Landscape Ecology **16:** 3–16, 2001.

Research Article

Changes to the landscape pattern of coastal North Carolina wetlands under the Clean Water Act, 1984–1992

Nina M. Kelly
University of California - Berkeley, Ecosystem Sciences Division, Department of Environmental Sciences, Policy and Management. 151 Hilgard Hall #3110, Berkeley, CA 94720-3110, USA (Tel: 510.642.7272; Fax: 510.642.1477; E-mail: mkelly@nature.berkeley.edu)

Received 8 December 1999; Revised 5 January 2000; Accepted 8 January 2000

Key words: North Carolina, Section 404 permit process, coastal wetlands, landscape scale, GIS, classified Landsat imagery

Abstract

Wetland management in the United States is organized through a permit process that requires a permit be filed with the U.S. Army Corps of Engineers prior to wetland alteration. A collection of these permits from 1984 through 1992 was analyzed in conjunction with classified Landsat Thematic Mapper data from 1984 and 1992 in order to quantify changes to wetland habitat in the study area in coastal North Carolina. The wetland management process in the U.S. focuses on a site-by-site review, possibly overlooking important changes to wetlands at the landscape-scale. These the two datasets were used to determine if wetland habitat loss was occurring at permit sites, but also to determine if landscape-scale wetland fragmentation and reorganization were occurring in the area surrounding each permit site under the wetland management process. The use of these two datasets attempted to span two scales: the site-specific scale often used in the management of wetlands, and the landscape-scale where effects of such management are evident. Important conclusions from the research include the following. First, while several sources imply that coastal wetlands are disproportionately protected as a result of the widespread recognition of their habitat value, estuarine wetlands were altered much more frequently in the study area than their inland counterparts. Second, despite federal level efforts that require compensatory mitigation when wetland habitat is lost, such mitigation was required in only three percent of permits, ensuring wetland loss. Third, correlation between estimates of wetland loss from the Permit Record and from the remotely sensed record was minimal, highlighting the problems inherent to wetland delineation and implying alterations to habitat not evidenced in the permit record. Finally, landscape-scale changes of loss, fragmentation and habitat reorganization have occurred in estuarine emergent wetland habitat in areas adjacent to several permit sites, implying unanticipated additional impacts to permitted actions. Wetland loss at the permit site occurred with additional fragmentation in 80 percent of the sites examined. The results highlight the lack of agreement between management and landscape-scale wetland structure, function and change, and imply the importance of examining the spatial context of permit sites in the permit review and evaluation procedure.

Introduction

Landscapes can be defined by their structure – the spatial relationship among distinct elements or structural components; their function – the flow of mineral nutrients, water, energy, or species; and change – the temporal alterations in the structure and function of landscape elements within a matrix (Bell et al. 1997; Turner 1990). Within this framework, a particular system of natural resource management can be viewed as part of the anthropogenic disturbance regime propagating through a landscape, changing structure and function (Coulson et al. 1990; Dunn 1990). As these landscape elements operate at multiple scales, changes can be overlooked or even exacerbated by a management regime that focuses on a particular scale in its operation (Bedford 1996; Bedford and Preston 1988; Haig et al. 1998; Leidy et al. 1992). This paper examines this scale discrepancy with respect to tidal wetland management in coastal North Carolina.

The wetland management process in the United States is organized around a permit system codified in Section 404 of the federal law called the Clean Water Act. This act requires that a permit - a ‘Section 404 permit’ be filed with the Army Corps of Engineers (Corps) before a wetland is altered. Examples of these permitted alterations range in size from clearing wetlands smaller than one acre to build a new dock on a landowner’s property, to extensive filing of wetlands 10s of acres in size necessary to build a new highway. In some cases, mitigation of wetland habitat is required to compensate for the loss of the original wetland. The Section 404 permit process involves a site-specific review of permits, yet the results of permitted action often have effects over an area larger than the permit site. The permit process can change the structure of the wetland landscape by allowing for alterations to wetland habitat at a series of isolated permit sites, coupled with the creation of wetland habitat elsewhere. This has the potential to re-configure the spatial distribution of the wetland ecosystems over large areas (Bedford 1996). It is hypothesized here that the wetland regulatory process, in addition to allowing wetland loss, has resulted in two previously unreported structural changes at the landscape-scale: an unanticipated fragmentation of wetland habitat in areas surrounding individual wetland permit sites, and a reorganization of the spatial pattern of wetland habitat as a result of wetland creation and restoration due to the compensatory mitigation process. While the fragmentation effect in wetland landscapes has been recognized (Harris 1988; Llewellyn et al. 1995; Semlitsch and Bodie 1998; Wu 1997), the spatial reorganization effect has not yet been examined. More importantly, neither of these elements of landscape change has been quantified within the context of a management regime.

The research utilizes two datasets: a collection of the wetland permits that were required by the U. S. government before wetland alteration could proceed, hereafter called the Permit Record, and classified Landsat Thematic Mapper (TM) imagery from two dates. These data were used to quantify changes to wetland habitat in the study area in coastal North Carolina, and to determine if wetland loss at each permit site, in addition to wetland fragmentation and reorganization in the area surrounding each permit site were occurring under Section 404 regulation. The use of these two datasets attempted to span two scales: the site-specific scale often used in the management of wetlands, and the landscape-scale where effects of such management are evident. Independently, these two datasets provide important evidence of changes to estuarine emergent wetlands in coastal North Carolina; combined, they provide an unexplored dataset to discover the landscape-scale changes to the wetland habitat that are overlooked by the management process.

Background

Wetlands loss

Wetlands in the United Stated have been disappearing throughout the country’s post-settlement history. According to several estimates, 54% of all wetlands that existed in this country at the time of European settlement have been destroyed or altered in some way as to diminish their original wetland function (United States Geological Survey 1996). Agriculture has been responsible for the majority of this change, but urban activities are increasingly altering wetlands, especially in the southeastern United States (Holman and Childres 1995; Kelly 1996). In North Carolina, increasing developmental pressures are necessitating the alteration of the valuable coastal and upland wetland resources. The continued loss of wetlands is troublesome in light of current research that clearly demonstrates the functional value that wetlands have with respect to hydrology, water quality, life support, as well as recreation and aesthetics (Mitsch and Gosselink 1993).

Wetland management

Recognition of the importance of wetland functions has led to federal and state regulation of the destruction or development of the nation’s wetlands. The most comprehensive, and often considered the most controversial of the legal regulatory frameworks associated with wetland protection is the Clean Water Act (CWA), first passed in 1972 and re-authorized recently. Section 404 of the act requires that a wetland permit – a ‘Section 404’ permit be filed before alteration to a wetland can proceed (Berry and Dennison 1993; Studt and Sokolove 1996). In North Carolina, as in many states, the administration of the Section 404 permit program is the responsibility of the U.S. Army Corps of Engineers (Corps), under the general overview of the U.S. Environmental Protection Agency, with advisory roles given to two federal level environmental agencies, the U.S. Fish and Wildlife Service and the National Marine Fisheries Service (NMFS). A wetland permit will only be issued after review by these relevant agencies and after an opportunity for public hearing and comment. If the impact of any proposed change is considered significant by any of these bodies, the permit can be denied or the project altered to reduce its impact, or mitigation can be required.

