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The purpose of this research project was to determine whether remote sensing and geographical information science (GISc) technologies could be used to model habitats and population distributions of the bog turtle, *Glyptemys muhlenbergii*. A subset of a Landsat 7 ETM+ image and color-infrared digital aerial photographs were used for a portion of Ashe County, North Carolina, where the wetlands occurred. Publicly available data may not be suitable for detecting small, isolated wetlands across the landscape due to heterogeneous landscape features, low spatial resolution of the images and the inherently poor quality of some of the images. However, the results of this study indicate that it is possible to define spectral signatures for wetlands when quality, high spatial and temporal resolution color-infrared data are available.

USING REMOTE SENSING AND GEOGRAPHICAL INFORMATION SCIENCE TO PREDICT AND DELINEATE CRITICAL HABITAT FOR THE BOG TURTLE, *GLYPTEMYS MUHLENBERGII*

by

Elizabeth M. Walton

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Approved by

____
Committee Chair

APPROVAL PAGE

This thesis has been approved by the following committee of the
Faculty of The Graduate School at
The University of North Carolina at Greensboro.

Committee Chair ________________________________
Roy S. Stine, Ph.D.

Committee Members ________________________________
Michael E. Lewis, Ph.D.

____
P. Daniel Royall, Ph.D.

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

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INTRODUCTION

Turtles are ancient creatures that have existed for more than 200 million years (Lovich et al. 2000). It is believed that they first appeared during the Triassic Period just before the arrival of dinosaurs and were originally terrestrial before some turtle species took to residing in freshwaters and others to the open sea. Turtles have a wide geographic distribution; terrestrial and freshwater species can be found on every continent except Antarctica, and sea turtles are often referred to as “ambassadors of the oceans” due to their highly migratory nature. Many turtle species are considered to be an indicator species—those species that can be used to gauge the overall health and fitness of an environment.

Historically, turtles have played a major role in the lives of indigenous peoples as cultural assets in their religious mythologies, art, writings and medicine. Turtles were also widely used as a plentiful food source, especially in terms of sea turtle meat, fat and eggs (Lovich 1994). They were revered for their fertility, longevity and intrinsic value (Schele et al. 1993; Cheng 1995; Dean 2005).

Scientists have been unable to accurately determine historic baseline numbers for turtle populations, but it has been estimated that some turtle population numbers were significantly larger than they are today. For instance, scientists have used current data, historical trade records, journals and population models for green sea turtle populations around the Cayman Islands and the Caribbean. These estimates put green sea turtle numbers anywhere from 60—600 million individuals in pre-Columbian times. Green sea turtle population numbers are currently estimated to be around 60,000 in that same geographic area (Davidson 2001; Jackson 2001).

Today, the world's chelonian[1] species are in serious trouble. After surviving many natural mass extinction events in the past, scientists now believe half of all turtle species are facing imminent extinction (Behler 2000; Lovich et al. 2000). Whether terrestrial, aquatic or marine, the global decline of turtle species can be attributed to independent or synergistic anthropogenic impacts. There are approximately 270 extant turtle species in the world;[2] however, unless immediate corrective measures are taken, many of these species will be extinct within the next few years (Lovich et al. 2000). This is particularly disturbing given the longevity of the chelonian family, and it is reprehensible that the causes of their rapid decline are intimately tied to anthropocentric activities.

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[1] Collective term referring to turtles and tortoises; a reptile of the order Chelonia.

[2] With new DNA analyses, some scientists now recognize as many as 306 species. Most of the statistical findings provided by national and international agencies are based upon the number of species recognized in the 1990s. Until there is a general consensus within the scientific community to accept these new cladistic findings, and for purposes of this paper, the more conservative number of 270 will be used.

It has only been in recent years that the magnitude of turtle species declines came to light and national and international efforts to scientifically quantify declines became essential. With the recent increase in the decline of turtle populations, there appears to be a general consensus amongst international chelonian researchers that the status of turtle species is more serious than current scientific data and research will support. As Gibbons (2000) states, ". . . the means of determining a species' conservation status is a rigorous and time-intensive process, and therefore counts of 'officially' recognized endangered and threatened species are likely to grossly underestimate the actual number of imperiled species." There is a current sense of urgency to locate remaining turtle populations and to evaluate their status before they experience further declines or become extinct. Therefore, determining turtle species' status in an effective, efficient, economical manner is a critical priority.

