Wetlands (2011) 31:1275–1285
DOI 10.1007/s13157-011-0242-z

ARTICLE

Estimating Wetland Losses and Gains in Coastal North Carolina: 1994–2001

Melissa Vernon Carle

Received: 23 August 2010 / Accepted: 23 September 2011 / Published online: 15 November 2011

Abstract Wetland resources have continued to decline in coastal regions of the United States despite passage of the 1972 Clean Water Act, creation of federal and state wetland permitting programs, and declaration of the goal of "no net loss" of wetland resources. Wetland loss rates were assessed across 20 counties in coastal North Carolina from 1994 to 2001 using 1994 wetland inventory data from the North Carolina Division of Coastal Management (NCDCM) and the 2001 National Land Cover Dataset. Accuracy assessment results were used to generate adjusted estimates of wetland loss, and the results were compared to restoration data from the NCDCM. Total wetland loss from 1994 to 2001 was 25,303 ha, or 1.95% of the 1994 wetland area. Of the total, 17,858 ha converted to upland and 7,445 ha converted to open water. These results are somewhat higher than published loss rates for Atlantic coastal watersheds and for the United States as a whole. By contrast, agency records suggest that a maximum of 4,591 ha of wetland restoration and 68 ha of wetland creation were begun in the 20 North Carolina coastal counties from 1994 to 2001.

Keywords Mitigation · Permitted impacts · Restoration · Spatial analysis

Electronic supplementary material The online version of this article (doi:10.1007/s13157-011-0242-z) contains supplementary material, which is available to authorized users.

M. V. Carle
Department of Environment and Natural Resources,
North Carolina Division of Coastal Management,
Raleigh, NC, USA

Present Address:
M. V. Carle (✉)
Energy, Coast, and Environment Building, Room 3179,
Louisiana State University,
Baton Rouge, LA 70803, USA
e-mail: mcarle1@tigers.lsu.edu

Introduction

Coastal wetlands are important components of estuarine systems that provide essential habitat for freshwater, estuarine, and marine species, buffer shorelines, export organic carbon to estuaries, and influence biogeochemical cycles (Nixon 1980; Knutson et al. 1981; Knutson et al. 1982; Hopkinson 1985; Farber 1987). While coastal management often stresses the habitat importance of tidal marshes and other wetlands that directly border estuaries, non-tidal wetlands in coastal-draining watersheds also play an important role in maintaining the health of the coastal system. Non-tidal wetlands within the coastal region influence the volume of freshwater discharge and the amount and form of nutrient inputs to estuarine systems (Day et al. 1977; Whigham et al. 1988; Johnston et al. 1990). They lessen the impacts of urban and agricultural development within coastal watersheds and reduce loadings of nitrogen, phosphorus, sediment, and pathogens to estuarine waters (Johnston et al. 1990; Weller et al. 1996; Mallin et al. 2001).

Historically, wetland loss in coastal watersheds of the United States has largely paralleled loss in the nation as a whole (Stedman and Dahl 2008). It has been estimated that 87–89 million hectares (ha) of wetlands existed in the conterminous United States prior to European settlement, approximately half of which were lost by the 1950's (Tiner 1984; Dahl and Johnson 1991). Wetland loss continued at a rate of 185,000 ha per year from the 1950's to the 1970's and 73,000–117,000 ha per year from the 1970's to the 1980's (Tiner 1984; Dahl and Johnson 1991; Brady and

Flather 1994). Wetland loss rates slowed in the later part of the 20th century, with only 23,700 ha lost per year from 1986 to 1997 (Dahl 2000). However, the relative contribution of wetland loss in coastal regions has increased since the 1980's (Brady and Flather 1994). From 1998 to 2004, wetland loss in coastal watersheds of the eastern United States continued at a rate of 24,300 ha per year, despite net gains of wetlands reported for the rest of the nation (Dahl 2006; Stedman and Dahl 2008).

The causes of wetland loss in the United States have shifted substantially over the past 60 years. Prior to the 1970's, most human-induced wetland loss was associated with agricultural and silvicultural activities (Tiner 1984; Hefner and Brown 1985; Brady and Flather 1994; Hefner et al. 1994). Since passage of the Swampbuster provisions of the Food Security Act of 1985, agriculture has decreased and urban and rural development have increased in importance as causes of non-tidal wetland loss (Dahl and Johnson 1991; Brady and Flather 1994; Dahl 2006). Coastal areas are the most rapidly developing areas of the country, seeing a population growth of 33 million people, or 23%, from 1980 to 2003 (Crossett et al. 2004). This trend is expected to continue, putting increased pressure on coastal resources, including coastal wetlands.

Study Area

The North Carolina coastal region consists of the 20 counties in eastern North Carolina with an ocean and/or estuarine shoreline, which are regulated by the 1972 North Carolina Coastal Area Management Act (CAMA). The coastal region encompasses over 23,000 km^2, and includes freshwater, brackish, and salt water systems and extensive forested and emergent wetlands (Sutter 1999). The primary goal of CAMA is to balance protection of coastal resources and economic growth in the coastal region. One objective is to prevent additional degradation of coastal resources, including coastal wetlands. CAMA provides strict protection for estuarine tidal wetlands in the 20 coastal counties. "Coastal wetlands" are defined by CAMA as tidally-influenced wetlands containing one or more of ten designated salt-tolerant and fresh marsh plant species (North Carolina General Statutes 113A–113(b)(1) and 113–229(n)(3)). CAMA does not provide direct protection for non-estuarine (palustrine, riverine, and lacustrine) wetlands within the coastal region, but it encourages planning to minimize wetland impacts. It is unknown whether planning alone has been sufficient to protect coastal wetlands that do not fall under CAMA jurisdiction.

Previous studies have estimated that between 44 and 54% of North Carolina wetlands were lost by the 1980's, with much of the loss occurring prior to the 1950's (Cashin et al. 1992; Moorhead and Cook 1992). Studies focused on analysis of the permit record found that estuarine wetland impacts were significantly reduced following the implementation of CAMA in 1972 (Stockton and Richardson 1987), but that this benefit did not extend to non-estuarine wetlands in the coastal region. Only 3% of Section 404 permits issued in coastal North Carolina from 1984 to 1992 required mitigation (Kelly 2001). Impacts were often greater than what was stated in the permit record and comparison to Landsat-based classifications revealed indirect impacts to surrounding wetlands not included in the permit (Kelly 2001).