Where appropriate, the law requires compensatory wetland mitigation, the process whereby modification or destruction of natural wetlands is permitted provided the loss is compensated for by the enhancement, creation or restoration of another wetland (Dennison and Berry 1993; Marsh et al. 1996; Studt and Sokolove 1996; Zedler 1996b). Recommended mitigation ratios (amount lost: amount mitigated) are 1:1, or 1:2, and they can be higher. There is an expressed preference for compensatory mitigation that is near, or adjacent to the altered wetland, called 'on-site' mitigation, rather than mitigation that is 'off-site'. The Permit Record contains, along with the location of the permit site and total acreage altered, information pertaining to any compensatory mitigation requirements. A collection of Section 404 wetland permits is a valuable record of wetland alteration in an area, and has been used in a few areas to determine trends in wetland loss (Kentula et al. 1992; Montana Audubon Society 1993; Rivera et al. 1992).

Landscape changes to wetlands

Wetland ecosystems are affected not only by individual impacts, but also react to impacts in a cumulative manner (Bedford 1996; Johnston et al. 1990; Leibowitz 1992). Impacts to individual wetlands can be examined in a larger context, using a synoptic, landscape approach (Bedford 1996; Detenbeck et al. 1993; Patience and Klemas 1993). While in many areas of environmental impact assessment there has been a scaling-up of approach from direct project impact inquiry, to cumulative impacts, to a landscape approach, the wetland permit process has not experienced a similar evolution in perspective (Race and Fonseca 1996). Time and manpower restrictions in the wetland management process essentially constrain consideration of the wetland landscape to individual sites, and thus landscape level changes and cumulative impacts are difficult to observe. This makes estimates of structural change all the more important.

Most estimates of wetland change report acreage lost, but it is necessary to distinguish between areal loss of wetlands and functional loss of wetlands (Zedler 1996a). The measurement of wetland acreage loss is often difficult, but it is more straightforward than the measurement of functional loss. The current management of wetlands allows wetlands to be drained, filled, and altered, and then recreated at different sites, changing the spatial characteristics of size, type, shape, location, and spatial configuration of wetland sites. It is not yet known what effect such spatial alterations and rearrangement might have on the functioning of the ecosystem at a landscape-scale. Recent research strongly suggests that these structural aspects of the landscape components are influential in controlling many ecosystem functions, including distribution, movement, and persistence of organisms, and redistribution of matter and nutrients (Bell et al. 1997; Detenbeck et al. 1993; Schwarz et al. 1996; Turner et al. 1991; Weller et al. 1996; Weller 1988). While this research does not examine the potential functional effects of management, it does provide an important method to examine changes to landscape-scale structure by examining the spatial context surrounding each individual permit site.

The study area

The research was conducted in the coastal region of North Carolina, in a portion of the White Oak watershed and a portion of the Neuse River watershed (Figure 1). The study area is in two coastal counties (Carteret and Craven) which fall under the jurisdiction of the NMFS in its capacity to review CWA Section 404 Permit applications. The area extends some 100 kilometers inland from the coast and contains extensive acreage of coastal, riparian, and palustrine wetland. This is a nearly level plain of peninsular headlands dissected by bays and rivers. Elevations do not exceed 6 m above mean sea level; soils are unconsolidated sediments. The landscape is predominantly rural, with agriculture, forest, wetlands and shrub communities comprise nearly 90 percent of the area (Holman and Childres 1995). Although mainly rural, coastal North Carolina has experienced significant alterations in the last 15 years through urban development.

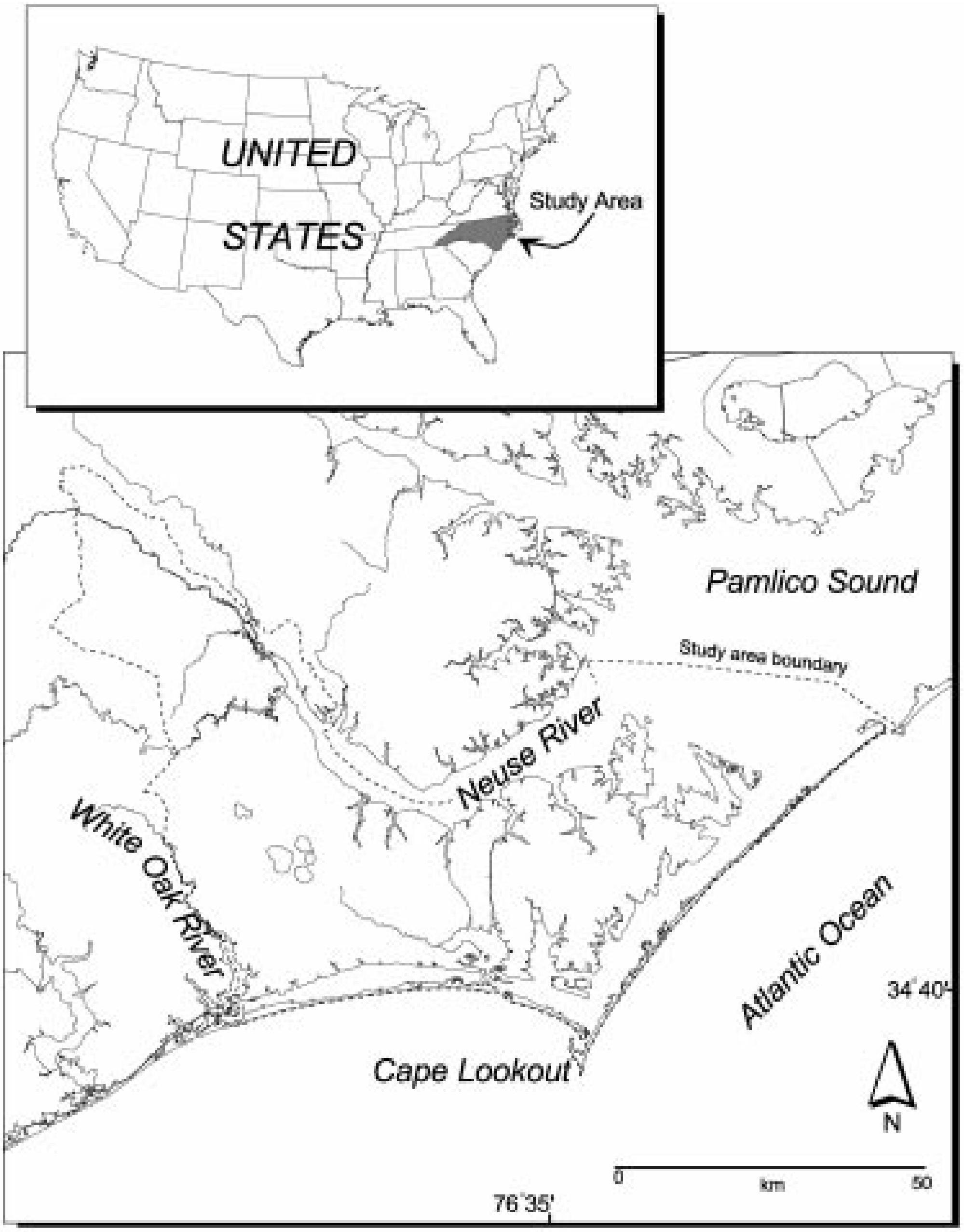

Figure 1. The study area in eastern North Carolina. The study area includes portions of the Neuse River watershed and the White Oak River watershed. The study area contains extensive acreage of estuarine, riverine and palustrine wetlands. The 27 estuarine emergent permits examined in the research are located within the study area.