The purpose of this research project was to determine whether remote sensing and geographical information science (GISc) technologies could be used to model habitats and population distributions of the bog turtle, *Glyptemys muhlenbergii,* a species in decline. The specific goal was to determine whether publicly available data, in the form of satellite and aerial imagery, could be used to identify and delineate known bog turtle wetland habitat sites and to predict where additional sites might occur. Because bog turtle status surveys in the Southeast are ongoing, it is important to identify additional habitat sites and relict populations. This methodology would minimize labor hours and optimize the use of financial resources. Ultimately, this information would be beneficial to researchers, land managers and policy makers in setting conservation priorities for the bog turtle. The methodology is such that it may be calibrated to locate other turtle species of interest.

CHAPTER II

LITERATURE REVIEW

Causes of Turtle Species Declines

Until recently, most scientists would have attributed the global decline of turtle species to habitat loss, alteration and degradation, and the illegal pet trade. While these issues remain paramount to turtle species declines, in just a few short years these causes have been equaled, and perhaps even surpassed, by the insatiable demand for turtle species in China where they are consumed as a delicacy and used for medicinal purposes. Taken separately, these impacts would prove difficult to mitigate; collectively they may drive many turtle species to extinction (Behler 2000; Rhodin 2000).

Habitat Loss, Alteration and Degradation

Nearly every turtle species has felt the effects of human encroachment. Terrestrial turtles are unable to adapt to a changing landscape and the associated loss or change in natural habitat. Previous natural areas now support agricultural practices, rapid development and urban sprawl. Other anthropogenic impacts include the introduction of new predators in the form of domestic companion pets and habitat barriers such as roads and railroad tracks.

Sea turtles have been hard hit on a global level by a host of anthropogenic impacts. Female sea turtles often encounter obstructions such as jetties, groins, sea walls and commercial and residential development which make it difficult to reach natal beaches for nesting purposes. Beach renourishment and human recreation cause sand compaction making the nesting process difficult and affecting hatchling survival. Beach lighting disturbs nesting females and draws hatchlings away from the ocean and onto roadways. Nesting turtles and their eggs are often poached for human consumption. Turtles encounter equal threats in their aquatic environment from ocean debris such as ghost nets and abandoned monofilament fishing line in which they become entangled and drowned. The ingestion of plastics, which resemble jellyfish, can cause intestinal obstruction, blockage and even death. Additional impacts include recreational boat injuries; an epidemic of a herpes virus called fibropapillomatosis (which many scientists believe may be caused by pollution); global warming; and the unparalleled impacts of shrimp trawling and longline fishing (Committee on Sea Turtle Conservation, National Research Council 1990; Davidson 2001). Due to their highly migratory nature, it will take a concerted international effort to ensure the future viability of sea turtles.

The bog turtle, *Glyptemys muhlenbergii*, is endemic to a narrow range of wetlands in the eastern United States. Yet, it is estimated that 70—90 percent of wetlands in the United States have been destroyed for agricultural purposes since the 1950s (Marsh 1991). The Southeastern United States has lost approximately 90 percent of its mountain wetlands, which serve as crucial bog turtle habitat, primarily due to drainage for agriculture, development and construction (Natural Resources Conservation Service 2002). Most of the remaining wetlands of the United States are small and are held by private landowners. Unlike federal and state agencies or land developers, private landowners are under no obligation to mitigate the loss of wetlands.

The Illegal Pet Trade

Many turtle species are gentle and charismatic by nature. It is no wonder then that so many turtles have been collected as pets. Many children growing up in the United States during the 1950s, 60s and 70s had a series of red-eared sliders or “stink pots” (common musk turtles) which were sold in dime stores as pets with a plastic pond and palm tree. Millions of hatchling-sized red-eared sliders were also heavily collected for the national and international pet trade and as a result can now be found as an exotic species all around the world. The US Food and Drug Administration passed regulations in 1975 that require turtles to be at least four inches long before they can be sold (US Food and Drug Administration 1975). However, the impetus for this law was not for environmental concerns, but to protect young children against *Salmonella* infections. While many pet stores are in compliance with the law, turtles of smaller sizes are still abundantly available.

