebook. A plus sign (+) indicates that assessment models and reference data are provided for the subclass and function. A blank cell indicates that the function is not assessed for that subclass.

FUNCTIONS	WETLAND SUBCLASSES, DELTA REGION OF ARKANSAS					
	FLAT	RIVERINE BACKWATER	RIVERINE OVERBANK	HEADWATER DEPRESSION	ISOLATED DEPRESSION	CONNECTED DEPRESSION
Detain Floodwater		+	+			+
Detain Precipitation	+	+	+			
Cycle Nutrients	+	+	+	+	+	+
Export Organic Carbon		+	+	+		+
Remove Elements and Compounds		+	+			+
Maintain Plant Communities	+	+	+	+	+	+
Provide Fish and Wildlife Habitat	+	+	+	+	+	+

In order to estimate the degree to which a wetland performs a particular function, HGM represents each function in terms of a simple logic model made up of variables that can be measured in the field or derived from existing information sources. Thus, for the example above, the ability of a riverine wetland to export organic carbon can be represented by the equation below.

$$FCI = V_{FREQ} \times \frac{\left[\frac{\left(V_{LITTER} + V_{OHOR} + V_{WD} + V_{SNAG}\right)}{4}\right] + \left[\frac{V_{TBA} + V_{SSD} + V_{GVC}}{3}\right]}{2}$$

In this case, the Functional Capacity Index (FCI) is a determined by 3 primary model terms.

1. Flood frequency (V_{FREQ}) which represents how often the wetland is inundated by overflow from a stream system, and provides the export mechanism for delivering organic carbon to the stream;

2. Detrital pools, comprising litter (V_{LITTER}), O-horizon thickness (V_{OHOR}), woody debris (V_{WD}), and snags (V_{SNAG}), representing the current and future availability of mobile particulate organic matter and sources of dissolved organic matter; and

3. Organic production sources, represented by tree basal area (V_{TBA}), shrub and sapling density (V_{SSD}), and ground vegetation cover (V_{GVC}), which represent the major sources of material that will replenish the detrital pools.

In order to run the models, the variable values must be determined or estimated. The flood frequency component can be estimated for a specific site based on gauge data, flood zone mapping, and similar sources. Information on living and dead vegetation can be obtained using standard forest sampling methods. Models used to assess all of the other function use similarly obtained information as model variables.

The FCI value generated by the assessment model is an index between zero and 1.0, where a value of 1.0 represents a fully functional condition. Under HGM methodology, the FCI is multiplied by a measure of the area of the wetland (e.g., acreage) to calculate the Functional Capacity Units (FCU) present for the Carbon Export function. This is essentially the same process used in the Habitat Evaluation Procedures (HEP) (U.S. Fish and Wildlife Service 1980), where indicators of habitat quality are combined into simple models to calculate a Habitat Suitability Index (HSI) and multiplied by a measure of area to produce Habitat Units (HU). There is one fundamental difference between the way these two assessment approaches are developed, however. Whereas the indicators employed in HEP models are calibrated based on literature and expert opinion, the calibration curves for HGM indicators are derived from extensive field sampling of reference wetlands.

The model variables employed in the assessment models are calibrated based on field data collected in the applicable wetland subclass. The calibration curve (also called the "subindex curve") for each variable in each subclass relates the variable value to an index between zero and 1.0, where the maximum value is that found in wetlands that represent the least-disturbed examples of the wetland subclass within the region. The shape of the calibration curve is established by sampling a set of wetlands that represent a range of condition classes between the least-disturbed, and severely disturbed. Figure 4 presents the calibration curves developed for the variables used in the production component of the Organic Carbon Export model discussed above, for the Riverine Backwater subclass in the Arkansas Delta Region. Similar sets of curves were developed for the other variables and wetland subclasses in the region (Klimas et al. 2004), based on sampling of more than 100 field sites.

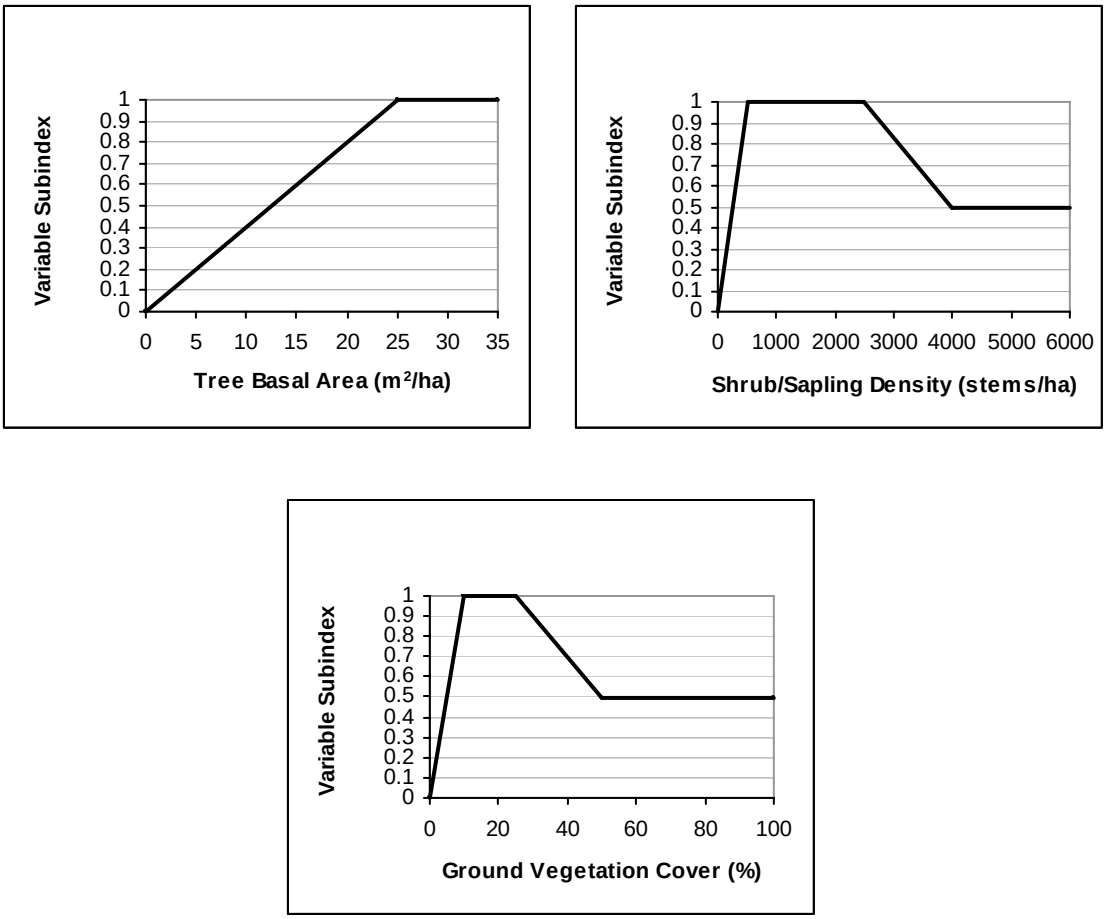

Figure 4. Subindex curves for 3 field indicators used as variables in the Organic Carbon Export functional assessment model.

As with all of the HGM guidebook development efforts, the Delta Region models, calibration curves, and application tools such as sampling methods and data summary spreadsheets were developed by a team of regional experts. Users of the guidebooks apply this information to specific assessment tasks, and can use the same models and reference data on various projects throughout the region. The models and calibration curves are applied in an assessment scenario by following detailed guidance presented in the Delta HGM Guidebook. The user collects field data from the assessment area, and compares that data to the calibration curve to derive a subindex. The subindex values are inserted into the model, generating an FCI for the function being assessed. Multiplying the FCI by acreage generates FCUs, which represent the functional units associated with the assessment area, and which can be compared among assessment areas of the same regional subclass. Pre- and post-project FCUs can be compared to determine impacts, and project alternatives can be compared to help identify the least-destructive alternative. However, in order to take into account the time required to recover functions following an impact or restoration actions, and to establish monitoring criteria that can be applied at intervals as the site matures, an additional set of curves representing recovery trajectories is required.