Despite state and federal policies aimed at preventing further wetland loss, North Carolina's coastal wetlands are threatened by both increasing coastal populations and sea level rise. The United States Census Bureau estimates that the population of North Carolina's coastal counties grew by 10% from 1994 to 2001 (North Carolina Office of State Budget and Management 2001). This population growth has spurred demand for urban and suburban development in many parts of the coastal region (Crossett et al. 2004). North Carolina is also experiencing one of the fastest rates of relative sea level rise on the east coast of the United States, and many low lying lands are vulnerable to submersion and increased erosion (Brinson 1989; Riggs and Ames 2003; Poulter 2005). The intent of this study was to quantify wetland losses and gains over the 7 year time period from 1994 to 2001 and provide an overview of the status of wetland resources in the North Carolina coastal region.

Methods

Overview

I determined wetland losses and gains between 1994 and 2001 for the North Carolina coastal region by comparing North Carolina Division of Coastal Management (NCDCM) 1994 Wetland Inventory data (Sutter 1999) with the 2001 National Land Cover Database (NLCD) (Homer et al. 2004). True-color aerial photography from 2004 to 2006, created by the National Agriculture Imagery Program (NAIP), was used as a base layer for reference and accuracy assessment (National Agriculture Imagery Program 2004, 2006). I calculated wetland gains over the same time period by querying the NCDCM Wetland Mitigation Site Database. The time period for the analysis was selected based on data availability.

NCDCM Wetland Inventory

The NCDCM Wetland Inventory dataset was created in the mid 1990's by combining National Wetlands Inventory

(NWI) data, county-level soils data, and landcover classifications derived from 1988 to 1994 LANDSAT data (Sutter 1999). The NWI data for eastern North Carolina were created by stereo interpretation of 1:58,000 scale color-infrared photography obtained during the winters of 1981, 1982, and 1983 (Hefner and Moorhead 1991; U.S. Fish and Wildlife Service 1995; Wilen and Bates 1995; Sutter 1999). Approximately one half day of field-checking was performed for each 1:24,000-scale wetland map (Hefner and Moorhead 1991). County-level soil surveys are 1:24,000-scale and were created from aerial photography by the U.S. Department of Agriculture, Natural Resource Conservation Service. The hard-copy soil maps were scanned or hand-digitized by the North Carolina Center for Geographic Information Analysis (NCCGIA) (Sutter 1999). The 1988 landcover classification was created for the Albemarle-Pamlico National Estuarine Study by NCCGIA and the North Carolina State University Computer Graphics Center by supervised classification of 30-m resolution Landsat Thematic Mapper (TM) satellite imagery (Sutter 1999). The 1994 landcover maps were created by NCCGIA using the same method (Sutter 1999).

Wetland polygons from the NWI served as the core dataset. To update the data, NCDCM used the 1988 and 1994 landcover classifications to identify wetlands that had been cleared for development or cutover since the NWI maps were created. The NWI program originally excluded certain types of farmed wetlands as a matter of policy (Dahl et al. 2009). NCDCM found through field investigation of randomly selected NWI polygons that pine plantation wetlands were among the categories omitted in North Carolina (Sutter 1999). The ancillary data were used to add a "managed pine" wetland class for areas that were mapped as pine plantations in the land cover classification and mapped as hydric soils in the soil surveys. The ancillary data were also used to improve the accuracy of some wetland classes, based on consistent classification issues determined during field investigation of randomly selected NWI polygons. Over 400 randomly selected polygons were visited in the field to calibrate the data. For the end product, the NWI wetland classes were simplified into 13 general wetland classes (Sutter 1999).

Accuracy assessment of the NCDCM wetlands data was performed on a stratified random sample of 626 sites (Shull 1999). The overall accuracy of the data was found to be 81.74% for distinguishing between wetlands and uplands (level I error matrix) and 65.87% for distinguishing among uplands and all wetland classes (level II error matrix) (Shull 1999). The highest accuracies were for the salt/brackish marsh, estuarine scrub-shrub, bottomland hardwood/swamp forest, and pocosin classes. The lowest accuracies were for the maritime forest, headwater, pine flat, and hardwood flat classes. Freshwater marshes and managed pinelands had intermediate accuracies (Shull 1999).

National Land Cover Database

The 2001 NLCD is a nationwide land cover classification produced by the Multi-Resolution Land Characteristics Consortium (MRLC). The project spans 65 distinct mapping zones within the conterminous United States and includes 16 land cover classes, including two wetlands classes (forested and marsh), five natural upland land classes, two agricultural classes, and four urban classes. The NLCD classification was based on three geometrically-corrected Landsat 5 and Landsat 7 images collected during the early, peak, and late growing season of 2001 (Homer et al. 2004). Ground reflectance was converted to at-satellite reflectance to normalize the data and a tassel-cap transformation was performed to reduce the size of the dataset while maintaining more than 97% of the spectral variance in the original bands (Homer et al. 2004). The results of the tassel-cap transformation were combined with ancillary data including elevation, slope, aspect, positional index, population density, and roads (Homer et al. 2004). Supervised classification was performed using decision and regression tree algorithms and training data collected from high-resolution orthoimagery, local datasets, field data, and Forest Inventory Analysis plot data (Homer et al. 2004; 2007). The resulting 30-m cells were aggregated to a 0.4047-ha minimum mapping unit (Homer et al. 2007). While the MRLC has not yet performed a formal accuracy assessment on the 2001 NLCD, cross-validation modeling gives rough overall map accuracy estimates of between 70 and 98% with an average of 83.9% across all mapping zones (Homer et al. 2007).

Combining NCDCM and NLCD

I identified the 2001 NLCD land cover class for each wetland polygon within the NCDCM Wetland Inventory by performing a county-level identity analysis in ArcGIS 9.1. The Identity Tool in ArcGIS 9.1 computes the geometric intersection of two spatial datasets. Wetland polygons that overlapped NLCD classifications received the NLCD attributes. Where a wetland polygon overlapped with two or more NLCD classifications, the original polygon was split into multiple new polygons. I created a new attribute to store wetland change class (no change, conversion to upland, or conversion to open water). I assigned each polygon a wetland change class using a set of decision rules based on the combination of 1994 wetland type and the 2001 land cover class (Online Table S1).