In the area, tidal salt marshes and brackish marshes extend along the intertidal shore of sounds, estuaries, creeks, and rivers where the water is salty or brackish. The primary plant in salt marshes in the study area is cordgrass (*Spartina alterniflora*) which grades into less salt tolerant species *Juncus roemerianus* and *Spartina patens* with elevation and decreasing salinity. These plants are highly productive because of regular inputs of nutrients, and support complex trophic and detritus-based food webs and provide habitat for economically valuable fish and shellfish species. Coastal wetlands also stabilize the shoreline, retain sediment, and cycle nutrients (Mitsch and Gosselink 1993; Thayer et al. 1978; Williams and Murdoch 1972). The homogeneous cover of grasses, and expansive nature of the salt marsh here, make it ideal for mapping from remotely sensed imagery.

Methods

The datasets

Two data sets were used to analyze spatial changes to the wetland ecosystem. The permit record for the study area was provided by the Corps records of Section 404 permit data. These records were stored in digital and paper form at the NMFS Habitat Conservation Office in Beaufort, NC. There were 109 permits granted between 1984 and 1992 in the study area. The record of spatial change at the landscape level was provided by an analysis of TM sensor data, classified according to the Coastal Change Analysis Program (C-CAP) protocol (Dobson et al. 1995). These data were used to quantify changes in the wetland habitat in areas of permit activity and in areas adjacent to permit sites, as well as to correlate the changes in wetland location and amount presented in the permit record. Analysis of changes to this type of wetland was made possible by the use of a common classification system. The Permit Record utilizes the Cowardin et al. (1979) system, in which coastal salt marsh is classified as estuarine emergent wetland. The C-CAP system is also based on the Cowardin system, and classifies coastal salt marsh as estuarine emergent wetland.

The permit record

A georeferenced dataset of permit activity was created by examining the spatial information found in the paper permit files granted during the time period September 1984 and October 1992. For all permits in the study area, location information was gathered from the paper files. Using this location information, each permit site was visited in the field using a Trimble ProXL Global Positioning System (GPS). The ProXL allows for real time differential correction using a local base station (Fort Macon, NC), yielding accuracy of around 3 meters (Trimble Navigation Limited 1994). The field-gathered location data were linked with the digital permit record, which contained information regarding the type of wetland altered, the type and acreage of alteration, and any mitigation requirements. The georeferenced point dataset was maintained as a spatial coverage using the Universal Transverse Mercator (UTM) projection system (Zone 18, meters, North American Datum 1983) (Snyder 1987) in Arc/Info software.

The Remotely sensed record

The C-CAP effort uses digital remote sensor data and in situ measurements in conjunction with GPS and GIS technology to monitor changes in coastal wetland habitats and adjacent uplands (Dobson et al. 1995). The use of remotely sensed data in general and the TM sensor specifically have proven effective in the mapping and monitoring of wetland ecosystems, in assessing vegetation health and type of individual wetland sites, and in the identification of temporal change in the type and condition of wetland ecosystems (Dobson et al. 1995; Haddad 1992; Patience and Klemas 1993). TM data have a spatial resolution of just under 30 meters, which is considered adequate to map large areas of wetlands, with special success in mapping coastal salt and brackish wetlands (Gross et al. 1987; Hardisky et al. 1986; Hurd et al. 1992). Addition of ancillary data such as National Wetland Inventory maps or aerial photography data was not attempted in this study. Adherence to C-CAP protocols was deemed to be the most important consideration in the classification. For a complete description of the method, see Kelly (1996).

Two near-anniversary date images were acquired for the study area (Path 14 and Row 36) from September 21, 1984 and October 13, 1992. Atmospheric effects were minimized by the choice of a fall scene, and the morning pass over the area. Both images were cloud free. The scenes differ in tide stage: the 1984 scene was imaged at medium low local tide, and the 1992 scene was imaged at near high tide. The absolute difference in tide level was 46 cm, or 1.5 feet. This tide difference is not ideal, but acceptable for vegetation classification according to the protocol document.

Acquisition of identical tidal stage is difficult in North Carolina, where many images are cloudy.

The two images were analyzed in Erdas Imagine software. Both images were geometrically corrected to the UTM projection system (Zone 18, meters, NAD83 datum), using 25 ground control points (gathered using the GPS method described above). Nearest neighbor resampling was used to rectify the images, and resulting RMSE values for each image were under 0.5 pixel. Radiometric correction was performed to reduce the effects of different atmospheric conditions on the two dates using a simple linear regression model between the brightness values for several spectrally stable target reflectors at the base time T_{1984} and the brightness values of the targets at T_{1992} for all bands (Dobson et al. 1995).

Bands 4, 5 and 7 were used in the classification process as they were particularly useful for wetland discrimination. Signatures for each landcover class (in areas where change was minimal) were gathered in the field using the GPS method described above. Supervised classification of bands 4, 5, and 7 for each date used a Minimum Distance classifier (Dobson et al. 1995) yielding 9 classes: cultivated land, grassland, forest or woody land, bare land, estuarine emergent, estuarine woody, palustrine emergent, palustrine forest, and water. A stratified random sample of ground control for each class was used in an accuracy assessment, and 100 ground control points were visited in the field. Overall accuracy for each date was acceptable – 1984 had an overall accuracy of 87 percent (with estuarine emergent wetland classified 100 percent), and 1992 had an overall accuracy of 88 percent (with estuarine emergent wetland classified at 92 percent). Common mis-classification errors include bare and cultivated land, due to crop rotation, woody and woody wetland, urban, bare and sand mixed together, and grassland as cultivated.

Analyzing change to the wetland habitat

Changes to wetland habitat were evaluated using both datasets. The Permit Record contains information regarding the amount of wetland habitat loss due to dredging, filling, or other activity permitted for each permit. Any compensatory mitigation is also quantified in the Permit Record. This information was summed for all permits granted in the study area. The remotely sensed record was provided by the classified imagery, and wetland loss was quantified by performing a change detection routine on the two images. The amount of wetland habitat in 1984 was compared to the amount of wetland in 1992.

Analyzing landscape effects

For each wetland permit site, a buffer was created that encompassed the area containing the permitted alteration (as estimated in the Permit Record), and a series of buffers were created that defined the area outside of the permit site, but immediately adjacent to it (Figure 2). The shape of alteration was not considered because information in the Permit Record was insufficient for any understanding of the shape of the permit alteration. Each permit was assumed to be circular, and the size of the permit itself was calculated from the acreage estimate provided in the permit file, with the following adjustment. A circle the size of the granted permit was determined, with radius equal to the square root of the area divided by π (Radius1). A second circle of twice that radius is drawn (Radius2). This second buffer (Radius2) is assumed to be suitably large to include the entire permit site.