Recovery Trajectory Development

The reference wetlands used to calibrate HGM indicators are selected to represent a full range of "conditions" in terms of wetland functionality. The factors that may influence wetland condition vary depending on the regional wetland subclass under consideration. For example, the functionality of depression wetlands in prairie regions may be influenced most strongly by drainage, cattle grazing, and changes in fire regime, and the reference data collection effort would focus on identifying and documenting the characteristics of wetlands that are influenced to varying degrees by each of these factors, as well as wetlands that represent the least-disturbed condition relative to these factors. In practice, in forested wetlands of the Lower Mississippi Valley, the principal factors influencing wetland functionality are related to the hydrologic changes that have occurred on a massive scale across the region (drainage and levee construction), land use changes (clearing for agriculture) and forest management (both clearcutting and selective harvests). The first two of these are largely represented by "physical setting" variables. Flood reduction, drainage, and changes to soils (leveling, filling) have effects that can be described as essentially static for the foreseeable future, or that can be modified to a new static condition as part of a restoration effort (e.g., flooding can be restored by filling ditches, fill can be removed, or microtopography can be restored by surface contouring prior to planting). However, most of the other variables that relate to community structure and vegetation composition can be expected to follow predictable trajectories of recovery following restoration. In practice, this generally means that a restored forested wetland with all physical factors intact will gain function over time, and will be fully functional when it has reached a "mature" (or equilibrium) structure and composition. The gain in function may not be linear for all functions, but the changes in indicators will proceed in a consistent manner until the equilibrium condition is reached.

The approach used to create the functional recovery curves is to index a subset of sampled stands to their time of initiation. This means that, where possible, the time-since-establishment is determined or estimated based on direct knowledge (usually with reference to young planted stands), on indirect evidence from aerial photos (where sequential photography of a site can be used to bracket when a field was abandoned or planted), from historical data (information on when a parcel of agricultural land was moved into the public domain for a wildlife refuge, military base, or similar use, and presumed to be allowed to reforest) or by using increment core data to estimate stand age based on the age of canopy trees. In practice, the first and last of these possibilities are likely to be used most often. Supplemental information (such as published studies of old-growth forests in the region or tree growth data from the forestry literature) can be used as secondary sources, but primary data should be based on sites sampled directly. Stands that have unclear origins, or that have obviously been subjected to partial harvests over time, should not be included in the basic dataset. However, managed stands can be evaluated separately to refine the assessment, as described below, and any available information regarding their history should be recorded.

Collection of reference data for the Arkansas Delta HGM Guidebook included assigning ages to approximately half of the sampled stands. Because considerable restoration has occurred in the Arkansas Delta region (particularly under the NRCS Wetland Reserve Program), numerous stands that were within the 1- to10-year-old range could be aged precisely based on the records and memories of persons responsible for the planting program. For older stands, increment cores were collected from overstory trees judged by the field team to represent the initial invaders of abandoned fields, or sprouts from complete harvests. Evidence for the initial condition of these stands included stumps, furrows, and similar clues regarding stand origins. Samples taken from

stands with more clouded past histories (sites likely to have been grazed by cattle as indicated by old fence remnants, or selectively harvested areas, for example) are not included in the data presented here, but they can be used similarly to estimate how such chronic impacts may have deflected recovery trajectories over time. In all cases except for documented planted stands, the age estimates are recognized as approximate – old fields are not uniformly invaded by all species in a single year following abandonment, for example, and ages determined from multiple canopy trees from a single such stand may span 5 –10 years or more. Similarly, simple age counts from trees of various species and growth rates may be inaccurate to some degree, because growth rings of some species are more difficult than others to count using simple magnifying gear, and some may grow more slowly than others before reaching the height at which the core is taken (generally we added 5 years to the measured age at breast height in stands believed to have established from seed, and 2 years in stands believed to have originated as stump sprouts). However, the purpose of this data collection is not to precisely determine stand age, but rather to develop a set of general curves that reflect the developmental trajectory for a suite of indicators. To imply any more precision than is warranted from this approach, which is intended to be applied by experienced field biologists, but not necessarily expert dendrochronologists, would be inappropriate and misleading. Rather, minor measurement errors and occasional misclassification of site origins are offset by collecting numerous samples, and developing curves that reflect the predominant trend in the data. For this same reason, statistical curve-fitting procedures are not recommended as part of the curve development process – simple hand-fitting of curves and critical evaluation of seeming "outlier" data points are more in keeping with the objectives of this approach.

Figure 5 illustrates the process of establishing a recovery trajectory for a single HGM regional subclass and a single functional indicator. In this case, tree basal area is plotted against stand age for the Riverine Backwater regional subclass in the Delta Region of Arkansas. As expected, basal area rises steadily with age. The ages of most young stands in Figure 5 were established by consulting planting records, while older stands were mostly aged using increment core data. The trend line was hand-fitted.

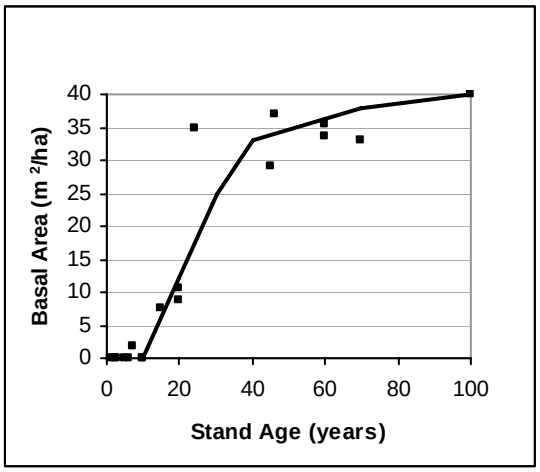

Figure 5. Changes in tree basal area (m^2/ha) over time, as based on increment core samples and restoration records in Riverine Backwater wetlands of the Arkansas Delta Region.

Using the same process, age trajectories were constructed for all of the HGM variables that would be expected to change significantly over periods of a century or less. These are primarily those variables concerned with biological processes, such as vegetation structure and the accrual of

detritus. Figure 6 presents the trajectory curves for three of the variables used in the Production term of the Organic Export model discussed previously. Note that, although the basal area trajectory line climbs steadily, both of the other trajectory lines climb steeply immediately after restoration, and then decline in non-linear patterns over time. This is to be expected, in that both shrub/sapling density and percent ground cover respond quickly to full sunlight, but decline as tree cover increases.