Generally, I assumed that NCDCM wetland polygons that were classified as urban or barren land in the 2001

NLCD had been converted to uplands. I also assumed that NCDCM wetland polygons that were classified as open water in the 2001 NLCD converted to open water through flooding or erosion. Comparison to the 2006 NAIP imagery indicated that NCDCM marshes and estuarine woody, estuarine shrub scrub, and maritime forest wetlands classified as barren land in the 2001 NLCD were almost always sandy areas of barrier islands, if they were located in counties with oceanfront shorelines. In counties without oceanfront shorelines, wetland classification as barren land in the 2001 NLCD represented an actual wetland conversion to upland. Therefore, I only used the barren land NLCD classification as an indicator of wetland conversion for counties without an oceanfront shoreline. Wetland polygons that were classified as grassland/herbaceous or agricultural in the 2001 NLCD were not included in the conversion to upland class. Comparison to the 2006 NAIP imagery suggested that most of these areas were recent clear-cuts that had been re-planted or left to naturally regenerate. Because of a high probability of confusion with forestry activities, I was unable to measure wetland conversion to agriculture in this study.

Accuracy Assessment

I performed an accuracy assessment for the wetland change analysis by comparing the wetland change classes of a subset of wetland polygons to the 2004 and 2006 true-color NAIP aerial photography (Online Figure S1). These sets of aerial photography were chosen because they were the closest to the end of the study period that were available over the entire coastal region. The 2004 images were 2-m true-color digital orthophotographs and were available for all or part of 14 of the 20 coastal counties. The 2006 images were 1-m true-color digital orthophotographs and were available for all 20 counties. While the preferred source of reference data for remote sensing accuracy assessments is field data, interpretation of high-resolution aerial photography is considered an acceptable substitute when the classification is derived from coarse resolution satellite imagery and a simple classification system is being used (Congalton 1991; Congalton and Green 1993). In this case, the classification system consisted of three simple classes: no change, conversion to upland, and conversion to open water. Because there was no attempt to distinguish between vegetated classes, the accuracy of the classification could be assessed with a high degree of confidence by visually comparing the classified polygons to the NAIP imagery.

I generated a stratified random sample of 300 wetland polygons from the wetland change analysis dataset for all 20 CAMA counties using the Hawth's Analysis Tools for ArcGIS "Create Random Selection" tool (Beyer 2004). I selected 100 wetland polygons for each of the three wetland-change classes (no change, conversion to upland, conversion to open water). This sampling distribution was determined to be sufficient to provide a statistically sound representation of each class and estimate accuracy with 95% confidence (Hord and Brooner 1976; Rosenfield et al. 1982; Congalton 1991). Each of the 300 selected polygons was compared to the 2006 and, when available, 2004 NAIP imagery to determine the accuracy of the wetland change classification. NCDCM wetland polygons that were still naturally vegetated in the 2004 and 2006 aerial photography were given a "no changet" reference classification. NCDCM wetland polygons that contained urban features in the aerial photography were placed in the "conversion to upland" reference class. NCDCM wetland polygons that were open water in the aerial photography were placed in the "conversion to open water" reference class. If only part of a polygon was accurately mapped, I based the reference classification on the change class that occupied the greatest percentage of the polygon area. If the accuracy of the change classification was not clear based on the 2006 NAIP imagery or if the polygon was equally split between two or more reference classes, the polygon was omitted from the accuracy assessment.

I generated an area-based confusion matrix by comparing the wetland change classification to the accuracy assessment data derived from the NAIP imagery for each accuracy polygon (Story and Congalton 1986; Congalton 1991; Stehman 1997). The confusion matrix was used to calculate overall map accuracy and producer's and user's accuracies for each class. Overall map accuracy is calculated as the area of correctly classified polygons in all classes divided by the total area of polygons sampled (Story and Congalton 1986; Congalton 1991). Producer's accuracy measures errors of omission and is defined as the area of correctly classified polygons in a particular class divided by the total area of reference polygons for that class (Story and Congalton 1986; Stehman 1997). User's accuracy measures errors of commission and is defined as the area of correctly classified polygons in a particular class divided by the total area of polygons from that class that were classified (Story and Congalton 1986; Stehman 1997). Standard error (SE) for each accuracy statistic was calculated according to the formula:

$$SE = \sqrt{\frac{p(1-p)}{n}}$$

where p is the proportional accuracy and n is the sample area used to calculate the accuracy statistic.

The totals for each wetland change class were adjusted for accuracy according to the ratio method (Hay 1988), which scales the class total by the ratio of the user's accuracy to the producer's accuracy for that class:

$$t_{adj} = \left(\frac{\text{user's accuracy for class}}{\text{producer's accuracy for class}} \right) \times t_{unadj}$$

where t_{adj} is the adjusted total for the class and t_{unadj} is the unadjusted total for the class. Ninety-five percent confidence intervals were constructed for the adjusted wetland loss rates according to the formula:

$$t_{unadj} \times \left[\left(\frac{\text{user's accuracy for class}}{\text{producer's accuracy for class}} \right) \pm 1.96 \times \text{standard error} \right]$$

where the standard error is the standard error calculated for the scaling factor.

Regression Analysis

I performed linear regression analysis to determine whether an increase in population density in the 20 coastal counties between 1990 and 2000 was associated with an increase in the percent of wetlands in the county converted to upland between 1994 and 2001. The percent of wetlands converted to uplands from 1994 to 2001 was calculated for each county as:

$$\frac{\text{1994 wetland area} - \text{2001 wetland area}}{\text{1994 wetland area}} \times 100$$

County population growth rates were obtained from the U.S. Census 2000 data (North Carolina Office of State Budget and Management 2001) and were divided by county area to determine changes in population density. Statistical analysis was performed using the SPSS Statistics program.

Quantifying Wetland Gains

Ideally, a similar GIS-based analysis of the NCDCM wetlands data and the 2001 NLCD could be used to estimate wetland gains to directly compare to wetland losses. However, accuracy assessments performed on the 1992 NLCD showed significant confusion of the forested wetland and forested upland categories (Yang et al. 2001). Since accuracy assessment results have not yet been released for the 2001 NLCD, there is no reason to believe that this issue has been improved in the new classification. While the NLCD can distinguish between wetlands and developed uplands and open water with a high degree of accuracy, it is inadequate for recognizing the more subtle changes associated with the restoration of wetland hydrology. Therefore, I instead estimated the total area of wetland restoration, creation, enhancement, and preservation performed as mitigation in the 20 coastal counties by querying the NCDCM Mitigation Site Database.