Today, the international trade in exotic reptiles is a multimillion dollar industry with the United States high on the list demanding bearded dragons, iguanas, lizards and exotic snakes. According to US Fish and Wildlife Service Director Jamie Rappaport Clark, “The legal international trade in reptiles has increased significantly in the last decade. At the same time, reptile smuggling has become a high-profit criminal enterprise which we cannot tolerate” (Fisher 2000, p. 12). According to USFWS data, “in 1997 the United States imported 1.8 million live reptiles worth more than $7 million and exported 9.7 million valued at more than $13.2 million” (Fisher 2000, p. 12).

Concurrent demands for turtles to supply the international pet trade have also been high. To supply these demands, teams of poachers comb rural areas in search of terrestrial and aquatic turtle species which are placed in gunnysacks, or burlap bags. Captured turtles are dumped into holding containers until the poachers amass enough to fill a cargo trailer—the typical size of a freight trailer pulled by an 18-wheeler. The cargo containers are placed aboard transoceanic cargo ships—without regard to crowding, temperature or access to food and water (Figure 1).

The condition of these turtles upon arrival at their destination, some two to three weeks later, is tragic: many will have died due to extreme temperatures and a lack of food and water; some will be crushed by the weight of other turtles above them; and many will be missing appendages due to competitive struggles. The survivors reach their destination weak and emaciated; all have been exposed to a variety of infectious diseases that may not present symptomatically for several months. The end result is that 50—75 percent will die in transit. An additional 20—45 percent will die within 6 weeks of arrival at their new home, and after one year, only 5 percent will have survived the entire ordeal (Williams 1999). However, since the supply of new turtles appears to be limitless, pet store operators are happy to buy additional turtles because their money is earned on the investment made by pet owners for turtle housing and accessory supplies. Turtle enthusiasts don't mind replacing dead turtles that can be purchased or replaced for a mere $5 to $15. Turtle collectors have been known to pay as much as $1,200 for a bog turtle, *Glyptemys muhlenbergii* (Herman, pers. comm.) or as much as $1,500 in China for the three-striped box turtle *Cuora trifasciata* which is believed to cure cancer (Lovich et al. 2000).

Figure 1. **Turtles transported to foreign markets.** Turtles are dumped into cargo trailers without concern for crowding, temperature, or access to food and water (Photo by Luiijf 1997).

Consumption by Humans

Nothing quite compares to the overwhelming and insatiable demands placed on turtle populations by the people of China in just the past decade. The recent industrialization and convertible currency has raised the level of affluence in China and created a demand from neighboring countries for turtles which are traded as a cash commodity (Altherr and Freyer 2000). Used as a preferred food source and in traditional medicines, the trade in turtles is measured at more than 10—12 million individual turtles per year (Salzberg 1998; Rhodin 2000). Since most native turtle populations in China have been extirpated, imports from other areas of Southeast Asia have increased considerably producing what is now hailed as the "Asian Turtle Crisis." These imports now constitute 80 percent of turtles found in Chinese food markets (McCord 2000). This crisis is so severe that currently more than 50 percent of native turtle species in Southeast Asia are facing extinction (Lovich et al. 2000). Today, China's demand for turtle species can be felt around the world, affecting nearly every country.

The conditions under which turtles are brought to Chinese markets are similar to those found with turtles that have been poached and shipped overseas. Turtles typically arrive in crates stacked on the back of trucks. Many turtles will die before they ever reach the marketplace. The survivors are kept in gunnysacks, boxes or tubs until they are ready for slaughter. Turtles are butchered alive at these open air markets as the Chinese have a fondness for "fresh" meat. The carapace is loosened by running a knife around the edges until it can be pried off like a top. The flesh is then carved out in chunks while the turtle tries to escape its attacker—an effort in futility (Williams 1999).

It is important to understand that while many countries have passed appropriate laws and regulations regarding endangered species and have assigned regulatory and administrative functions to legitimate national agencies, the level of efficacy of legal enforcement is severely inadequate to address the magnitude of global and international trade. Though well intentioned, most countries, including the United States, simply lack the manpower necessary to patrol political borders or to monitor and investigate the contents of every airplane, cargo ship, or any other human or mechanical vessel that transverse geographic regions on a daily basis. Thus in many areas, the unsustainable turtle harvests continue unabated. However, in the case of Chinese imports, authorities make little effort to identify imported turtle species, country of origin or conservation status. Further complicating the matter are international shipments of turtles to China under the label of “fish/seafood,” a commodity which is rarely inspected (McCord 2000).