This method tended to overestimate the size of the permit site, and was a crude estimation of the shape of the alteration, however the method reduced the chance that any loss of wetland habitat in the area outside of the permit site would be wrongly attributed to permitted action on-site. The method exaggerated the size of the permit site, and thus might under-estimate the amount of wetland fragmentation (discussed below). A series of buffers greater than the Radius is also created, at Radius2 $+5$, $+10 \ldots +55$, $+60$, $+90$, and $+120$ meters. This series of buffers was used to determine the amount of wetland within the permit site in 1984, and again in 1992 – determining loss of wetland in the site, and to determine the amount of wetland in the area adjacent to the site in 1984 and in 1992 – to determine the change to structure of the wetland at a landscape scale.

The classified imagery from both dates was imported into the Arc/Info Grid format. The classes were reduced from nine to two classes: estuarine emergent wetland and non-wetland. The buffers were overlayed on the binary classified remotely sensed imagery, and the amount of area classed as estuarine emergent wetland determined for each buffer zone for each year using the zonal functions of Grid. The presence of wetland at 1984 and 1992 was calculated for each of the permit areas (defined as areas with radius $<=$ Radius2) and for those areas in each of the successively larger buffer zones. For each wetland permit site, a sig-

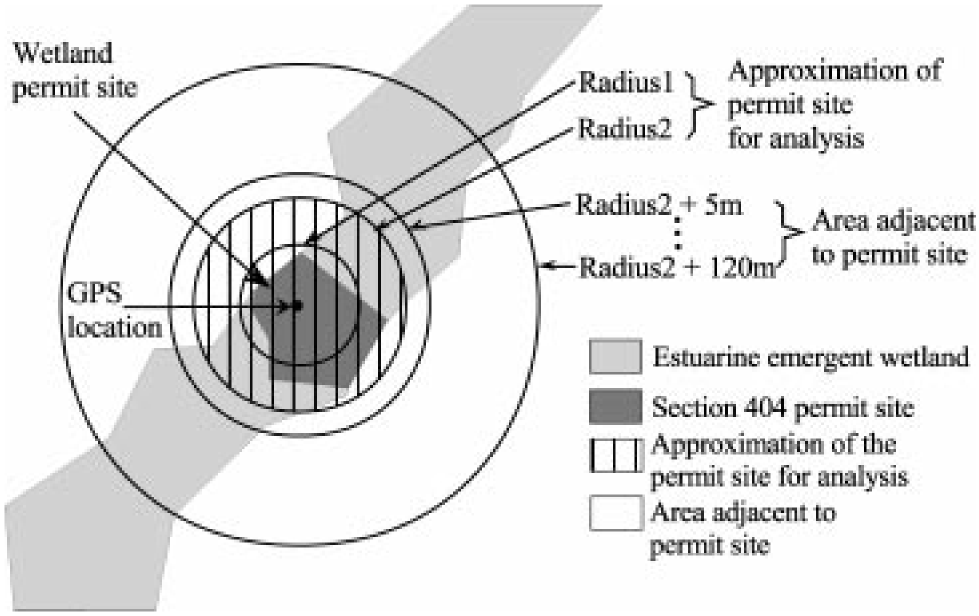

Figure 2. An example of the buffer routine applied to each permit location. The permit site is approximated by the Radius1 and Radius2 values. The area adjacent to the permit is defined by increasingly large buffer radii.

nature curve of wetland change within the site and in the area adjacent to it was created as described below.

Characteristic wetland landscape patterns – homogeneous wetland habitat, patchy wetland landscape, and isolated wetlands – can be demonstrated by graphical representation (Figure 3). When mapped over distance from a site, the amount of habitat will yield a signature curve that demonstrates landscape pattern. In a similar fashion, changes to wetland habitat over space can be discerned by comparing such signatures over time. Examples of the three landscape patterns searched for in the area: loss, fragmentation, and reorganization are displayed in Figure 4. In 4(a–c), the x-axis represents distance away from the permit site, and the y-axis represents the amount of wetland habitat found via classified remotely sensed imagery. The vertical dashed line represents the edge of the permit site; to the left of this line is the permit site itself, to the right of this line is area immediately adjacent to the permit site. The location of this vertical line varies with the size of the permit, as estimated in the Permit Record. Loss occurs when wetland habitat in 1984 is greater than in 1992. Fragmentation occurs when loss of habitat from 1984 to 1992 occurs in the area immediately adjacent to the permit site: to the right of the vertical dashed line. Reorganization occurs when wetland habitat increases in the area to the permit from 1984 to 1992. Figure 4(a) shows a hypothetical situation of wetland loss at the permit site with no additional changes in the area adjacent to the permit site. This is the expected pattern. In Figure 4(b), loss is shown as a decrease in wetland habitat from 1984 to 1992 in the permit area and fragmentation is shown as a decrease in wetland habitat from 1984 to 1992 in the area adjacent to the permit site. In Figure 4(c), reorganization is shown as increased wetland habitat in the area adjacent to the permit site.

Signature landscape curves were created for each of the 27 estuarine emergent wetland permit sites for which alteration was granted by the Corps. These graphs were interpreted to determine the amount of loss, fragmentation and reorganization associated with each of the 27 permit sites examined in the study area. In order to investigate the significance of these observed changes, a general model of the kinds of landcover change that might be expected under wetland management was developed, and the observed changes were compared to this general model. This is a useful technique in landscape analysis (Frohn 1998). The development of this general model was difficult, and relied on the following assumptions. Wetland loss at the permit sites was expected in all cases, as the dataset examined, and each permit site examined included only permitted activity. The coarse method of estimating the permit site from circular buffers might result in some loss of wetland habitat being clas-

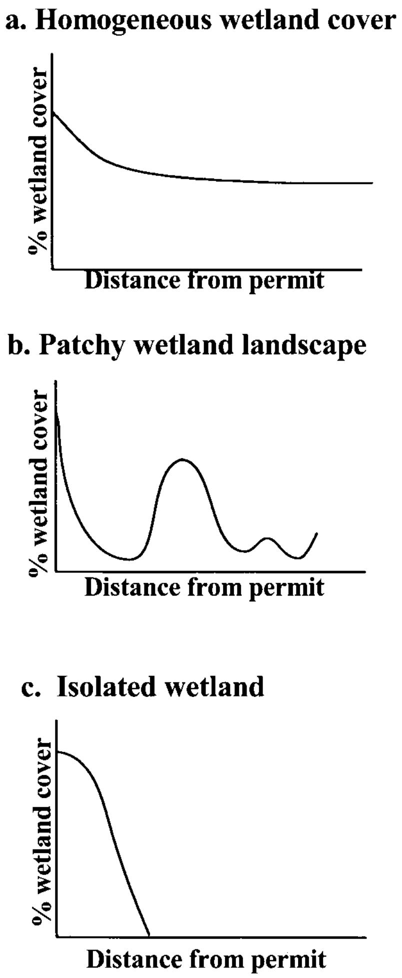

Figure 3. Hypothetical landscape signature curves, describing three different wetland landscapes: (a) homogeneous wetland cover, (b) patchy or discontinuous wetland cover, and (c) isolated wetland habitat.