The NCDCM Mitigation Site Database is a relational Microsoft Access database that stores information related to individual mitigation projects in the North Carolina coastal region. Data are obtained from joint permits issued by the U.S Army Corps of Engineers for Section 404 impacts, NCDCM for CAMA impacts, and North Carolina's Section 401 water quality certification program. Additional data are derived from associated mitigation plans and mitigation banking instruments. Data include the location, owner, and size of each individual mitigation site as well as the total area of wetland restoration, creation, enhancement, and preservation performed at each site by wetland habitat type. The NCDCM database was reconciled with other mitigation site databases maintained by the NC Department of Transportation (NCDOT), the NC Ecosystem Enhancement Program (NCEEP), and the NC Division of Water Quality (NCDWQ). NCDOT and NCEEP are the two largest suppliers of wetland mitigation in the state and NCDWQ oversees the Section 401 water quality certification program in North Carolina.

I queried the NCDCM database to select all mitigation sites that were begun in the 20 coastal counties between 1994 and 2001. I performed a separate query to select all mitigation sites in the coastal counties with an unknown start date. Because areal data on restoration projects performed for reasons other than mitigation was incomplete or uncertain, these projects were excluded from the analysis.

Results

Accuracy Assessment

The overall accuracy of the wetland change classification was 82.7% (Table 1). Producer's accuracies were 69.2% for the "conversion to upland" class, 100.0% for the "conversion to open water" class, and 81.1% for the "no change" class. User's accuracies were 41.1% for the "conversion to upland" class, 74.3% for the "conversion to open water" class, and 95.5% for the "no change" class. The scaling factors used to calculate accuracy-adjusted totals were 0.59 for the "conversion to upland" class and 0.74 for the "conversion to open water" class.

Wetland Losses

The accuracy-adjusted wetland change classification indicates that 24,676 ha of wetlands, or approximately 1.91% of the wetlands remaining in the coastal region, were lost from 1994 to 2001 (Table 2, Figs. 1 and 2, Online Figures S2–S4). The 95% confidence interval for the adjusted wetland loss rate is 21,399 to 27,941 ha. Of the total wetland loss, 15,494 ha (95% confidence interval: 11,687–19,304) were lost to upland development and 9,182 ha (95% confidence interval: 7,792–10,572) were lost to open water conversion. Managed pine

Table 1 Confusion matrix showing agreement between 1994 and 2001 wetland change estimates and reference polygons based on 2004 and 2006 aerial photography

Reference Class Area (ha)		No Change	Conversion to Upland	Conversion to Open Water	Total
1994–2001 Wetland Change Class Area (ha)	No Change	108.13	5.09	0.00	113.22
	Conversion to Upland	16.41	11.44	0.00	27.85
	Conversion to Water	8.79	0.00	25.47	34.26
	Total	133.33	16.53	25.47	175.33
Overall Accuracy=82.7%					
Overall Standard Error=0.029					
Producers Accuracy		81.1%	69.2%	100.0%	
Standard Error		0.034	0.11	0.00	
Users Accuracy		95.5%	41.08%	74.34%	
Standard Error		0.019	0.093	0.075	

wetlands accounted for 63.2% of all wetlands converted to upland classes from 1994 to 2001. When this class was excluded, total wetland loss from 1994–2001 was 14,767 ha, or 1.58% of 1994 wetland area.

Total wetland loss was highest for the managed pineland, salt/brackish marsh, and riverine swamp forest wetland classes. Total percent loss was greatest for the freshwater marsh, salt/brackish marsh, estuarine forest, and maritime forest classes. Wetland conversion to upland was highest for managed pinelands, riverine swamp forests, pine flats, and pocosins. Percent conversion to upland was highest for maritime forest, managed pinelands, freshwater marsh, and headwater swamps. Wetland conversion to open water was highest for the salt/brackish marsh, freshwater marsh, and riverine swamp forest wetland classes. Percent conversion to open water was highest for freshwater marsh, salt/brackish marsh, and estuarine forest.

Wetland losses to upland development were highest in Craven, New Hanover, Brunswick, Carteret, Bertie, and Onslow counties (Table 3). The multiple regression analysis indicated that change in population density was significantly correlated to the percent of wetlands converted to uplands within the coastal counties between 1994 and 2001 (Fig. 3), with all coefficients significant at the 0.05 level. However, the relationship was strongly driven by the

Table 2 Accuracy-corrected estimated wetland conversion (ha) between 1994 and 2001, by wetland class

Wetland Class	Total Wetland Area in 1994	Converted to Upland Classes by 2001	Percent Change	Converted to Open Water by 2001	Percent Change	Total Wetland Loss	Total Percent Loss
Bottomland hardwood forest	45,566	369	0.81%	81	0.18%	450	0.99%
Depressional swamp forest	87,951	486	0.55%	320	0.36%	806	0.92%
Estuarine forest	425	4	0.83%	18	4.33%	22	5.15%
Estuarine shrub scrub	12,892	143	1.11%	281	2.18%	425	3.29%
Freshwater marsh	11,291	191	1.69%	1,154	10.22%	1,345	11.91%
Hardwood flat	55,097	519	0.94%	63	0.11%	581	1.05%
Headwater swamp	12,528	148	1.19%	31	0.25%	180	1.44%
Maritime forest	1,479	58	3.95%	12	0.80%	70	4.75%
Pine flat	120,127	1,098	0.91%	223	0.19%	1,322	1.10%
Pocosin	223,728	985	0.44%	96	0.04%	1,081	0.48%
Riverine swamp forest	275,232	1,304	0.47%	815	0.30%	2,120	0.77%
Salt/brackish marsh	87,146	395	0.45%	5,970	6.85%	6,366	7.30%
Total without managed pine	933,461	5,701	0.61%	9,066	0.97%	14,767	1.58%
Managed pine	361,060	9,793	2.71%	116	0.03%	9,909	2.74%
Total with managed pine	1,294,521	15,494	1.20%	9,182	0.71%	24,676	1.91%