Turtle Species of the United States

The United States is home to approximately 57 turtle species including 6 sea turtle species that nest on our shores. Yet even here, the threat to the future viability of native turtle species raises grave concerns. According to Lovich et al.

(2000), "25 species (45 percent) require conservation action, and 21 species (38 percent) are protected or are candidates for protection."

There are 14 turtle species currently listed under the Endangered Species Act (ESA) as administered by the USFWS. Table 1 provides a list of the levels of protection afforded by the ESA and a description of each.

Table 1. Federal Levels of Species Protection (modified from USFWS Endangered Species website)

Category	Description
Extinct	A species which is no longer in existence; the last individual has died leaving no living representatives.
Endangered	A species which is in danger of becoming extinct in the near future.
Threatened	A species which is likely to become endangered within the foreseeable future throughout all or a significant portion of its range.
Candidate	A species for which USFWS or NOAA Fisheries has on file sufficient information on biological vulnerability and threats to support a proposal to list as endangered or threatened.

It should be noted that the listing process for a species of concern requires substantial quantitative scientific data before a species receives protection. This is a lengthy procedure. The process can often take years, during which time the species in question may go from a species of concern to a species facing imminent extinction. Individual states can often pass legislation more expediently than the USFWS and thus can provide limited protection within their political borders. Many states have adapted their own category levels and corresponding protective descriptions. Table 2 is a generalized overview of the various state categories found.

Table 2. State Levels of Species Protection	
Category	**Description**
S1	Critically imperiled in a state because of extreme rarity or otherwise very vulnerable to extirpation in a state.
S2	Imperiled in a state because of rarity or otherwise vulnerable to extirpation in a state.
S3	Rare or uncommon in a state.
S4	Apparently secure in a state, with many occurrences.
S5	Demonstrably secure in a state.

In an effort to evaluate the current status of turtle species within individual US states, an Internet search was conducted with a visit to each of the 50 state's websites for endangered and threatened species. Only 3 of the 50 states didn't list a turtle species as a species of concern (Idaho, Nebraska and New Hampshire); the other 47 states had varying levels of protection for many turtle species. This information was combined with data obtained from the USFWS's Endangered Species website (http://www.fws.gov/ endangered/) which contains a list of species protected under the Endangered Species Act (ESA) (1973).

Using a current taxonomic species list provided by Dr. Lovich and consolidating information obtained from the USFWS' Endangered Species website and each individual state, a grim picture emerged substantiating the figures given by Lovich et al (2000). While there are 14 turtle species covered under the endangered, threatened or candidate categories of the ESA, the total species covered under similar categories by individual states is 46—more than 3 times the number afforded protection under the ESA. Figure 2 illustrates the number of turtles afforded protection at federal and state levels.

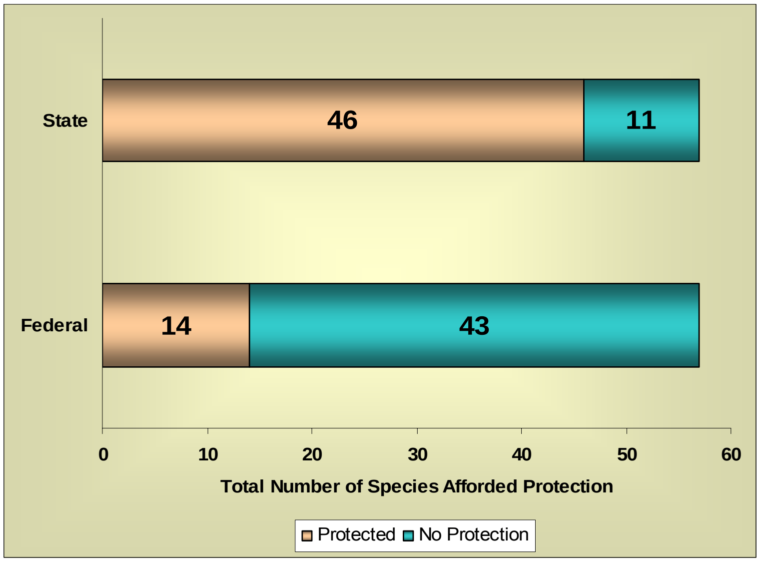

Figure 2. Comparison of protection offered to turtle species between federal and state levels (*n* = 57).