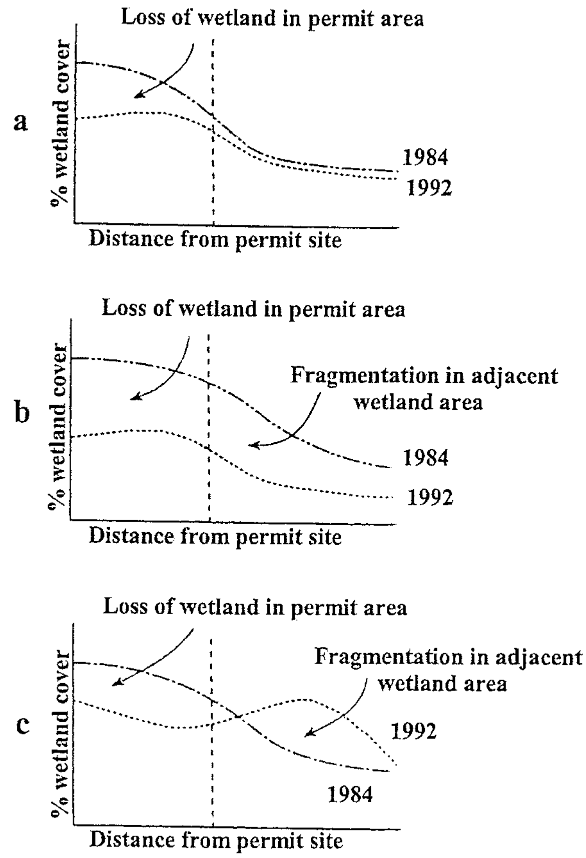

Figure 4. (a) Loss, (b) fragmentation and (c) reorganization demonstrated. In all three charts the dashed vertical line represents the spatial extent of a hypothetical permit site. Alteration to the left of this line is attributed to the original permit work, alteration to the right of this line represents hypothetical additional impacts: fragmentation and reorganization.

sified as fragmentation in the area surrounding the permit site. The expected amount of reorganization of wetland habitat was expected in levels comparable to the amount of permitted compensatory mitigation on-site. While general in form, this model was nonetheless useful for determining the significance of the landscape-scale changes evidenced in the study area.

Results

Wetland habitat change according to the permit record and TM imagery

Both datasets indicated that estuarine emergent wetland has faced significant losses from 1984 to 1992. Results from the Permit Record are listed in Table 1. The Permit Record indicated that estuarine emergent wetland was altered disproportionately more than other types of wetland in the study area. More permits were granted for this type of wetland, and the area affected was larger. According to the Permit Record, losses of nearly 20.23 ha of estuarine emergent wetland were permitted between 1984 and 1992 in the study area. Compensatory mitigation was required for 0.31 ha, yielding a mitigation ratio far below that recommended (1:0.015). Palustrine wetland had

Table 1. Alteration of wetland in the study area and the state, according to the permit record, classed by Cowardin et al. (1979) system.

Cowardin classification system	Number of permits in study area	Permitted ha affected	Required compensatory mitigation	Mitigation ratio
Estuarine	91	19.84	0.31	1:0.015
Palustrine	10	0.77	0.63	1:0.81
Riverine	8	0.72	0.00	1:0
Lacustrine	0	0.00	0.00	–
Marine	0	0.00	0.00	–
Total	109	21.32		

Table 2. Observed loss, fragmentation and reorganization in and around permit sites in the study area between 1984 and 1992.

Type of change	Number of permit sites
Loss alone	2
Fragmentation alone	7
Reorganization alone	2
Loss and fragmentation	9
Loss and reorganization	1
Fragmentation and reorganization	1
Loss, fragmentation, and reorganization	3

the largest mitigation ratio in the study area (1:0.8). Overall, mitigation was required in only three permits (out of 109), and of these three permits, none listed the location of the proposed mitigation site in the paper permit file. In addition to the analysis of the Permit Record, the classified image from September 1984 was compared to that of October 1992. A simple change detection routine determined a loss of 151.76 ha of estuarine emergent marsh in the study area. This represents a loss of 0.5% of the total estuarine marsh in the study area, far more than that found in the Permit Record.

Landscape changes to coastal wetlands: loss, fragmentation, and reorganization

While the individual alterations recorded were small, an examination of the additional changes in the area surrounding each permit site in its adjacent area was enlightening. Of the 109 permit examined, 27 permits were for activities affecting estuarine emergent marsh that had an areal estimate included in the permit file from which a buffer measurement could be constructed. Signature change curves for 1984 and 1992 were produced for each of these 27 permits using the classified imagery. Figure 5 shows examples of these signature curves from three representative permits, including the location of permit site in the left column, the classified imagery for each date with buffers in the two center columns, and the respective landscape graphs in the right column. The permit location figures can be used to differentiate between land and water in the classified images. Figure 5(a) shows an example of wetland loss at the permit site, and wetland fragmentation in the area surrounding the permit site. This permitted alteration was a moderately sized ($\sim$0.40 ha) alteration, for a landowner to place fill material in the emergent marsh on the property. Figure 5(b) displays a rearrangement of wetland habitat in the area, and reorganization in the area surrounding the permit site. This represented a permit for a small, sub- 0.40 ha alteration for a bulkhead and dock system. Figure 5(c) displays small losses at the permit site, but fragmentation in the area surrounding the permit. This third alteration was over 0.40 ha in size, and received a permit for road construction in an area with wetland habitat.

The signature landscape curves for each of the 27 permits were interpreted to determine the occurrence of loss, fragmentation and reorganization. Of the 27 permit sites examined in this manner, 15 showed some loss at the permit site, 20 showed some additional fragmentation, and 7 showed reorganization. Of the 15 cases that showed some loss, 12 of these, or 80% had accompanying loss in areas outside the permit, or fragmentation (Table 2).