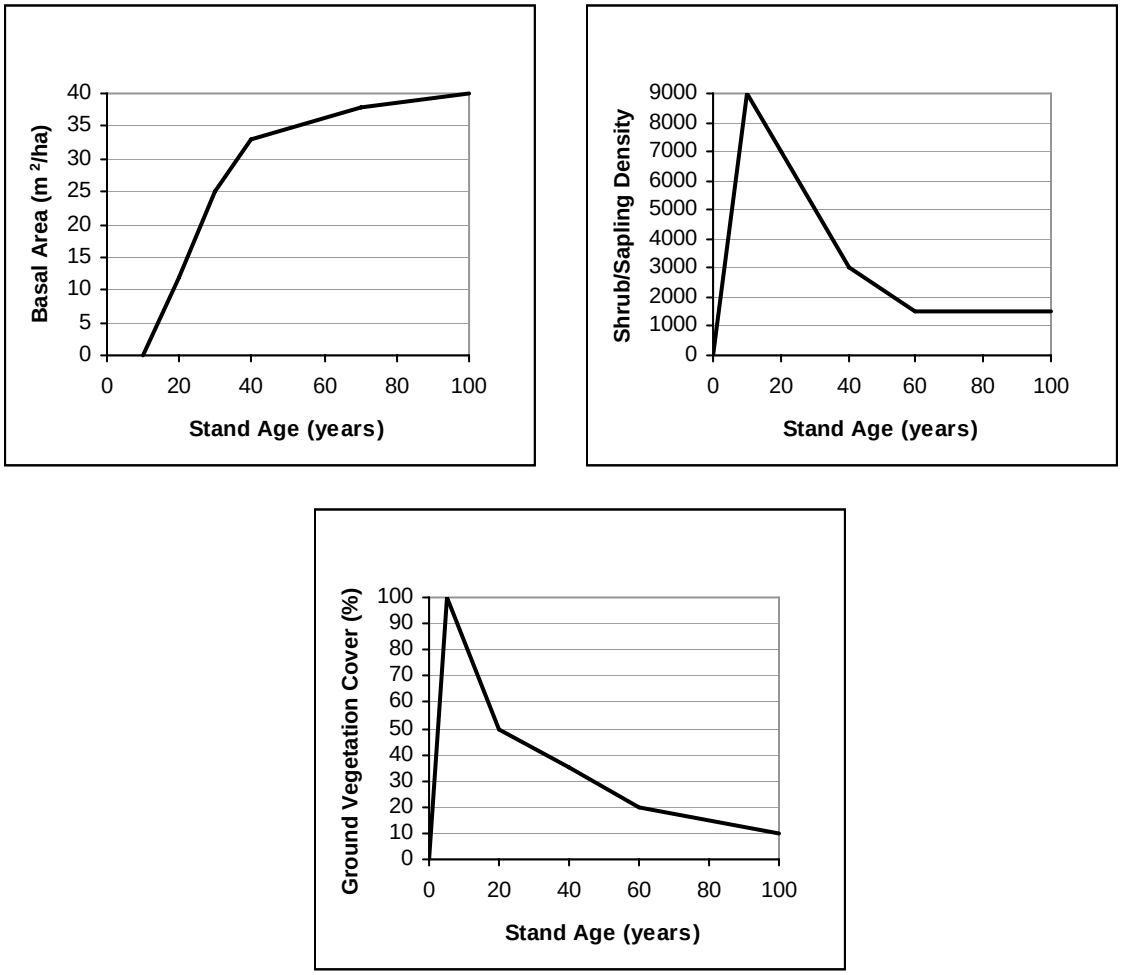

Figure 6. Recovery trajectory curves for three variables used in the Organic Carbon Export HGM model, Riverine Backwater wetlands, Arkansas Delta Region.

Not all model variables are appropriate for development of trajectory curves, and the predictive analysis must involve making assumptions regarding them. For example, the HGM models for wildlife habitat and precipitation detention in Riverine and Flat wetlands include consideration of the area capable of ponding surface water (vernal pools and microdepressions). These features occur as the result of geomorphic processes, and often are destroyed by agricultural practices such as land-leveling. Restoration plans may include surface sculpting to restore the degree of ponding found in reference wetlands of the same regional subclass, but some sites are replanted without consideration of microtopography. In either case, the degree of ponding present at the time the site is planted must be assumed to remain static for the forseeable future. Similarly, the future condition of variables concerned with flood frequency must be assumed to be static, or

changes must be predicted based on anticipated engineering changes such as ditch-filling. A more complex consideration involves the Wildlife Habitat assessment model, which includes variables that relate to site-specific arrangement of forest blocks and corridors. Clearly, trajectory curves cannot be constructed based on reference data to predict future clearing or land abandonment patterns, but they can be used to assess how the maturation of the restored site will influence the existing spatial distribution of wetlands over time.

Applications

Figure 7 illustrates how the trajectory curves presented in Figure 6 are used in conjunction with the corresponding subindex curves presented in Figure 4 to estimate the subindex values in the Organic Carbon Export model over time. In this example, the age trajectory for the Tree Biomass variable (V_{TBA}) indicates that a basal area of approximately 12m^2/ha is predicted for a restored site 20 years after planting. (Note: the trajectory curves assume specified minimum planting densities or colonization rates, as described in the Arkansas Delta HGM Guidebook). Consulting the corresponding subindex curve produces a predicted variable subindex of 0.5 at a stand age of 20 years.

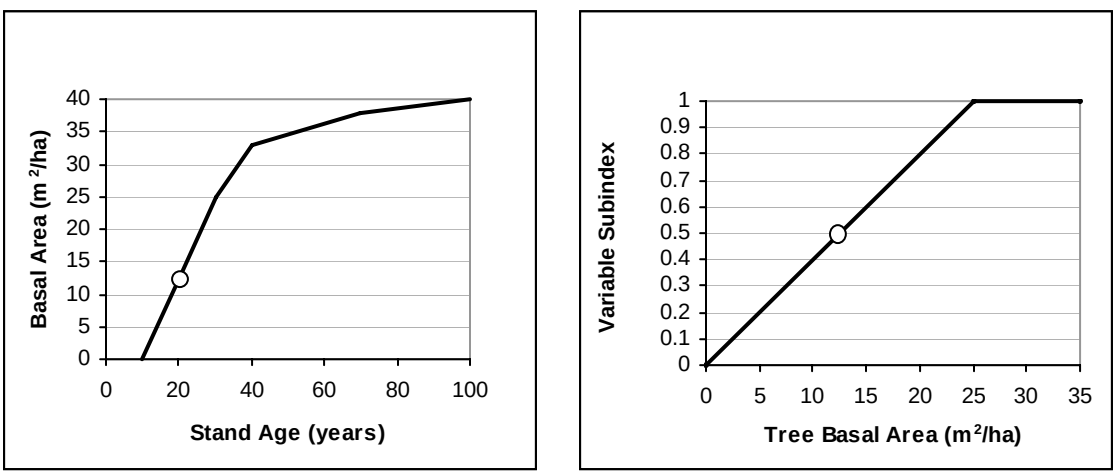

Figure 7. Use of the age trajectory curve for basal area to estimate a Tree Biomass subindex value for a Riverine Backwater wetland 20 years after restoration.

The same process used in Figure 7 can be applied at other time intervals to generate additional predicted values for the Tree Biomass subindex, and for the other variables used in the Organic Carbon Export HGM model. Table 2 presents the results of running the Organic Carbon Export model, using the predicted subindex values, for intervals over a 100-year period. The results are presented graphically in Figure 8. (Note that both Table 2 and Figure 8 are presented in terms of FCI values, not FCUs, and that the Flood Frequency variable is assumed to be 1.0 across all time intervals). As indicated in Figure 8, the predicted values for the Organic Carbon Export function increase rapidly during the first two decades following restoration. This reflects the immediate establishment of ground and shrub cover, and the accumulation of litter and particulate organic debris on the soil surface from that fast-growing vegetation. However, all of the remaining production and storage variables (tree basal area, snag density, and woody debris) depend on tree

growth and the gradual accumulation of biomass. Thus, full functionality for the Organic Export function for Riverine Backwater wetlands in the Arkansas Delta Region is expected to require approximately 40 years following restoration, when the overall FCI value approaches 1.0. The analysis presented above is applied in the same manner to the other functions normally assessed in a particular wetland subclass (Table 1).

Table 2. Calculation of the Organic Carbon Export Functional Capacity Index (FCI) at intervals over a 100-year period following restoration (Riverine Backwater HGM subclass, Arkansas Delta Region).

HGM VARIABLE	YEARS FOLLOWING RESTORATION						
	0	**10**	**20**	**40**	**60**	**80**	**100**
	Subindex Values (Export Organic Carbon Function)						
V_{FREQ}	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V_{LITTER}	0.0	1.0	1.0	1.0	1.0	1.0	1.0
V_{OHOR}	0.0	0.2	1.0	1.0	1.0	1.0	1.0
V_{WD}	0.0	0.2	0.8	1.0	1.0	1.0	1.0
V_{SNAG}	0.0	0.0	0.0	1.0	1.0	1.0	1.0
V_{TBA}	0.0	0.0	0.4	1.0	1.0	1.0	1.0
V_{SSD}	0.0	0.5	0.6	0.9	1.0	1.0	1.0
V_{GVC}	0.0	0.5	1.0	1.0	1.0	1.0	1.0
FCI	**0.0**	**0.34**	**0.68**	**0.98**	**1.0**	**1.0**	**1.0**

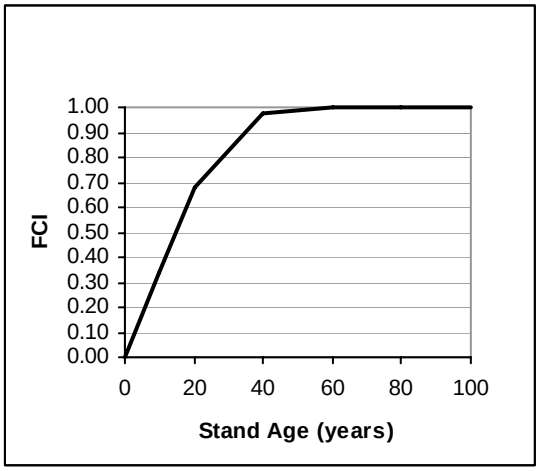

Figure 8. Predicted change in the Organic Carbon Export Functional Capacity Index (FCI) over a 100-year period following restoration (Riverine Backwater HGM subclass, Arkansas Delta Region).