Table 3 is a compilation of Dr. Lovich's list as well as respective federal and state listings. Essentially, nearly 81 percent of our nation's turtle species are endangered or threatened in all or a significant portion of their range.

Table 3. TAXONOMIC LIST FOR TURTLE SPECIES OF THE UNITED STATES

(Taxonomic List Provided by Dr. Jeff Lovich. See Appendix for Websites Accessed)

Genus	Species	Sub-species	Federal Status	State Status
Cheloniidae (Marine Turtles)				
1	*Caretta caretta* (Loggerhead Seaturtle)		**T**	AK(R); AL(S1) CA(T); CT(T); DE(E); FL(T); GA(T); HI(T); LA(T); MA(T); MD(T); ME(T); MS(T); NC(T); NJ(E); OR(T); RI(T); SC(T); TX(T); VA(S1); WA(T)
2	*Chelonia mydas* (Green Seaturtle)		**E, T**	AK(R); AL(S1); CA(T); CT(T); DE(E); FL(E); GA(T); HI(T); LA(T); MA(T); MD(E); MS(T); NC(T); NJ(T); OR(E); RI(T); TX(T); WA(T)
3	*Eretmochelys imbricata* (Hawksbill Seaturtle)		**E**	DE(E); FL(E); GA(E); HI(E); LA(E); MA(E); MD(E); MS(E); NC(E); NJ(E); NY(E); TX(E)
		E. i. imbricata (Atlantic Hawksbill Seaturtle)**		
		E. i. bissa (Pacific Hawksbill Seaturtle)**		
		** Crother et al. recognize these subspecies.		
4	*Lepidochelys kempii* (Kemp's Ridley Seaturtle)		**E**	AL(S1); CT(E); DE(E); FL(E); GA(E); LA(E); MA(E); MD(S1); ME(E); MS(E); NC(E); NJ(E); NY(E); RI(E); TX(E); VA(S1)
5	*Lepidochelys olivacea* (Olive Ridley Seaturtle)		**T**	CA(T); HI(E); OR(E)
Chelydridae (Snapping Turtles)				
6	*Chelydra serpentina* (Snapping Turtle)			MN(SC); MT(SC); ND(SC)
		C. s. serpentina (Eastern Snapping Turtle)		
		C. s. osceola (Florida Snapping Turtle)		
7	*Macrochelys temminckii* (Alligator Snapping Turtle)			AL(S2); FL(SC); GA(T); IL(E); IN(E); KY(T); OK(S2); TX(T)
Dermochelyidae (Leatherback Seaturtles)				
8	*Dermochelys coriacea* (Leatherback Seaturtle or Luth)		**E**	AK(R); AL(S1); CA(T); CT(E); DE(E); FL(E); GA(E); HI(E); LA(E); MA(E); MD(E); ME(E); MS(E); NC(E); NJ(E); NY(E); OR(E); RI (E); TX(E); WA(E)
Emydidae (Semiaquatic Pond and Marsh Turtles)				
9	*Actinemys marmorata* (Pacific Pond Turtle)			WA(E)
		A. m. marmorata (Northern Pacific Pond Turtle)		
		A. m. pallida (Southern Pacific Pond Turtle)		
10	*Chrysemys picta* (Painted Turtle)			OK(S2); KY(T); WY(T)
		C. p. picta (Eastern Painted Turtle)		
		C. p. bellii (Western Painted Turtle)		
		C. p. dorsalis (Southern Painted Turtle)		
		C. p. marginata (Midland Painted Turtle)		

Table 3. TAXONOMIC LIST FOR TURTLE SPECIES OF THE UNITED STATES

(Taxonomic List Provided by Dr. Jeff Lovich. See Appendix for Websites Accessed)