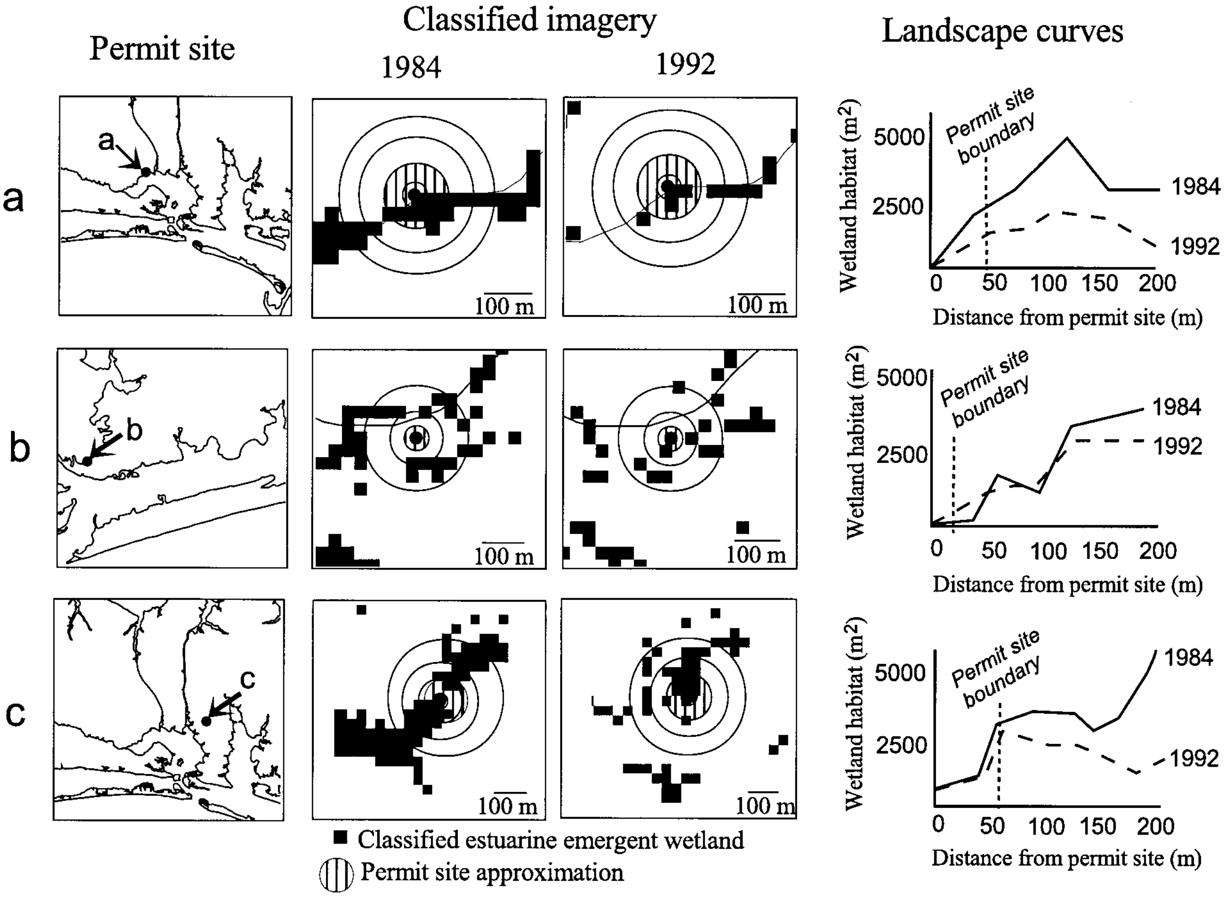

Figure 5. Examples of 3 permit sites, and landscape-scale changes that occurred between 1984 and 1992. The left column displays the location of the permit site in the study area. The middle column displays the classified remotely sensed record, with the dark squares represent estuarine emergent habitat. The corresponding landscape curve is shown in the right column. The upper row of diagrams (a) depict wetland loss at the permit site, and associated loss in the area adjacent to the permit site. The middle row of diagrams (b) depict habitat reorganization at the permit site. The lower row of diagrams (c) show no loss at the permit site, but loss in the area adjacent to the permit site.

Table 3. Expected and observed rates of loss, fragmentation and reorganization in and around the permit sites in the study area between 1984 and 1992. Included is the Chi-Square value for loss and fragmentation. The amount of loss and fragmentation is significantly more than what might be expected under a general model of landscape change under CWA wetland management regime.

	Expected	Observed	$(O–E)^2/E$
Total sites showing loss	27	15	5.3
Total sites showing fragmentation	13	20	3.8
Total sites showing reorganization	0	7	N.A.

Chi-Square score = 9.1; Degrees of freedom = 1, $\alpha(0.005) = 7.88$

These results were compared with an expected pattern of change under a typical wetland management regime. An expected pattern of change in each individual permit site and in the area surrounding the permit site is displayed in Table 3. Since each permit examined was granted, there would be expected losses at every site, or in 27 cases. An extremely rough approximation of fragmentation might allow for additional loss in the area surrounding the permit site in one-half of the cases, given that the buffer estimation that approximated the size of the permit is coarse. This would yield 13 cases. Reorganization would be expected in those cases where compensatory mitigation was required on-site. In this series of permits, as stated above, there was no spatial information within the permit file indicating mitigation acreage or location. Reorganization thus was expected in zero cases. A χ^2 test was performed on the number of permit sites showing loss and fragmentation to determine the significance of these changes (Ebdon 1994). A null hypothesis was developed that stated that the pattern of loss and fragmentation observed is not significantly different from that expected. The χ^2 value of 9.03 suggests significant alteration in the two categories of landscape-scale structural change with a significance value of ($\alpha = 0.005$). Patterns of wetland loss and fragmentation derived from the method presented here are significantly different than might be expected given the typical management regime described above.

Discussion

This research investigated changes to wetlands evidenced in two very different datasets. The Permit Record is the sole national-level attempt at managing, monitoring and inventorying the changes to wetlands in the United States. Landsat TM imagery is a synoptic, timely and spectrally sensitive digital dataset that allows for landscape level investigations of landcover change. The results of this research highlight several important technical and wetland management issues.

First, both datasets used here displayed continued loss of estuarine emergent wetlands. These wetlands are valuable for a host of functions including fish and shellfish spawning and breeding habitat, bird habitat, and shoreline stabilization. More permits are granted for alterations in estuarine emergent wetland in the study area, and more area is affected than their inland and marine counterparts. This is important to document. Estuarine emergent wetland is an extremely valuable coastal resource, providing habitat, shoreline stabilization and other functions. Disproportionate losses of one wetland type has the potential to reconfigure the type and spatial distribution, and thus change the function, of wetland ecosystems in this coastal area.

Second, there is little correlation between the estimates provided by these two datasets, as the Permit Record estimated far less alteration than did the classified imagery. The explanations for this discrepancy include possible underestimation in the Permit Record and overestimation in the remotely sensed record. In the first case, the characterization of wetland alterations from the permit record relied directly upon the area estimates found in the dataset. These were the area estimates used in compiling regional and national wetland inventory statistics. Again, of the permits reviewed, many had area estimates of 0.0, shedding considerable doubt on the overall accuracy of this variable in the dataset. With limited ground verification from field staff, other techniques to monitor wetland change are important. In the second case, classification errors may account for much of the over-estimation of losses to estuarine emergent wetland. Because of the tidal stage of the imagery, tide changes could easily account for some of the wetland losses. While the classification process seemed to remove the errors caused by mis-classification of waterlogged wetland as water, locations not visited in the ground truth process might be mis-classified, accounting for higher errors of omission than reported. Moreover, the Clean Water Act does not govern all wetland alterations in the study area. Alterations to wetlands not governed by the CWA could be occurring in the study area (i.e. agricultural exemptions to the CWA, or natural losses). Finally, the results could indicate additional impacts from the permits listed in the permit database. Thus, the discrepancy between the datasets only highlights the struggle within wetland science and management over wetland delineation, wetland value, and management strategy, and continued improvements in monitoring wetlands are warranted.