In order to use functional recovery rates in the context of establishing mitigation requirements, the trajectory curves are applied to both the impact area and the proposed mitigation site. When the results are expressed in terms of Functional Capacity Units (FCUs), they are directly translatable into area ratios, and allow comparisons between proposed impact and mitigation areas. In particular, they are useful for establishing the relationship between the initial functional

deficit (temporal lag in development of the mitigation site) and alternative mitigation ratios (acreage of mitigation versus impact), as discussed in the Introduction and illustrated in Figures 1 and 2.

Figure 9 provides examples of such comparisons for the Organic Carbon Export Function as calculated above. In the first example, one hectare of an existing mature wetland is represented by a flat dashed line indicating that it is fully-functional (FCU=1.0) and would be expected to remain so for the entire 100-year period included in the graph. In the event that the wetland is destroyed, the area under the dotted line represents the total loss of function for the assessment period. The solid line in the first graph represents a possible option for offsetting the loss of the Organic Carbon Export function. and the area under both lines (area D) represents direct replacement of lost function by the mitigation site once it has matured sufficiently. A 1.5 ha mitigation area, established at the same time that the existing site is destroyed, will fully replace the lost function beginning approximately 20 years after the initial impact and restoration. After that time, the level of function, considered on an annual basis, will exceed the amount lost to the impact for the remainder of the assessment period (area D). However, during the first 20 years following the initial impact, there will be a net deficit in function, as time is required for the restoration site to reach the fully-functional level. One potential way to offset the lag in function is to credit part of the increased function on the mitigation site after 20 years (area B on the graph) against the deficit accrued during the first 20 years (area A on the graph). Using that approach, the impact would be fully offset after approximately 50 years. If the lag in recovery of the Carbon Export function is considered a critical problem, the recovery time can be accelerated by restoring a larger mitigation area. In the second graph in Figure 9, expanding the replacement ratio from 1.5:1 to 2:1 reduces the time to full replacement to approximately 35 years. In both of these example cases, there will be a period when there is a net loss of function in the early years following restoration. An additional potential use of the trajectory analysis is to illustrate that restoration accomplished well before any impact occurs (e.g., mitigation banking) can minimize or avoid that early net loss of function, and potentially reduce replacement ratios.

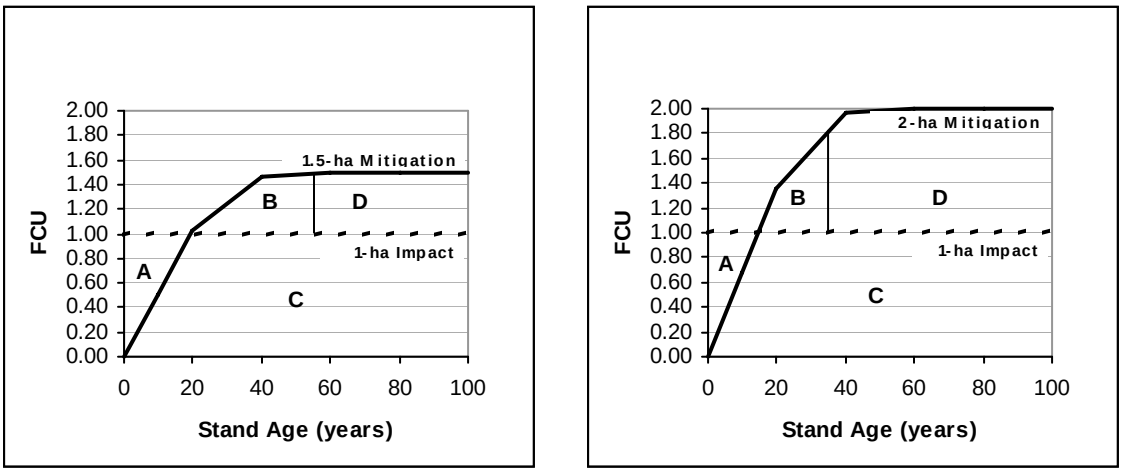

Figure 9. Use of recovery trajectories to examine the effects of mitigation ratios on time required for functional replacement.

Because HGM uses spatial factors concerning the size, shape, and connectivity of forest blocks to assess wildlife functions, maturation of restored sites can influence the functionality of adjacent, existing forested wetlands. Thus, the use of recovery trajectory curves can expand the assessment

(and the restoration objectives) beyond the target site and allow consideration of landscape-scale issues.

Figure 10 illustrates a common situation in the Delta Region of the Lower Mississippi Valley. While some large blocks of forested wetlands occur in association with the major streams, most of the landscape has been cleared for agriculture and forested wetlands often occur as small woodlots. HGM assessment of small isolated stands produces low Wildlife Habitat Function scores regardless of the habitat structure within the stand. In the example illustrated in Figure 10, each of the forest blocks (labeled A, B and C) is assumed to be fully mature and functional in all respects, except that stands B and C are very small blocks (e.g. several hectares) with no connection to the larger tract A. In their current condition, blocks B and C would remain at a low level of function (about 0.15 FCI) with regard to wildlife habitat, because they provide no interior habitat for birds, and have no connection to larger blocks that would allow many terrestrial animals access to them. However, if a large adjacent area encompassing block B is restored as Riverine Backwater wetland, providing continuity with the large block A, the effects on the formerly-isolated block are significant. Within a few years of installation of the restoration project, sufficient shrub and ground cover will be in place that the restored site will provide a functional corridor for movement to and from the existing forest areas, and the FCI score for wildlife habitat in the small existing forest block would increase to approximately 0.75 (Figure 11). By about 40 years following restoration, the forests on the restored site would be mature enough that the formerly-isolated block would be part of a large, fully functional forest block, and would be providing habitat for a full suite of animals. Note that block C, which remains unconnected to any larger tract, would continue to have an FCI score of approximately 0.15 indefinitely.

The use of functional trajectories in a landscape context also provides a mechanism for considering the use of existing wetlands to reduce the functional "lag time" discussed above with respect to the Organic Carbon Export Function. Where an existing, but isolated wetland is included within the boundaries of a mitigation project, wildlife functions accrue more quickly in the existing site because a mature community structure is already in place. Therefore, FCUs accumulate more quickly, partly offsetting the lag in functional recovery on the restored site.

Thus, by using trajectory analysis to predict the rate of structural change on a restoration site, we can simultaneously consider the influence of the restoration site on an adjacent area. This has the potential to greatly increase the options for achieving meaningful mitigation in areas where land available for restoration is limited.