11	*Clemmys guttata* (Spotted Turtle)			DE(R); GA(U); IL(E); IN(E); MA(SC); ME(T); MI(T); RI(P); SC(T); VT(S1); WV(S1)
12	*Deirochelys reticularia* (Chicken Turtle)			AR(S3); MO(T); OK(S2); VA(S1);
		D. r. reticularia (Eastern Chicken Turtle)		
		D. r. chrysea (Florida Chicken Turtle)		
		D. r. miaria (Western Chicken Turtle)		
13	*Emydoidea blandingii* (Blanding's Turtle)			IA(T); IL(T); IN(E); MA(T); ME(E); MI(SC); MN(T); OH(T); PA(C); SD(E); WI(S3)
14	*Glyptemys insculpta* (Wood Turtle)			CT(SC); IA(E); MA(SC); MI(SC); MN(T); NJ(T); RI(P); VA(S2); VT(S3); WI(S3); WV(S2)
15	*Glyptemys muhlenbergii* (Bog Turtle)		**T(S/A) T**	CT(E); DE(E); GA(T-S/A); MA(E); MD(T); NC(T); NJ(E); NY(T); PA(E); SC(T); TN(T); VA(S1)
16	*Graptemys barbouri* (Barbour's Map Turtle)			AL(S2); FL(SC); GA(T)
17	*Graptemys caglei* (Cagle's Map Turtle)			TX(T)
18	*Graptemys ernsti* (Escambia Map Turtle)			AL(SC)
19	*Graptemys flavimaculata* (Yellow-blotched Map Turtle)		**T**	MS(T)
20	*Graptemys geographica* (Northern Map Turtle)			GA(R); KS(T); MD(S1); OK(S1); VA(S2); VT(S3); WV(S2)
21	*Graptemys gibbonsi* (Pascagoula Map Turtle)			**1**
22	*Graptemys nigrinoda* (Black-knobbed Map Turtle)			AL(SC)
		G. n. nigrinoda (Black-knobbed Map Turtle)		
		G. n. delticola (Delta Map Turtle)		
23	*Graptemys oculifera* (Ringed Map Turtle)		**T**	LA(T); MS(T)
24	*Graptemys ouachitensis* (Ouachita Map Turtle)			**2**
		G. o. ouachitensis (Ouachita Map Turtle)		
		G. o. sabinensis (Sabine Map Turtle)		
25	*Graptemys pseudogeographica* (False Map Turtle)			ND(T); OH(T); OK(S2); SD(T)
		G. p. pseudogeographica (False Map Turtle)		
		G. p. kohnii (Mississippi Map Turtle)		
26	*Graptemys pulchra* (Alabama Map Turtle)			AL(SC); GA(R)
27	*Graptemys versa* (Texas Map Turtle)			**3**
28	*Malaclemys terrapin* (Diamond-backed Terrapin)			AL(S1); DE(SC); MA(T); NC(SC); RI(E)
		M. t. terrapin (Northern Diamond-backed Terrapin)		
		M. t. centrata (Carolina Diamond-backed Terrapin)		
		M. t. littoralis (Texas Diamond-backed Terrapin)		

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Genus	Species	Sub-species	Federal Status	State Status
		M. t. macrospilota (Ornate Diamond-backed Terrapin)		
		M. t. pileata (Western diamond-backed Terrapin)		
		M. t. rhizophorarum (Mangrove Diamond-backed Terrapin)		
		M. t. tequesta (Florida East Coast Diamond-backed		
		The above subspecific designations of *Malaclemys terrapin reflects Crother (Chair) 2000. It may be modified*		
29	*Pseudemys alabamensis* (Alabama Red-bellied Cooter)		E	AL(S1); MS(E)
30	*Pseudemys concinna* (River Cooter)			FL(SC); IL(E); IN(E); WV(S1)
		P. c. concinna (Eastern River Cooter)		
		P. c. floridana (Coastal Plain Cooter)		
31	*Pseudemys gorzugi* (Rio Grande Cooter)			NM(T)
32	*Pseudemys nelsoni* (Florida Red-bellied Cooter)			**4**
33	*Pseudemys peninsularis* (Peninsula Cooter)			**5**
34	*Pseudemys rubriventris* (Northern Red-bellied Cooter)		E	DE(SC); MA(E); PA(T); WV(S1)
35	*Pseudemys suwanniensis* (Suwannee Cooter)			**6**
36	*Pseudemys texana* (Texas River Cooter)			**7**
37	*Terrapene carolina* (Eastern Box Turtle)			CT(SC); DE(SC); MA(SC); ME(E); MI(SC); OH(T); RI(P)
		T. c. carolina (Eastern Box Turtle)		
		T. c. bauri (Florida Box Turtle)		
		T. c. major (Gulf Coast Box Turtle)		
		T. c. triunguis (Three-toed Box Turtle)		
38	*Terrapene ornata* (Ornate Box Turtle)			AR(S2); IA(T); IN(E); WI(S2); WY(T)
		T. o. ornata (Ornate Box Turtle)		
		T. o. luteola (Desert Box Turtle)		
39	*Trachemys gaigeae* (Mexican Plateau Slider)			**8**
		T. g. gaigeae (Big Bend Slider)		
40	*Trachemys scripta* (Pond Slider)			VA(S1); WV(S1)
		T. s. scripta (Yellow-bellied Slider)		
41	*Kinosternon arizonae* (Arizona Mud Turtle)			**9**
42	*Kinosternon baurii* (Striped Mud Turtle)			FL(E); SC(SC)
43	*Kinosternon flavescens* (Yellow Mud Turtle)			CO(SC); IA(E); IL(E)
44	*Kinosternon hirtipes* (Rough-footed Mud Turtle			TX(T)
		K. s. murrayi (Mexican Plateau Mud turtle)		