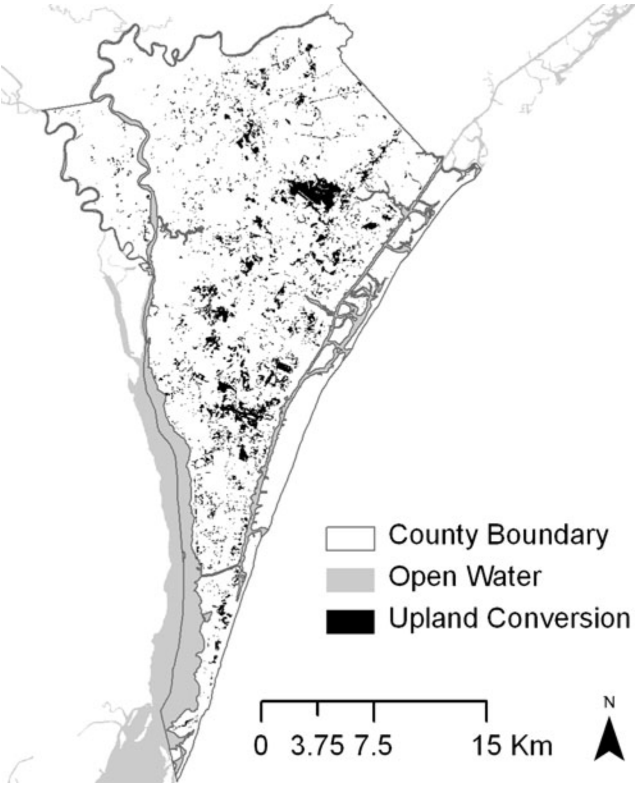

Fig. 1 Example of wetland loss to upland development, New Hanover County, NC

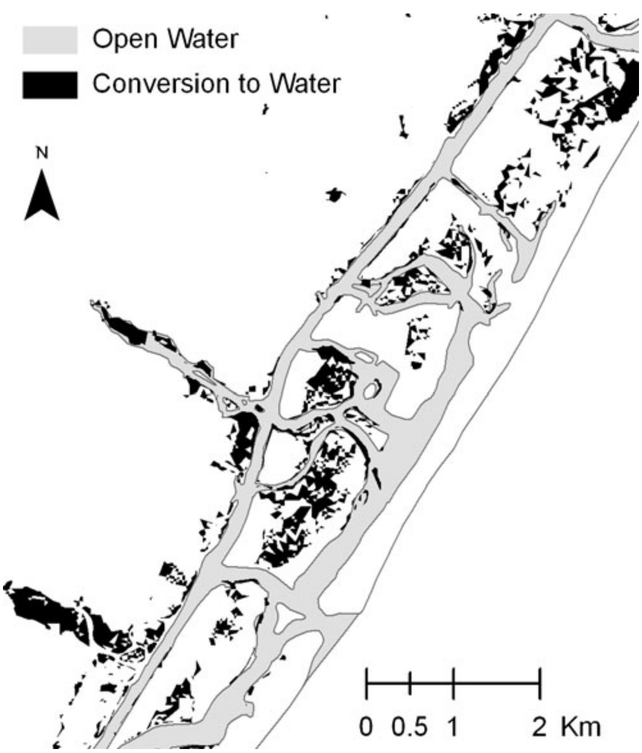

Fig. 2 Example of wetland conversion to open water near Wrightsville Beach, NC

data point for New Hanover County, which was the only urbanizing county in the study area and the only county that had a large increase in population density. When this point was included, changes in population density accounted for 92.7% of the variation among the counties in the percent of wetlands converted to uplands between 1994 and 2001 (Fig. 4). If this point is removed, there is no correlation between population density change and percent wetland loss among the remaining counties (r^2=0.04), all of which experienced population density changes of less than 8 persons/km^2 and rates of wetland conversion to upland of less than 2%. Additional data from counties experiencing moderate and rapid population growth is needed to determine whether the relationship between population growth and wetland conversion is valid or if New Hanover County represents an outlier.

Wetland Gains

The best available data from the NCDCM Wetland Mitigation Site Database indicated that a total of 11,836 ha of wetland compensatory mitigation projects were begun in the North Carolina Coastal Counties between 1994 and 2001 (Table 4). This includes 3,443 ha of restoration, 1,548 ha of enhancement, 63 ha of creation, and 6,782 ha of preservation. An additional 6,054 ha of mitigation were included in the database but lacked a start date for the projects. This includes 1,148 ha of restoration, 1,549 ha of enhancement, 5 ha of creation, and 3,352 ha of preservation. The majority of wetland projects have focused on non-riverine wetland systems. The counties with the most wetland compensatory mitigation projects from 1994 to 2001 were Tyrrell, Craven, and Beaufort Counties. These counties were each home to one or more large (> 500 ha) projects.

Discussion

The accuracy assessment for the wetland change analysis demonstrated a moderate degree of overall classification error (17%) associated with the use of the NLCD to update existing wetlands GIS data. Some of this error is related to the combined error of the two datasets and the different methods used to produce them. Other error is related to the use of a “single moment in time” snapshot to estimate land use change. It is also important to note that the use of 2004 and 2006 aerial photography to assess the accuracy of a 2001 classification introduces a certain amount of error into the accuracy assessment results.

The overall annual wetland loss rate that I found for coastal North Carolina is somewhat higher than would be expected based on recent national studies by the U.S. Fish and Wildlife Service (USFWS) (Online Table S2). Dahl

Table 3 Accuracy-corrected estimated wetland conversion (ha) between 1994 and 2001, by county

County	Total Wetland Area in 1994	Conversion to Upland by 2001	Percent Change	Conversion to Open Water	Percent Change	Total Wetland Loss	Total Percent Loss
Beaufort	66,769	1,045	1.57%	216.64	0.32%	1,262	1.89%
Bertie	95,859	1,314	1.37%	102.68	0.11%	1,417	1.48%
Brunswick	99,306	1,587	1.60%	779.81	0.79%	2,367	2.38%
Camden	31,693	159	0.50%	38.27	0.12%	197	0.62%
Carteret	95,224	1,414	1.48%	1728.92	1.82%	3,143	3.30%
Chowan	22,724	49	0.22%	21.03	0.09%	70	0.31%
Craven	149,119	2,080	1.39%	329.67	0.22%	2,410	1.62%
Currituck	33,217	224	0.67%	340.09	1.02%	564	1.70%
Dare	81,321	689	0.85%	1060.09	1.30%	1,750	2.15%
Gates	48,247	440	0.91%	2.68	0.01%	442	0.92%
Hertford	29,068	372	1.28%	14.53	0.05%	386	1.33%
Hyde	86,325	626	0.73%	832.61	0.96%	1,459	1.69%
New Hanover	19,370	1,673	8.64%	723.94	3.74%	2,397	12.37%
Onslow	116,878	1,262	1.08%	1126.23	0.96%	2,389	2.04%
Pamlico	63,464	565	0.89%	202.25	0.32%	767	1.21%
Pasquotank	13,897	199	1.43%	26.00	0.19%	225	1.62%
Pender	113,400	524	0.46%	441.91	0.39%	966	0.85%
Perquimans	30,673	489	1.60%	21.48	0.07%	511	1.67%
Tyrrell	62,360	375	0.60%	298.61	0.48%	674	1.08%
Washington	35,347	402	1.14%	874.31	2.47%	1,277	3.61%
Total	1,294,259	15,489	1.20%	9181.76	0.71%	24,671	1.91%