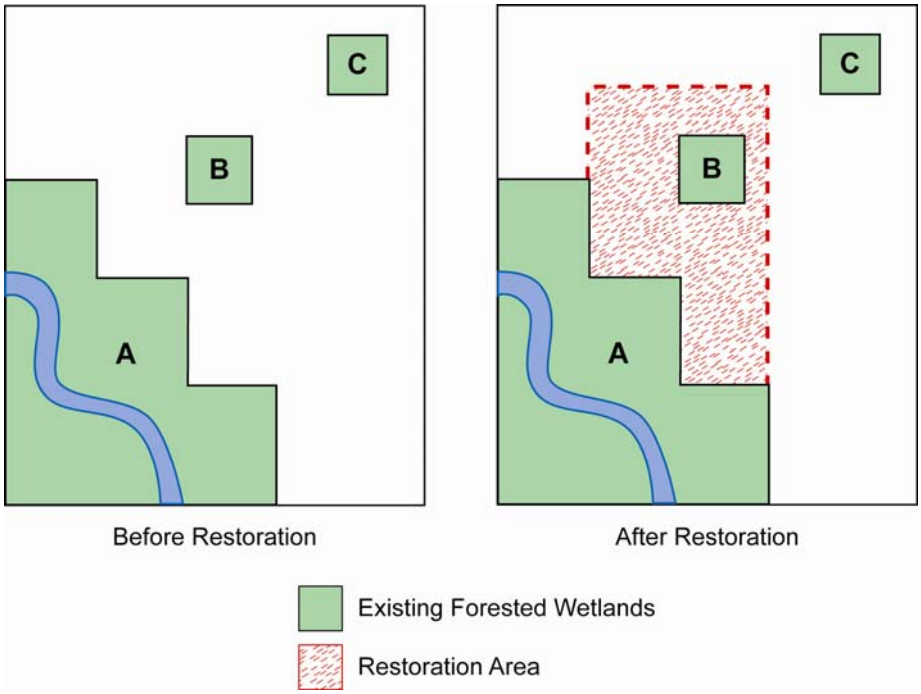

Figure 10. Hypothetical arrangement of wetland forest and a restoration area in an agricultural landscape.

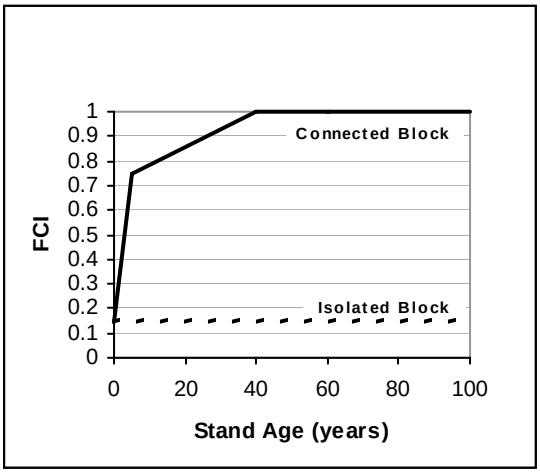

Figure 11. Influence of an adjacent restoration project on the Wildlife Habitat FCI score of small forested wetlands (Sites B and C, from Figure 10).

Monitoring Applications

In order to track the success of a mitigation or restoration project, a set of specific indicators can be selected for sampling at specified monitoring intervals, and criteria ("success criteria") established (based on the appropriate trajectories) to determine if the restoration site is meeting project objectives. As demonstrated previously, biological indicators related to vegetation structure and detrital pools vary predictably as forested wetlands mature, and measures such as basal area and woody debris volume can be monitored easily and compared to the trajectory curves to determine if the restoration is developing at the rate predicted when mitigation ratios and design criteria were established.

Not all HGM variables are appropriate for use in developing success criteria that derive from recovery trajectories. It is helpful, in establishing monitoring standards, to recognize the purpose and potential limits of various field indicators. The following classification applies to the variables used in the Arkansas Delta HGM Guidebook, but the general principles are applicable to other types of assessment systems.

1. Indicators related to physical setting and initial condition

Microtopographic relief, the presence of native soils or fill material, and flood frequency are all examples of physical-setting HGM model variables that would not be expected to change as a result of community development when it is monitored on a scale of decades. However, the HGM subindex curves indicate the range of values for those variables encountered in reference sites, and may provide guidance applicable to restoration design. For example, the highest-functioning Riverine Backwater sites in the Arkansas Delta typically are at least 20% ponded during the wet season, due to microtopographic storage. Where leveled fields are targeted for restoration, site preparation should include re-contouring to achieve at least 20% ponding as an initial, pre-planting condition. However, ponding is not an appropriate measure for subsequent monitoring, as no change would be expected within a century or more after restoration. Generally, this applies to all of the variables that relate to physical setting; the initial condition should be measured and verified as appropriate to the site and restoration objectives, but subsequent monitoring is unrelated to the development of recovery trajectories.

Initial site condition is also a consideration in applying recovery trajectories that track the characteristics of planted vegetation. The recovery trajectories presented in the Arkansas Delta HGM Guidebook are predicated on the assumption that initial tree planting densities and species composition meet certain minimum standards. Sites that do not meet those standards can be compared to trajectories for monitoring purposes (see the following section), but are likely to fail to meet performance targets. The future performance of sites that are planted at inadequate densities, or with inappropriate species cannot be assessed using functional trajectories for the purpose of estimating replacement ratios, at least as far as functional indices based on the characteristics of planted vegetation are concerned.

2. Indicators related to community structure

Most of the recovery trajectory curves are concerned with biological components of community structure, such as tree basal area, shrub density, litter and woody debris accumulation, and snag density. The variability associated with each of these indicators becomes apparent in the process of constructing the trajectory curves, and should be considered in determining which indicators to use as success criteria. Unfortunately, for most indicators, the highest levels of variability tend to occur in the earliest years following restoration, which is usually the period of greatest interest for determining whether the project is likely to be successful. This means that, while it is reasonable to use long-term projections of community structure to estimate mitigation adequacy and replacement ratios, it is probably not reasonable to use specific projections based on average

trajectory trends as success criteria in the early years following restoration. For example, the Basal Area trajectory curve presented in Figure 6 indicates that a reasonable performance criterion for a restored site would be approximately $10m^2$/ha of basal area at age 20. However, Figure 5, which includes the data points used to construct the basal area projection curve, indicates variation of about $5m^2$/ha around the trend line, suggesting that a more reasonable criterion might be that a restored area could support as little as $7.5m^2$/ha at age 20. Similar critical evaluation of variability should be used in setting any performance standards based on recovery trajectories.

Although the examples given here primarily concern monitoring to track development of a wetland toward a mature condition, trajectory curves also can be used to identify developmental points where management intervention may be desirable. For example, many HEP models concern species that use early- or mid-successional habitats, and trajectory curves can be used to estimate when community structure for those animals will be optimal, or when some management action may be necessary if appropriate habitat for those species is to be maintained. Similarly, where fire is a potential management tool, understory density projections may be used to estimate likely burn intervals when preparing long-term management plans.

3. Indicators related to spatial arrangement

Functional recovery trajectories can be used to estimate the development of shrub and canopy cover, which are the principal indicators used to determine if spatial variables (block size and connectivity) are developing as predicted. As with other indicators related to community structure, these have more variance associated with the early years of development than with later years. Therefore performance criteria based on trajectories affecting spatial considerations cannot be overly rigid.

As indicated by the discussion above, although trajectory curves are a powerful and defensible way to estimate functional recovery of restored sites and set mitigation ratios, they are not, of themselves, sufficient to set performance criteria, at least in the early years following restoration. Performance criteria intended to reflect the recovery of ecosystem functions should include assessments of initial condition (both physical setting and initial planting densities) as well as the traditional monitoring of plant survival in the first few years after planting. However, in some situations, trajectories might be usefully employed at the end of the survival monitoring period (year 5 or 10, perhaps) to determine if the site is developing the complex structural characteristics and spatial relationships anticipated when the initial mitigation ratios were established.

Case Study

In 2003, the Arkansas State Highway and Transportation Department (AHTD) established the Glaise Creek Wetland Mitigation Bank Site in White County Arkansas. The site occupies 342 contiguous hectares, most of which is agricultural land. The intention is to restore native wetlands and small inclusions of upland plant communities and preserve them in perpetuity. The credits derived will be used as compensatory mitigation for AHTD construction and maintenance projects that are the least environmentally damaging practicable alternatives, and when on-site compensation is not practicable or preferable to use of the bank.

The restoration plan for the Glaise Creek site is to restore hydrology by filling ditches and restoring ponding, and planting native trees (approximately 500 stems/ha or more) such that species are distributed according to hydrologic regime. The entire site will be planted over a 3-year period, and monitoring will continue annually for at least 5 years beyond that time. Performance standards require 70 percent survival of planted trees for the first two years, then 50 percent survival of planted trees, or equivalent colonization of desirable species, until the end of

the 5-year monitoring period. Over the monitoring period, plant communities in all wetland areas within the mitigation site must have a preponderance of wetland plant species present, and a minimum density of trees that produce hard mast (oaks and hickories) must be maintained. The restoration plan for the bank site, the geographic area to which bank credits can be applied for offsetting impacts, the method to be used to calculate mitigation credits, and monitoring schedules and performance standards have all been agreed to by the multiple State and Federal agencies that are signatories to the documents establishing the bank (AHTD 2003).