The third issue raised by this research concerns compensatory mitigation. Despite the difference in estimates of loss provided by the Permit Record and TM, what both datasets clearly show is that as wetland habitat is lost, compensatory mitigation is not replacing lost wetlands. As described in the CWA, compensatory mitigation and mitigation banking have the potential to rearrange wetland habitat at a landscape-scale, to exchange one kind of wetland for another, and to move habitat patches from one part of a watershed to another location. This process is impossible to follow or document given the information regarding compensatory mitigation currently found in the Permit Record. Whether or not the mitigation is performed, or if it is required to be on-site or allowed off-site is impossible to interpret. Clearly, more tracking of mitigation sites is necessary.

The fourth and final issue raised is that there are important landscape level changes occurring in the study area in association with the CWA. Of the three landscape changes documented here (loss, fragmentation, and reorganization), loss of wetland habitat in a permit site was expected, but fragmentation seemed to be an additional but common occurrence – it occurred in 80% of cases examined. This might indicate a kind of habitat 'nibbling' that is not anticipated in the present permit review process. Moreover, there is evidence of significant habitat reorganization in areas surrounding individual permits. The functional ramifications of such change are numerous. If the change in pattern revealed here is an expected result of the permit process in coastal North Carolina, widespread losses of wetlands not defined in the Permit Record might be occurring unnoticed, having detrimental effects on fish spawning and breeding stocks and local impacts on shoreline stabilization.

Conclusion

This paper presented a method to assess the spatial pattern of wetland alteration as a result of site-specific management decisions. The results confirm that there were changes to the landscape structure of coastal wetlands in the study area that were overlooked by the current management process. Several of the changes discussed in this paper – the disproportionate losses of estuarine emergent marsh, the lack of information tracking mitigation, and the fragmentation and reorganization at the permit site – all have landscape-scale consequences to the wetland ecosystem. They have the potential to re-configure the wetland landscape, and suggest possible functional changes to wetlands that were not investigated in this research.

Evidence that fragmentation and reorganization are occurring in the study area have two important practical consequences. First, these results suggest that the area surrounding a permit site seems to be affected by permit action, and should be included in the review of any permits. Such an activity could be achieved with the use of spatial techniques, high resolution data, and a landscape approach. This echoes recent calls for such an approach in wetland mitigation planning. Second, these results suggest that landscape-scale structural changes to wetlands are occurring as a result of the Clean Water Act wetland management process. The results presented here reinforce the concept, discussed more than a decade ago (Bedford and Preston 1988), that there is a scale discrepancy between management and the effect of such management. This concept continues to be a core issue of wetland management in the United States.

Remotely sensed satellite data combined with GIS have proved to be an approach successful in measuring broad scale landscape patterns and correlating such patterns with ecological functional changes (Aspinall 1994; Frohn 1998; Johnston 1998; Stow 1994). Indeed, many aspects of wetland management are increasingly utilizing these spatial techniques: wetland restoration siting, mitigation bank siting, and wetland inventory have recently benefited from the use of GIS and remote sensing (Llewellyn et al. 1995; Moorehead 1999). However, the wetland management process needs to better incorporate these techniques to examine the spatial effects of management. Evidence of changes to landscape-scale pattern that are the result of management is an important precursor to understanding functional change in an ecosystem. Such evidence can, and should be used as an intelligent aid to wetland permit application review, improving the wetland management process in the United States.

Acknowledgements

The author would like to thank several people for assistance in the completion of this research. Many thanks are due to Bud Cross of National Ocean Service for providing funding support, and B. J. Copeland for granting a Marine Science Fellowship through the North Carolina Sea Grant College Program. Several people helped in the computational aspects of the research: Dave Colby from the National Marine Fisheries Service, and John Helly of the San Diego Supercomputer Center in San Diego deserve mention. Thanks are also due to the staff at the NMFS Habitat Conservation Division for assistance with the Permit Record. I would like to thank Diane Borggaard for helpful reviews of the manuscript, Paula Whitfield for invaluable technical assistance in the field, and Charlie Krouse for systems assistance. Thanks are also due

Drs Mark Kumler and Michael Hodgson for leadership in graduate school. The author would also like to thank the comments of two anonymous reviewers for their insightful comments.

References

Aspinall, R. 1994. GIS and spatial analysis for ecological modeling. *In* Environmental Information Management and Analysis: Ecosystem to Global Scales. Pp. 377–396. Edited by W. K. Michener, J. W. Brunt, and S. G. Stafford. Taylor and Francis, Bristol, PA.

Bedford, B. L. 1996. The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecol Appl 6 (1): 57–68.

Bedford, B. L. and Preston, E. M. 1988. Developing the scientific basis for assessing cumulative effects of wetland loss and degradation on landscape functions: status, perspectives, and prospects. Environ Manag 12 (5): 751–771.

Bell, S. S., Fonseca, M. S. and Motten, L. B. 1997. Linking restoration and landscape ecology. Restoration Ecol 5 (4): 318–323.

Berry, J.F. and Dennison, M. S. 1993. Wetland mitigation. *In* Wetlands: Guide to Science, Law, and Technology. Pp. 278–303. Edited by M. S. Dennison and J. F. Berry. Noyes Publications, Park Ridge, New Jersey.

Coulson, R. N., Lovelady, C. N., Flamm, R. O., Spradling, S. L. and Sauders, M. C. 1990. Intelligent geographic information systems for natural resource management. *In* Quantitative Methods in Landscape Ecology. Pp. 153–172. Edited by M.G. Turner and R.H. Gardner. Springer-Verlag, New York.

Cowardin, L. M., Carter, V., Golet, F. C. and LaRoe, E. T. 1979. A Classification of Wetlands and Deepwater Habitats of the United States, Office of Biological Services, Fish and Wildlife Service, U.S. Department of the Interior, Washington DC.

Dennison, M. S. and Berry, J. F. 1993. Wetlands: guide to science, law, and technology. Noyes Publications, Park Ridge, New Jersey.

Detenbeck, N. E., Johnston, C. and Niemi, G. J. 1993. Wetland effects on lake quality in the Minneapolis/St. Paul metropolitan area. Landscape Ecol 8 (1): 39–61.

Dobson, J. E., Bright, E. A., Ferguson, R. L., Field, D. W., Wood, L. L., Haddad, K. D., Iredale, H., Jensen, J. R., Klemas, V. V., Orth, R. J. and Thomas, J. P.. 1995. NOAA Coastal Change Analysis Program (C-CAP): guidance for regional implementation. NOAA Technical Report NMFS 123, Coastwatch Change Analysis Project, Coastal Ocean Program, NOAA, U.S. Department of Commerce.

Dunn, C. P., Sharpe, D. M., Guntenspergen, G. R., Stearns, F. and Yang, Z. 1990. Method for analyzing temporal change in landscape pattern. *In* Quantitative Methods in Landscape Ecology. Pp. 173–198. Edited by M. G. Turner and R. H. Gardner. Springer-Verlag, New York.

Ebdon, D. 1994. Statistics in Geography. Blackwell Publishers, Oxford, UK, 232 pp.

Frohn, R. C. 1998. Remote Sensing for Landscape Ecology. Lewis Publishers, Washington D. C., 99 pp.