(2006) found an annual loss rate of 35,586 ha of wetlands per year for the entire conterminous United States from 1998 to 2004, if gains from freshwater ponds are excluded. Freshwater ponds are not mapped as wetlands by NCDCM, so excluding them made the results of the two studies more directly comparable. Stedman and Dahl (2008) found an annual wetland loss rate of 5,790 ha for coastal-draining watersheds along the Atlantic coast. When adjusted for the accuracy of the wetland change classification, my results show a wetland loss rate of 3,615 ha per year in North Carolina, or about 62% of the USFWS loss rate for the entire Atlantic coastal region and one-tenth the reported loss rate for the nation as a whole.

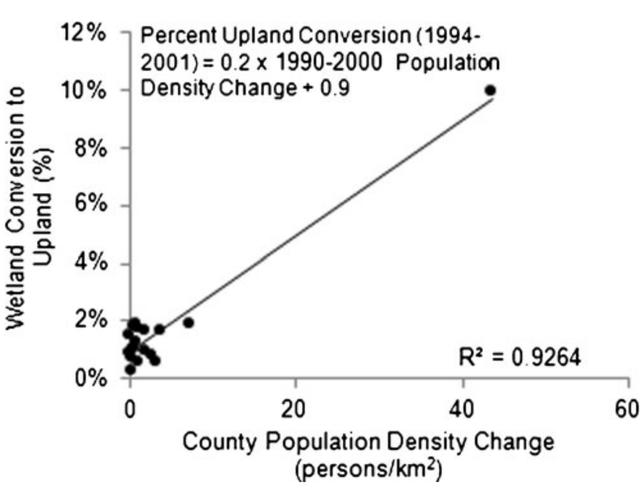

Fig. 3 Multiple regression model for percent wetland conversion to upland from 1994 to 2001 as a function of change in county population density from 1990 to 2000

Standardizing by initial wetland area allows for a more direct comparison of the rates of wetland loss between the three studies (Fig. 5). I calculated an annual total percent wetland loss of 0.28% for coastal North Carolina. This is three times greater than the annual percent wetland loss estimated for the Atlantic Coast Region and four times greater than the annual percent wetland loss estimated for the entire conterminous U.S. Part of the difference may be related to the time lag between my study (1994–2001) and the USFWS studies (1998–2004). It is possible that the regional and national wetland loss rates decreased between 1994 and 2004 and that my study captured the higher rate of wetland loss at the beginning of that time frame.

Another reason why the wetland loss rate found in this study may be high compared to the USFWS regional and national wetland loss estimates is that my estimates include managed pineland wetlands. Managed pine wetlands account for 27.9% of all wetlands in the 20 North Carolina coastal counties, but most were not included in the NWI maps for North Carolina (Sutter 1999). The USFWS Status

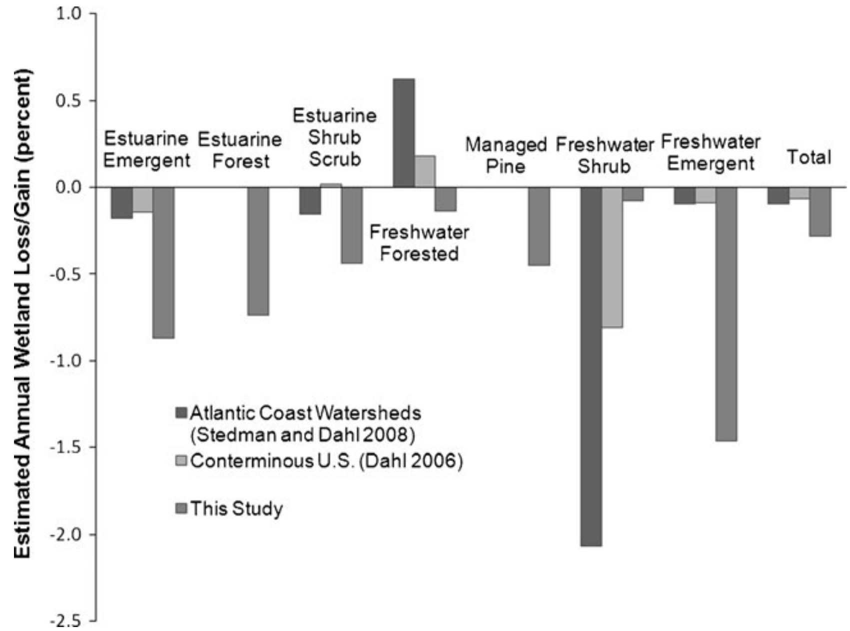

Fig. 4 Comparison to annual percent weland loss calculated from the U.S. Fish and Wildlife Service Status and Trends Reports

and Trends Reports (Dahl and Johnson 1991; Hefner et al. 1994; Dahl 2000; 2006; Stedman and Dahl 2008) use the same wetland mapping methodology and classification system as the NWI, and may also exclude most managed pine wetlands in coastal North Carolina. While managed pine wetlands account for 27.9% of the wetlands in the North Carolina coastal counties, they account for a disproportionately high 63.2% of wetland loss to upland land uses. When they are excluded, the overall wetland loss rate drops to 1,989 ha per year—about 34% of the loss rate reported by USFWS for the Atlantic coast region and about 6% of the loss rate reported for the entire conterminous United States.

The results of the multiple regression analysis indicate that population growth may have been an important driver of wetland conversion to upland in New Hanover County during the study time period. However, additional data points from other areas experiencing rapid growth would be needed to determine whether a true relationship exists between increasing population density and wetland conversion. This would be consistent with national studies that have found urban development to be an increasing cause of wetland loss throughout the United States (Dahl and Johnson 1991; Brady and Flather 1994; Dahl 2006). Additional research is also needed to determine the major causes of wetland conversion in rural

Table 4 Wetland gains (ha) from 1994–2001 estimated from the NC Division of Coastal Management restoration site database

	Restored	Enhanced	Created	Preserved	Total
Compensatory Mitigation (1994–2001)					
Riverine	29	103	0	375	507
Non-Riverine	3,129	1,307	0	2,124	6,560
Tidal	66	78	60	211	415
Upland Buffer	0	0	0	54	54
Unknown	219	60	3	4,018	4,300
Total	3,443	1,548	63	6,782	11,836
Compensatory Mitigation (unknown start date)					
Riverine	1	0	1	157	159
Non-Riverine	1,109	1,544	0	2,652	5,305
Tidal	6	5	4	184	199
Upland Buffer	0	0	0	43	43
Unknown	32	0	0	316	348
Total	1,148	1,549	5	3,352	6,054
Overall Total	4,591	3,097	68	10,134	17,890

counties in coastal North Carolina, where changing population density does not explain the variation in wetland conversion.