The AHTD also is a member of the Arkansas Multi-Agency Wetland Planning Team, which developed the HGM regional guidebook (Klimas et al. 2004) applicable to the Delta Region where the Glaise Creek Mitigation Bank is located. The HGM guidebook was not available in final form at the time the bank was established, and could not be used as an accounting tool for calculating mitigation credits, but the AHTD is interested in testing the HGM procedures, and agreed to allow data to be collected within the Glaise Creek mitigation bank for use in the examples presented below. The information developed for this case study is intended only to demonstrate the uses of trajectory analyses in a typically complex Delta setting, and does not replace or alter any of the existing plans or agreements outlined in the banking instrument (AHTD 2003).

The Glaise Creek mitigation bank site consists of two basic geomorphic settings (Figure 12). Most of the area is within the Holocene meander belt of Glaise Creek and is subject to frequent (annual) flooding. That portion includes approximately 190 ha available for restoration, which is classified as Riverine Backwater according to HGM criteria. The remainder of the site is much older Pleistocene terrace deposits that are flooded infrequently and maintain their wetland character through ponding of rainwater. Approximately 93 ha of the terrace zone are wetlands classified as Flats. An additional 59 ha within the boundaries of the mitigation bank site are classified as non-wetland, existing forest, open water, roads, and other areas not available for wetland restoration. These 59 ha are not identified separately in Figure 12, but are mostly inclusions within the subsection of the tract labeled as Flat. Under natural conditions, the Riverine Backwater areas would be expected to support a mix of hardwoods characterized by species such as overcup oak, green ash, and Nuttall oak. The unflooded terrace areas would support a "hardwood flat" community dominated by species such as water oak, cherrybark oak, and shagbark hickory. Figure 12 also indicates the location of a small (approximately 4 ha) forested flat area that is used in this case study to demonstrate how trajectory analyses can be employed to assess the influence of wetland restoration on adjacent existing wetlands.

Figures 13 and 14 are typical views of the mitigation bank site and the mature woodland area in May, 2004, when sampling was conducted for this case study. At that time, samples of the pertinent HGM variables were collected at representative locations within the unplanted Flat area, the unplanted Riverine Backwater area, and the forested Flat on the perimeter of the mitigation bank site. An initial functional condition (Functional Capacity Units) was calculated for each of the three areas, using the Arkansas Delta HGM Guidebook, then the trajectory curves were used to calculate FCUs for each site at intervals over a 100-year period following planting.

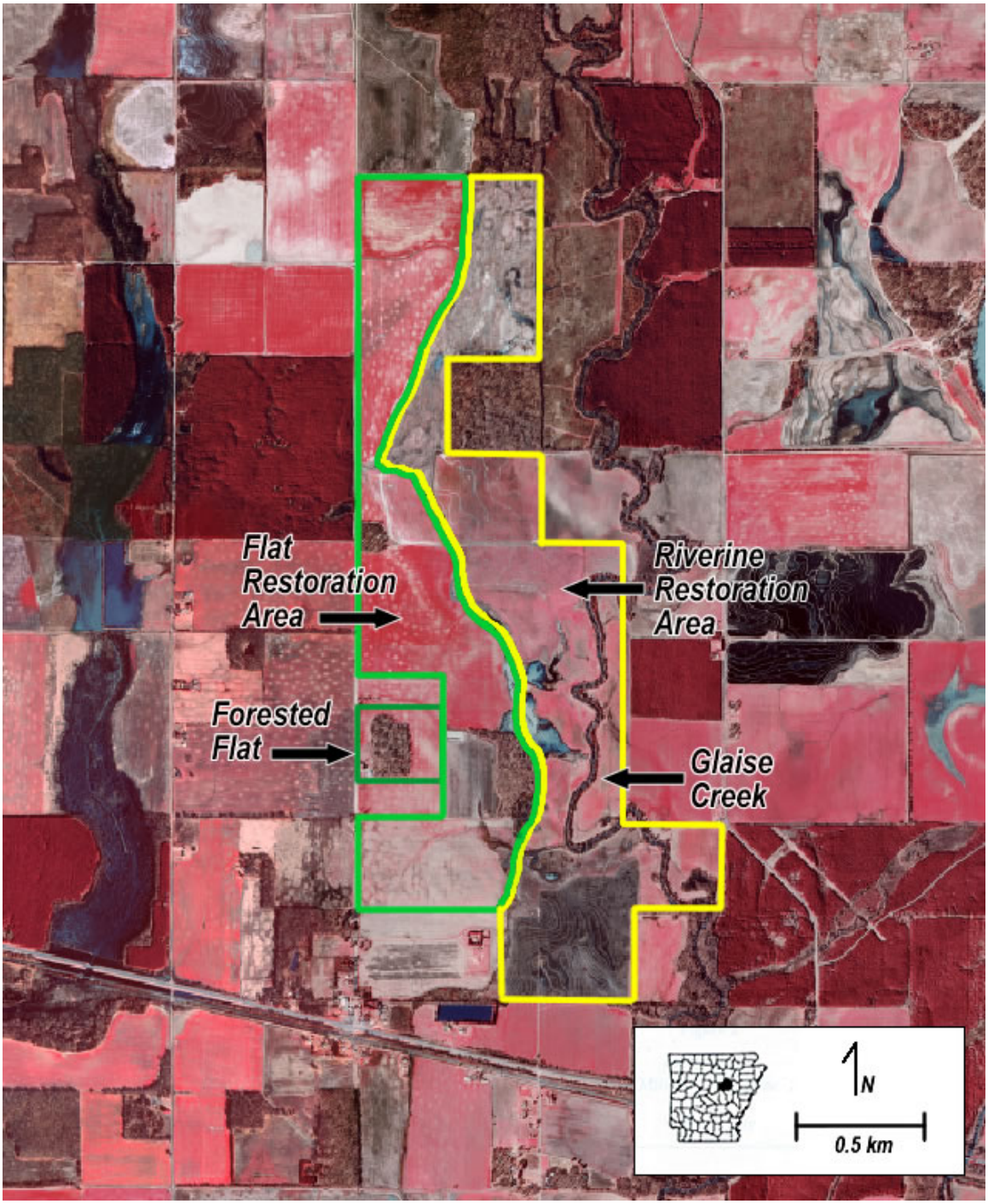

Figure 12. Glaise Creek Wetland Mitigation Bank Site in White County, Arkansas.

Figure 13. View of the Glaise Creek Wetland Mitigation Bank Site prior to planting.

Figure 14. View of the existing forested Flat adjacent to the Glaise Creek Wetland Mitigation Bank Site.

Figure 15 presents the current functional condition and anticipated changes in the 190 ha Riverine Backwater section of the Glaise Creek Mitigation Bank Site. Seven functions are assessed (Note: the projected responses of the Carbon Export and Nutrient Cycling functions over time happen to be identical in this case, and they are combined in a single graph).