Gross, M. F., Hardisky, M. A., Klemas, V. and Wolf, P. L. 1987. Quantification of biomass of the marsh grass *Spartina alterniflora* loisel using Landsat Thematic Mapper imagery. Photogrammetric Eng. Remote Sensing 53 (11): 1577–1583.

Haddad, K. D. 1992. Coastwatch Change Analysis Program (C-CAP): Remote Sensing and GIS Protocols. Global Change and Education, Vol. 1. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Haig, S. M., Mehlman, D. W. and Oring, L. W. 1998. Avian Movements and wetland connectivity in landscape conservation. Cons Biol 12 (4): 749–758.

Hardisky, M. A., Gross, M. F. and Klemas, V. 1986. Remote sensing of coastal wetlands. Bioscience 36: 453–460.

Harris, L.D. 1988. The nature of cumulative impacts on biotic diversity of wetland vertebrates. Environ Manag 12 (5): 675–693.

Holman, R. E. and Childres, W. S. 1995. Wetland restoration and creation: development of a handbook covering six coastal wetland types. WRRI Project No. 50186. UNC-WRRI-95-3, North Carolina State University Water Resources Research Institute.

Hurd, J. D., Civco, D. L., LaBash, C. L. and August, P. V. 1992. Coastal wetland mapping and change detection in the northeast United States. Global Change and Education, ACSM 92 Tech. pap, Vol. 1. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Johnston, C. A. 1998. Geographic Information Systems in Ecology. Blackwell Publishers, Oxford, 239 pp.

Johnston, C. J., Detenbeck, N. E. and Niemi, G. J. 1990. The cumulative effect of wetland on stream water quality and quantity: a landscape approach. Biogeochemistry 10: 105–141.

Kelly, N. M. 1996. An assessment of the spatial changes to estuarine emergent wetland in coastal North Carolina under Section 404 of the Clean Water Act. Ph.D. Thesis, University of Colorado: Boulder. 204 pp.

Kentula, M. E., Sifneos, J. C., Good, J. W., Rylko, M. and Kunz, K. 1992. Trends and patterns in Section 404 permitting requiring compensatory mitigation in Oregon and Washington, USA. Environ Manag 16 (1): 109–119.

Leibowitz, S. G., B. Abbruzzese, P. R. Adamus, L. E. Hughes, J. T. Irish 1992. A synoptic approach to cumulative impact assessment: a proposed methodology. EPA/600/R-92/167, U.S. Environmental Protection Agency.

Leidy, R. A., Fiedler, P. L. and Micheli, E. R. 1992. Is wetter better? Bioscience 42 (1): 58–65.

Llewellyn, D. W. et al. 1995. A decision-support system for prioritizing restoration sites on the Mississippi River alluvial plain. Cons Biol 10 (5): 1446–1455.

Marsh, L. L., Porter, D. R. and Salvesen, D. A. 1996. Mitigation Banking: Theory and Practice. Island Press, Washington D.C., 300 pp.

Mitsch, W. J. and Gosselink, J. G. 1993. Wetlands. Van Nostrand Reinhold, New York.

Montana Audubon Society 1993. Protecting Montana's Wetlands: An Overview of Montana's Section 404 Program, Montana Audubon Council, Helena, MT.

Moorehead, K. K. 1999. Contiguity and edge characteristics of wetlands in five coastal counties of North Carolina, USA. Wetlands 19 (1): 276–282.

Patience, N. and Klemas, V. 1993. Wetland functional health assessment using remote sensing and other techniques: literature search and overview. Technical Memorandum NMFS-SEFSC-319, U.S. National Oceanic and Atmospheric Administration.

Race, M. S. and Fonseca, M. S. 1996. Fixing compensatory mitigation: what will it take? Ecol Appl 6 (1): 94–101.

Rivera, J. A., A. Mager, J., Ferguson, R. L., Field, D. W. and Cross, F. A. 1992. Verification of submerged aquatic vegetation alterations associated with Corps of Engineers permit requests, Proceedings of the First Thematic Conference on Remote Sensing for Marine and Coastal Environments, New Orleans, LA, June 15–17, 1992.

Schwarz, W. L., Malanson, G. P. and Weirich, F. H. 1996. Effect of landscape position on the sediment chemistry of abandoned-channel wetlands. Landscape Ecol 11 (1): 27–38.

Semlitsch, R. D. and Bodie, J. R. 1998. Are small isolated wetlands expendable? Cons Biol 12 (5): 1129–1133.

Snyder, J. P. 1987. Map projections – A working Manual, U.S. Geological Survey Professional Paper 1395. United States Government Printing Office, Washington DC, 383 pp.

Stow, D. A. 1994. The role of geographic information systems for landscape ecological studies. *In* Landscape Ecology and Geographic Information Systems. Pp. 11–22. Edited by R. Haines-Young, D. R. Green and S. Cousins. Taylor and Francis, London.

Studt, J. and Sokolove, R. D. 1996. Federal wetland mitigation policies. *In* Mitigation Banking: Theory and Practice. Pp. 37–53. Edited by L.L. Marsh, D. R. Porter and D. A. Salvesen. Island Press, Washington D. C.

Thayer, G. W., Stuart, H. H., Kenworthy, W. J., Ustach, J. F. and Hall, A. B. 1978. Habitat values of salt marshes, mangroves and seagrasses for aquatic organisms. *In* Wetland Function and Values: The State of our Understanding. Pp. . Edited by P. E. Greeson, J. R. Clark and J.E. Clark. American Water Resources Association, Minneapolis, MN.

Trimble Navigation Limited 1994. Pro XL System Operation Manual, Trimble Navigation Limited, Sunnyvale California.

Turner, M. G. 1990. Spatial and temporal analysis of landscape pattern. Landscape Ecol 4 (1): 21–30.

Turner, S., O'Neill, R. V., Conley, W., Conley, M.R. and Humphries, H. C. 1991. Pattern and scale: statistics for landscape ecology. *In* Quantitative Methods in Landscape Ecology. Pp. 3–16. Edited by M. G. Turner and R. G. Gardner. Springer-Verlag, New York.

United States Geological Survey 1996. National Water Summary on Wetland Resources. Water Supply Paper 2425, U.S. Geological Survey. Washington, DC.

Weller, C. M., Matzin, M. C. and Wang, D. 1996. Role of wetlands in reducing phosphorus loading to surface waters in eight watersheds in the Lake Champlain Basin. Environ Manag 20 (5): 731–739.

Weller, M. W. 1988. Issues and approaches in assessing cumulative impacts on waterbird habitat in wetlands. Environ Manag 12 (5): 695–701.

Williams, R. B. and Murdoch, M. B. 1972. Compartmental analysis of the production of Juncus roemerianus in a North Carolina salt marsh. Chesapeake Sci 13 (2): 69–79.

Wu, Y., F. H. Sklar, and K. Rutchey. 1997. Analysis and simulations of fragmentation patterns in the Everglades. Ecol Appl 7 (1): 286–276.

Zedler, J. B. 1996a. Coastal mitigation in southern California: the need for a regional restoration strategy. Ecol Appl 6 (1): 84–93.

Zedler, J. B. 1996b. Ecological issues in wetland mitigation: an introduction to the forum. Ecol Appl 6 (1): 33–37.