Both fresh and salt/brackish marshes converted to open water at a high rate during the study period. This is consistent with results reported by Stedman and Dahl (2008), who found that 96% of estuarine intertidal wetland loss in the United States from 1998 to 2004 was due to conversion to open water. The authors of that study found a 1% loss of estuarine wetlands in Atlantic coastal-draining watersheds over 6 years. This study suggests that the rate of erosion of North Carolina's estuarine wetlands may be higher than that, with conversion rates of 8.29% for freshwater marsh and 5.55% for salt/brackish marsh over 7 years. The difference between the estimates may be a result of methodological differences or temporal changes in the rate of conversion to open water between the studies. Or, regional averaging in the USFWS studies could mask a higher rate of estuarine wetland loss in North Carolina compared to the rest of the Atlantic coast region.

Conversion to open water as a result of relative sea level rise is the most important cause of tidal wetland loss throughout the United States (Hefner and Brown 1985; Brady and Flather 1994; Dahl 2006; Stedman and Dahl 2008). Measured rates of relative sea level rise in North Carolina are among the highest on the east coast, ranging from 1.79 for the southern part of the state to up to 4.6 mm/year around the northern sounds (Riggs and Ames 2003; Poulter et al. 2009). Several studies have demonstrated the particular vulnerability of the low-lying, peat-rich Albemarle-Pamlico peninsula in eastern North Carolina to wetland loss from sea level rise, relative to other types of shorelines (Moorhead and Brinson 1995; Riggs and Ames 2003; Poulter 2005).

By contrast, the rate of conversion of estuarine wetlands to upland was very low (0.52% for salt/brackish marsh, 0.95% for estuarine forest, and 1.28% for estuarine shrub scrub). This supports the effectiveness of the CAMA regulations and permitting process in protecting these wetland resources. Similarly low rates of salt marsh impact for upland development were found immediately following the implementation of CAMA (Stockton and Richardson 1987). Despite increasing population pressure in the coastal region, conversion to open water as a result of erosion and sea level rise appear to have been a much larger threat to estuarine wetlands in North Carolina than urbanization during this time period.

Estimated wetland losses to upland land uses between 1994 and 2001 were over three times higher than the total amount of wetland mitigation performed in the coastal counties over the same time period. While 17,858 ha of wetlands were converted to upland during this seven-year time period, only 4,659 ha have been replaced through restoration or creation and another 3,097 ha have been functionally enhanced. It is important to note that mitigation in North Carolina is performed on a watershed basis, not within each individual county. It is possible that some mitigation for impacts occurring in the coastal counties was performed in parts of coastal watersheds located outside the coastal counties. It is also possible that NCDCM's mitigation records for this time period are incomplete. However, the difference may also be related to minimum wetland impact thresholds for mitigation and/or unpermitted indirect losses. Kelly (2001) found that 80% of wetland permits in coastal North Carolina were associated with additional habitat fragmentation and indirect wetland losses beyond what was authorized in the permit. The exact cause of the continued loss of wetlands in the coastal region warrants further investigation.

Conclusions

Despite a relatively low overall accuracy, wetland change analysis using the National Land Cover Database (NLCD) can be an effective tool to roughly quantify losses of wetlands over time. Combined with summary data of mitigation projects in North Carolina, this analysis provides an overview of the relative scale of wetland losses and gains in the coastal region. The results suggest that erosional losses associated with sea level rise are the most important cause of estuarine wetland loss in the coastal region. While estuarine wetlands are well protected from development by state law and experienced relatively little loss from 1994 to 2001, the same cannot be said for non-tidal freshwater wetlands. During the study period, North Carolina continued to lose non-tidal freshwater wetland resources to upland development, despite both state and federal laws regulating wetland impacts.

Acknowledgments Funding for this project was provided by the National Ocean and Atmospheric Administration under CZM Strategic Planning Grant # NA17OZ2345 to the North Carolina Division of Coastal Management. I thank staff at the NC Ecosystem Enhancement Program, NC Department of Transportation, and NC Division of Water Quality for assistance in calibrating the NCDCM mitigation site database with other statewide databases. I am also grateful to Dr. Kenneth Rose (LSU), the associate editor, and two anonymous reviewers for helpful comments on earlier drafts of this manuscript.

References

Beyer HL (2004) Hawth's analysis tools for ArcGIS. Available via www.spatialecology.com/htools. Accessed 12/7/2010

Brady S, Flather C (1994) Changes in wetlands on nonfederal rural land of the conterminous United States from 1982 to 1987. Environmental Management 18:693–705

Brinson MM (1989) Fringe wetlands in Albemarle and Pamlico Sounds: landscape position, fringe swamp structure, and response to rising sea level. Albemarle-Pamlico Estuarine Study Report 88-14

Cashin G, Dorney J, Richardson C (1992) Wetland alteration trends on the North Carolina coastal plain. Wetlands 12:63–71

Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment 37:35–46

Congalton RG, Green K (1993) A practical look at the sources of confusion in error matrix generation. Photogrammetric Engineering and Remote Sensing 59:641–644

Crossett KM, Culliton TJ, Wiley PC, Goodspeed TR (2004) Population trends along the coastal United States: 1980–2008. Coastal Trends Report Series. National Oceanic and Atmospheric Administration. Silver Springs, MD, USA

Dahl TE (2000) Status and trends of wetlands in the conterminous United States: 1986 to 1997. U.S. Fish and Wildlife Service, Washington, DC

Dahl TE (2006) Status and trends of wetlands in the conterminous United States: 1998 to 2004. U.S. Fish and Wildlife Service, Washington, DC

Dahl TE, Johnson CE (1991) Wetlands status and trends in the conterminous United States: mid-1970's to mid-1980s. U.S. Fish and Wildlife Service, Washington, DC