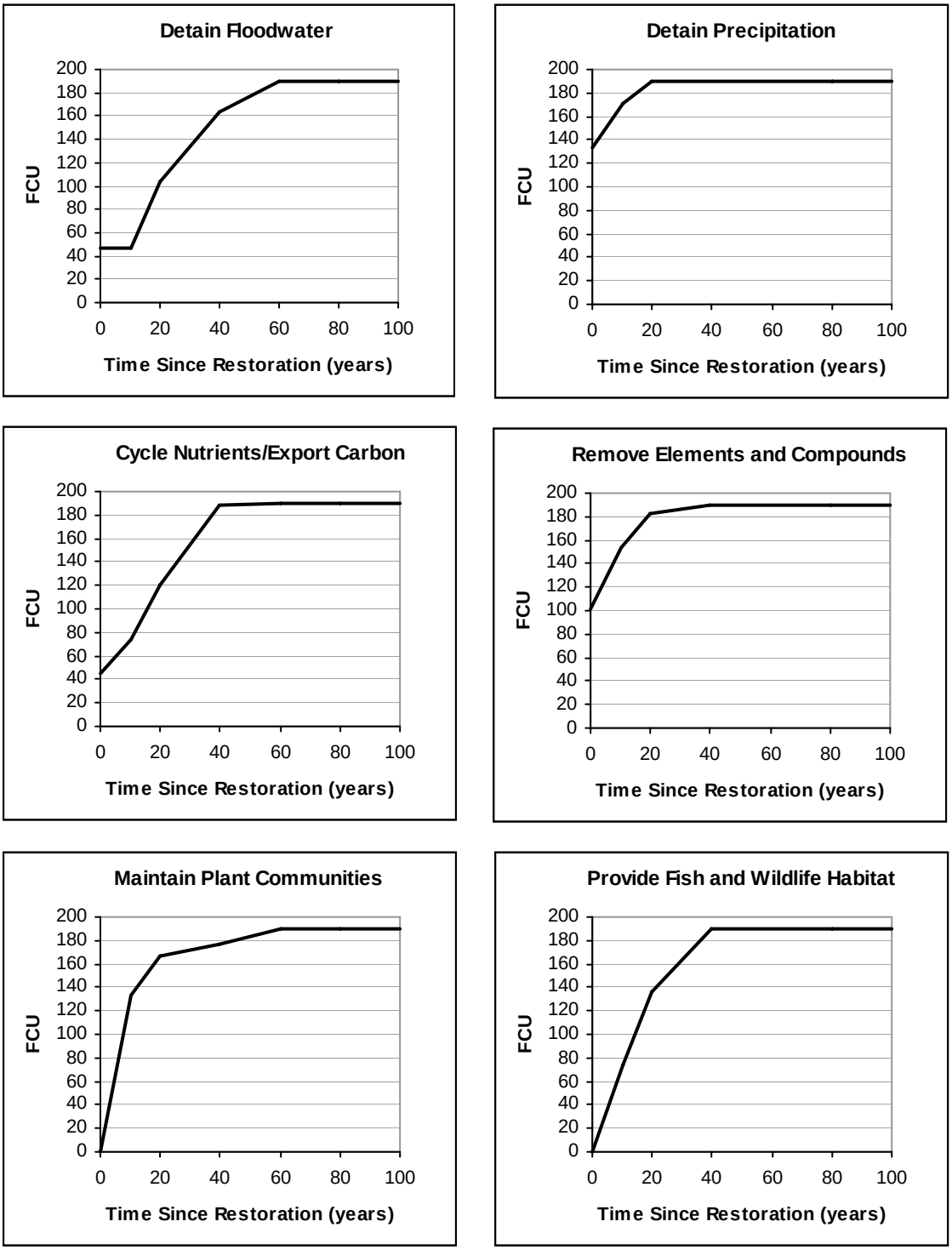

Figure 15. Projected changes in Functional Capacity Units over a 100-year period following wetland restoration on the 190 ha Riverine Backwater portion of the Glaise Creek Wetland Mitigation Bank Site.

As expected, the pre-planting condition (year zero) of the Riverine Backwater site yields low FCU scores for most functions. An exception is illustrated in the curve for the Precipitation Detention function, which shows that the restoration site is already performing the function to large extent prior to any planting. This reflects the fact that the Riverine Backwater site has a great deal of microtopographic relief already in place (due to old rice levees and furrows) and on-site storage of rainwater is within the range found in fully functional forested sites. A similarly high FCU score for the pre-planting condition is seen in the Element and Compound Removal function, which reflects the frequent flooding and native soils already in place on the site. However, the rest of the functions assessed are to some extent dependent on plant community maturation, so they are initially at a low level of functionality.

The rate at which the Riverine Backwater site achieves full functionality varies depending on the function being assessed. The projections in Figure 15 indicate that the full potential of 190 FCUs are available for the Precipitation Detention function 20 years after planting, while 60 years are required to generate 190 FCUs for the Plant Community and Floodwater Detention functions. All other functions reach maximum levels at 40 years after planting.

Figure 16 illustrates the current and projected functional condition of the Flat portion of the mitigation area for the four functions assessed in Flats.

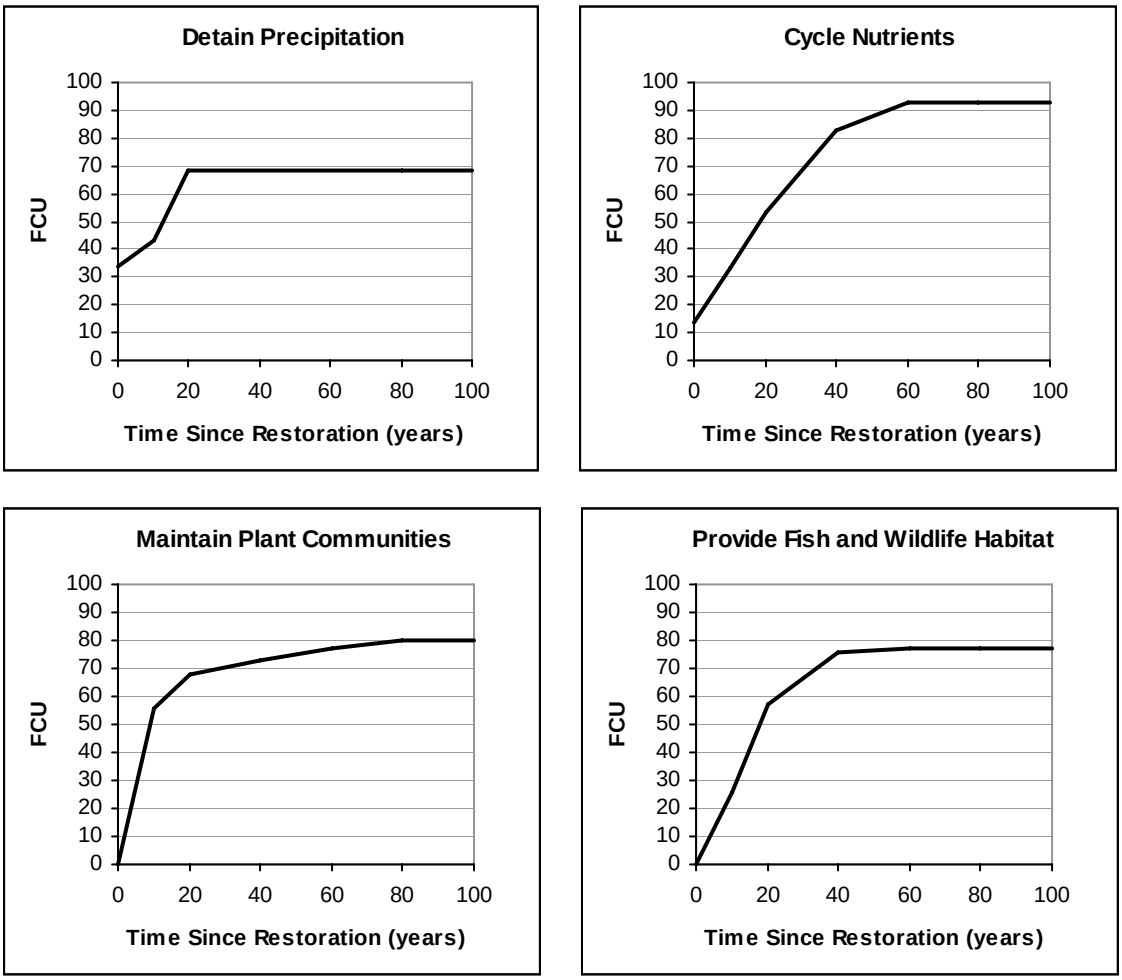

Figure 16. Projected changes in Functional Capacity Units over a 100-year period following wetland restoration on the 93 ha Flat portion of the Glaise Creek Wetland Mitigation Bank Site.