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(Taxonomic List Provided by Dr. Jeff Lovich. See Appendix for Websites Accessed)

	Genus Species Sub-species	Federal Status	State Status
Kinosternidae (Mud and Musk turtles)			
45	*Kinosternon sonoriense* (Sonora Mud Turtle)		AZ(C)
	K. s. sonoriense (Sonora Mud Turtle)		
	K. s. longifemorale (Sonoyta Mud Turtle)		
46	*Kinosternon subrubrum* (Eastern Mud Turtle)		IN(E); NY(SC)
	K. s. subrubrum (Eastern Mud Turtle)		
	K. s. hippocrepis (Mississippi Mud Turtle)		
	K. s. steindachneri (Florida Mud Turtle)		
47	*Sternotherus carinatus* (Razor-backed Musk Turtle)		AL(S2)
48	*Sternotherus depressus* (Flattened Musk Turtle)	**E**	AL(S2)
49	*Sternotherus minor* (Loggerhead Musk Turtle)		NC(SC); VA(S2)
	S. m. minor (Loggerhead Musk Turtle)		
	S. m. peltifer (Stripe-necked Musk Turtle)		
50	*Sternotherus odoratus* (Stinkpot, or Common Musk Turtle)		IA(T); VT(S2)
Testudinidae (Tortoises)			
51	*Gopherus berlandieri* (Texas Tortoise)		TX(T)
52	*Gopherus polyphemus* (Gopher Tortoise)	**T**	AL(S2); FL(SC); GA(T); LA(T); MS(T); SC(E)
53	*Xerobates agassizzii* (Desert Tortoise)	**T(S/A) T**	AZ(T); CA(T); NV(T); UT(T)
Trionychidae (Softshelled Turtles)			
54	*Apalone ferox* (Florida Softshelled Turtle)		**10**
55	*Apalone mutica* (Smooth Softshelled Turtle)		KY(SC); MN(SC); ND(SC)
	A. m. mutica (Midland Smooth Softshelled Turtle)		
	A. m. calvata (Gulf Coast Smooth Softshelled Turtle)		
56	*Apalone spinifera* (Spiny Softshelled turtle)		MD(S1); MT(SC); NC(SC); VA(S2); VT(T); WY(T)
	A. s. spinifera (Eastern Spiny Softshelled Turtle)		
	A. s. aspera (Gulf Coast Spiny Softshelled turtle)		
	A. s. emoryi (Texas Spiny Softshelled Turtle)		
	A. s. guadalupensis (Guadalupe Spiny Softshelled		
	A. s. hartwegi (Western Spiny Softshelled Turtle)		
	A. s. pallida (Pallid Spiny Softshelled Turtle)		
57	*Palea steindachneri* (Wattle-necked Softshelled Turtle)		**11**

*****Note***:** The taxonomy and the common names used in this list are modified slightly from: Crother, B.I. et al. 2000. *Scientific and standard English names of amphibians and reptiles of North America north of Mexico, with comments regarding confidence*

Protecting Endangered Species

The field of conservation biology has experienced a shift in population ecology paradigms. MacArthur and Wilson's (1967) island biogeography model defined the species-area relationship stating that larger islands would support more species than smaller islands and a state of dynamic equilibrium would be attained as new species immigrated and filled ecological niches previously filled by a species that had become extirpated or extinct. This model was widely accepted and evolved to include national parks, wildlife refuges and nature reserves with an inherent concept that conservation measures should be applied to large, contiguous habitats and those currently occupied by species of concern.