Dahl TE, Dick J, Swords J, Wilen BO (2009) Data collection requirements and procedures for mapping wetland, deepwater, and related habitats of the United States. US Fish and Wildlife Service, Madison

Day JW Jr, Butler TJ, Conner WG (1977) Productivity and nutrient export studies in a cypress swamp and lake ecosystem in Louisiana. In: Wiley M (ed) Estuarine Processes. Academic, New York, pp 255–269

Farber SC (1987) The value of coastal wetlands for protection of property against hurricane damage. Journal of Environmental Economics and Management 14:143–151

Hay AM (1988) The derivation of global estimates from a confusion matrix. International Journal of Remote Sensing 9:1395–1398

Hefner JM, Brown JD (1985) Wetland trends in the southeastern United States. Wetlands 4:1–11

Hefner JM, Moorhead KK (1991) Mapping pocosins and associated wetlands in North Carolina. Wetlands 11:377–389

Hefner JM, Wilson BO, Dahl TE, Frayer WE (1994) Southeast wetlands: status and trends, mid-1970's to mid-1980's. U.S. Fish and Wildlife Service, Atlanta

Homer C, Huang C, Yang L, Wylie B, Coan M (2004) Development of a 2001 National Land-Cover Database for the United States. Photogrammetric Engineering and Remote Sensing 70:829–840

Homer C, Dewitz J, Fry J, Coan M, Hossain N, Larson C, Herold N, McKerrow A, VanDriel JN, Wickham J (2007) Completion of the 2001 National Land Cover Database for the conterminous United States. Photogrammetric Engineering and Remote Sensing 73:337–341

Hopkinson CS Jr (1985) Shallow-water benthic and pelagic metabolism: evidence of heterotrophy in the nearshore Georgia. Marine Biology 87:19–32

Hord RM, Brooner W (1976) Land-use map accuracy criteria. Photogrammetric Engineering and Remote Sensing 42:671–677

Johnston CA, Detenbeck NE, Niemi GJ (1990) The cumulative effect of wetlands on stream water quality and quantity: a landscape approach. Biogeochemistry 10:105–141

Kelly NM (2001) Changes in landscape pattern of coastal North Carolina wetlands under the Clean Water Act, 1984-1992. Landscape Ecology 16:3–16

Knutson PL, Ford JC, Inskeep MR (1981) National survey of planted salt marshes (vegetative stabilization and wave stress). Wetlands 1:129–157

Knutson PL, Brochu RA, Seelig WN, Inskeep MR (1982) Wave damping in *Spartina alterniflora* marshes. Wetlands 2:87–104

Mallin MA, Ensign SH, McIver MR, Shank GC, Fowler PK (2001) Demographic, landscape, and meteorological factors controlling the microbial pollution of coastal waters. Hydrobiologia 460:185–193

Moorhead K, Brinson M (1995) Response of wetlands to rising sea level in the lower coastal plain of North Carolina. Ecological Applications 5:261–271

Moorhead K, Cook A (1992) A Comparison of hydric soils, wetlands, and land-use in coastal North Carolina. Wetlands 12:99–105

National Agriculture Imagery Program 2004 NAIP Digital Orthophotography. U.S. Farm Service Agency,,. Available via http://www.apfo.usda.gov. Accessed 6/18/2010

National Agriculture Imagery Program 2006 NAIP Digital Orthophotography. U.S. Farm Services Agency,,. Available via http://www.apfo.usda.gov. Accessed 6/18/2010

Nixon SW (1980) Between coastal marshes and coastal waters—A review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In: Hamilton P, MacDonald KB (eds) Estuarine and wetland processes. Plenum, New York, pp 437–525

North Carolina Office of State Budget and Management (2001) April 2000 County Census Populations, with Growth and Migration from April 1990. Available via http://www.osbm.state.nc.us/ncosbm/facts_and_figures/socioeconomic_data/population_estimates/demog/cens00gr.html. Accessed 12/11/2010

Poulter B (2005) Interactions between landscape disturbance and gradual environmental change: plant community migration in response to fire and sea level rise. PhD dissertation, Duke University

Poulter B, Feldman RL, Brinson MM, Horton BP, Orbach MK, Pearsall SH, Reyes E, Riggs SR, Whitehead JC (2009) Sea-level rise research and dialogue in North Carolina: creatings windows for policy change. Ocean and Coastal Management 52:147–153

Riggs SR, Ames DV (2003) Drowning the North Carolina coast: sea-level rise and estuarine dynamics. NC Sea Grant, Raleigh

Rosenfield GH, Fitzpatrick-Lins K, Ling HS (1982) Sampling for thematic map accuracy testing. Photogrammetric Engineering and Remote Sensing 48:131–137

Shull LN III (1999) An Accuracy Assessment of GIS Wetland Mapping in the Coastal Counties of North Carolina. NC Division of Coastal Management, Raleigh, NC, USA

Stedman SM, Dahl TE (2008) Status and trends of wetlands in the coastal watersheds of the eastern United States: 1998 to 2004. National Marine Fisheries Service and U.S. Fish and Wildlife Service, Washington, DC

Stehman SV (1997) Selecting and interpreting measures of thematic classification accuracy. Remote Sensing of Environment 62:77–89

Stockton M, Richardson C (1987) Wetland development trends in coastal North Carolina, USA, from 1970 to 1984. Environmental Management 11:649–657

Story M, Congalton RG (1986) Accuracy assessment: a user's perspective. Photogrammetric Engineering and Remote Sensing 52:397–399

Sutter L (1999) DCM wetland mapping in Coastal North Carolina. N. C. Division of Coastal Management, Raleigh

Tiner RW (1984) Wetlands of the United States: current status and recent trends. U.S. Fish and Wildlife Service, Washington, DC

U.S. Fish and Wildlife Service (1995) Photointerpretation conventions for the National Wetlands Inventory. St. Petersburg, FL, USA

Weller CM, Watzin MC, Wang D (1996) Role of wetlands in reducing phosphorus loading to surface water in eight watersheds in the Lake Champlain Basin. Environmental Management 20:731–739

Whigham DF, Chitterling C, Palmer B (1988) Impacts of freshwater wetlands on water quality: a landscape perspective. Environmental Management 12:663–671

Wilen BO, Bates MK (1995) The US Fish and Wildlife Service's National Wetlands Inventory Project. Vegetatio 118:153–169

Yang L, Stehman SV, Smith JH, Wickham J (2001) Thematic accuracy of MRLC land cover for the eastern United States. Remote Sensing of Environment 76:418–422