As with the Riverine Backwater site, the Precipitation Detention function on the Flat restoration area is already operating at the time the site is planted, but because microrelief on the Flat sites is less than that found in fully functional Flats, the recovery trajectory curve never reaches full potential over the 100-year period of the analysis. Of the 93 potential FCUs, the curve levels off at approximately 70 FCUs, which is reached after 20 years. The lack of sufficient microtopographic complexity also depresses the potential functionality of the Plant Communities and Fish and Wildlife functions, both of which include ponding as an assessment variable. This is an example of how the trajectory analysis can be used to inform design of the restoration. If site preparation includes additional sculpting of the surface prior to planting to achieve surface ponding in the range of the fully functional reference sites, then full functionality (93 FCUs) would be achieved eventually for all three of these functions.

Figure 17 presents an analysis of the current and anticipated future functionality of the existing forested Flat area adjacent to the Glaise Creek Mitigation Bank site. This area is included in the Case Study to illustrate several points. First, the site is very small (4 ha), but is fully functional with respect to the Precipitation Detention function, because approximately 60% of the area is capable of trapping rainfall due to complex microtopography and impermeable soils (Figure 14). The Nutrient Cycling and Plant Community functions also are nearly at full potential, and both will reach full functionality (4 FCUs) in approximately 20 years, as the plant community continues to mature. If a similar area was to be unavoidably impacted and the Glaise Creek Mitigation Bank used to offset the loss, determining the mitigation ratios required would be a simple matter of comparing these 3 graphs with the corresponding mitigation trajectory curves in Figure 15. However, for the Fish and Wildlife function, the situation is more complex. Under current conditions (no restoration in place), the Fish and Wildlife function is severely depressed by the isolation of this small forest block. This situation would improve little over time as long as the adjacent lands remain unrestored, generating just 0.6 FCUs (dashed line in Figure 17). However, the planned restoration of the adjacent Flat will dramatically change that situation by incorporating the small forested flat into a large forest block, and the full potential for the site (4 FCUs) will be achieved within 20 years. This illustrates how off-site effects might be taken into consideration in a mitigation scenario, and how incorporation of mature, but functionally constrained, wetlands into a mitigation site can be used to offset the unavoidable temporal deficits that occur in restored sites.

The reason for generating FCUs is to provide a means for determining how much area within the mitigation site must be dedicated to offsetting losses on an impact area. As these examples illustrate, this decision can reflect various considerations other than simple acreage ratios because there are multiple functions assessed, and the trajectory analysis allows estimation of functionality at any point over the life of the project. Characterization of the impact area can focus on the functional condition at the time of impact, or it can include consideration of how function might change over time in the absence of the impact. Replacement ratios can be based on an annualized accumulation of FCUs over time, including consideration of the time lag (temporal deficit) in achieving functional replacement, as illustrated in Figure 9. Selection of which function or functions are compared to determine replacement ratios can be based on regional resource priorities (i.e. which functions are deemed "most important" in a given region or site), or on which functions are slowest to be replaced, or similar concerns. And as demonstrated in Figure 11, changes to the functionality of areas adjacent to the impact or mitigation site can be part of the analysis, where spatial relationships will change and influence wildlife habitat functions. All of these types of analysis are possible when recovery trajectories are incorporated into the assessment.

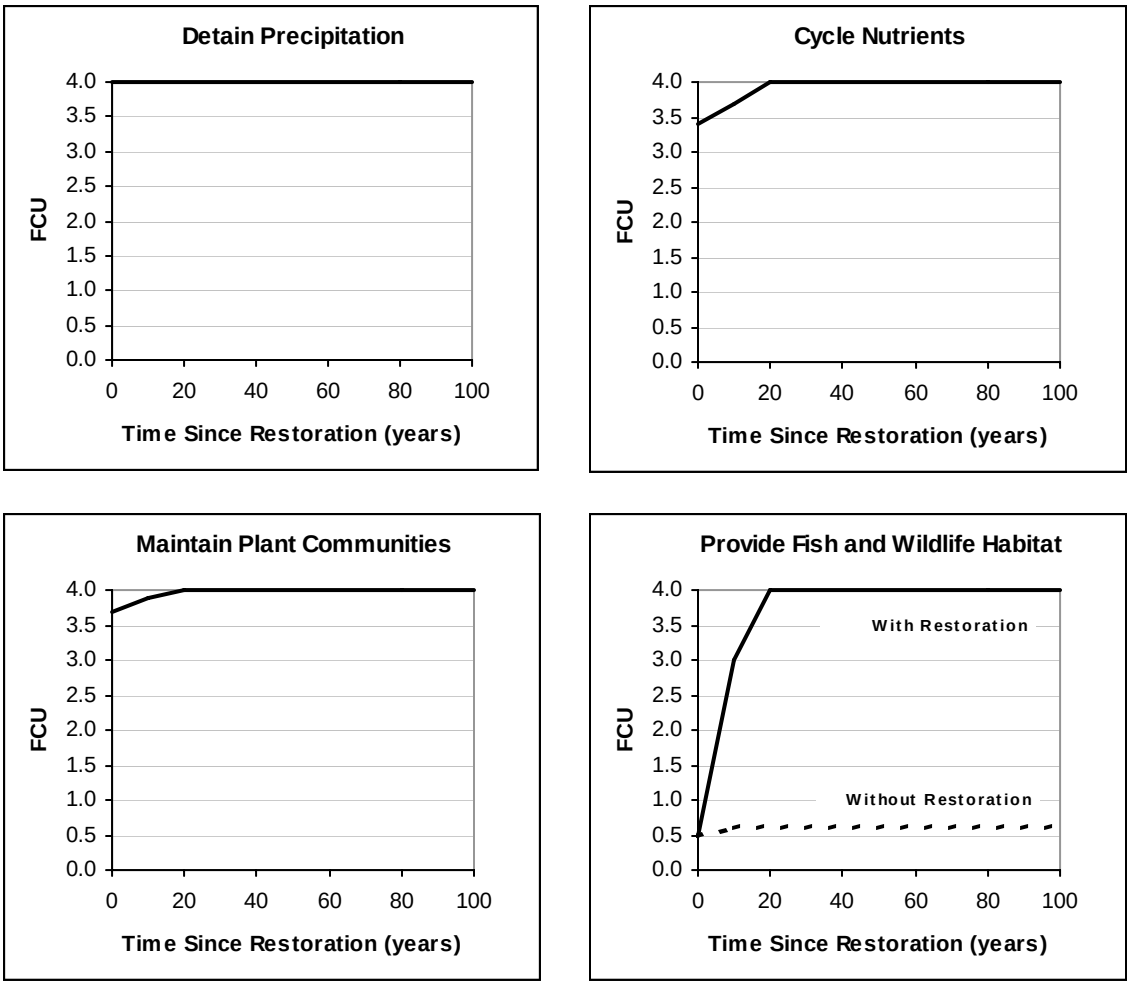

Figure 17. Projected changes in Functional Capacity Units over a 100-year period in a 4 ha existing forested Flat adjacent to the Glaise Creek Wetland Mitigation Bank Site.

Summary

A wide variety of approaches have been devised to estimate the functionality or "health" of ecosystems, especially wetlands. Most such systems involve comparison of some indicator of the current condition of the wetland to a standard, which may in turn be derived from field studies or other sources. Where field studies provide the reference data for comparison, and where the reference sites include a broad range of wetland functionality, an opportunity exists to develop functional trajectories that describe the rate of change in selected indicators of ecosystem function.

Functional recovery trajectories can inform decisions regarding wetland mitigation design and adequacy because they project anticipated changes over time that will result from particular mitigation actions. When the projected changes in community structure and processes are interpreted in terms of standardized assessment approaches, such as HGM and HEP models, they generate accounting units (e.g. FCUs or HUs) for various points in time. This allows users to identify and quantify which wetland functions can be expected to recover quickly, and which will

have a substantial time lag before they can replace lost functions within an impact area. Recovery trajectories also point out possible sources of failure in mitigation design, because they identify which functions are unlikely to recover fully, and why. Recovery trajectories also provide long-term performance standards against which restoration projects can be compared, and suggest specific areas to focus adaptive management.

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