However, a new paradigm, the metapopulation paradigm, emerged in the 1990s. A metapopulation is a set of local populations contained within a network of habitat patches that allows some migration from one population to another (Levins 1969; Hanski and Simberloff 1997). As opportunities for preserving larger, contiguous habitats became more and more infrequent, and development pressures fragmented and degraded existing habitats, conservation biologists began to emphasize the importance of not only habitats currently occupied by species of concern, but of disjunct habitats and corridors that could serve as sites for occasional migration, recolonization, refugia or conservation relocation programs.

When it comes to protecting imperiled species, conservation biologists, government agencies and other stakeholders are characteristically burdened with a perpetual need for financial resources to sustain research efforts and conservation measures while racing against a ticking clock. Unfortunately, many species simply do not have the genetic ability or the resource of time to adapt to an ever-changing and often degraded environment, and as a result the fate of these species and their continued survival is uncertain (Primack 1995). This is particularly true for specialist[3] species, such as the bog turtle, that act as resource "sinks" in terms of labor and financial investments. Yet, when working with endangered species, it is critical to locate potential or additional habitats, monitor existing populations and establish conservation measures, all while working with limited resources.

The current methodology for remnant population discovery and evaluation of endangered species populations is field surveys whereby researchers search for a particular species in a predefined, preferred habitat with the hope of discovering and protecting remnant populations. For instance, in North Carolina and much of the bog turtle's southern range, the current methodology for discovering new wetland habitats involves countless hours of driving around the countryside conducting visual inspections of the landscape. If potential wetlands are observed, landowners are contacted to seek permission to explore for bog

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[3] A specialist species is one that has specific habitat requirements and a narrow tolerance for dietary, climatic or environmental conditions. A generalist, on the other hand, can easily adapt to a variety of habitats and environmental conditions.

turtles. Many more hours are spent in the site to establish bog turtle presence or absence status. This process and others like it are labor intensive and fiscally exhaustive (Vogiatzakis 2003; Rushton et al. 2004), and in cases where there are reduced population numbers, the success rates of discovery are often marginal. Therefore, the need exists to design a method of investigation that would minimize search time while optimizing the use of limited financial resources to assist researchers, land managers and policy makers in setting conservation priorities.

Using Remote Sensing and GISc Technologies

In recent years, conservation biologists have discovered the application of remote sensing and geographical information science (GISc) technologies to model habitats and population distributions (Davis et al. 1990; Aspinal 1995; Akçakaya 1996; Scott et al. 1996; Chen and Peterson 2000; Peterson et al. 2002; Venkataraman et al. 2002; Turner et al. 2003). A Geographical Information System (GIS) allows researchers to compile various layers of digital data that are spatially referenced. Spatial analysis tools allow scientists to map metapopulation habitats and in some cases to monitor individual movement between habitat patches. However, some species fall below the threshold that qualifies them for spatial monitoring. This is usually the result of a species' small physical size (Ramanujan 2004) or rarity. In such cases it may be more effective and economical to establish a habitat fingerprint or signature based upon known habitat parameters that would predict suitable habitat patches and then investigate those areas for the presence or absence of the species of concern.

Remote sensing offers the opportunity to use known parameters to discover additional areas that are similar in biological composition and environmental conditions to those supporting species of interest and to detect where such species are likely *not* to occur. Using multispectral bands, a signature of the exact biological and environmental assemblages supporting a given species can be employed to find other habitat areas that have the same fingerprint (Turner et al. 2003) and potential capacity for support. Furthermore, once the remotely sensed imagery is obtained, the data can be read and interpreted in the convenience of an office, reserving field investigation time and expenditures for sites that have a high predictive success rate.

Using these new spatial technologies, Raxworthy et al. (2003) created an ecological niche model using a GIS that incorporated environmental characteristics with records of occurrence (both current and historical) to predict the distribution of rare chameleons in Madagascar. Upon investigating three areas with the highest predictive success rates, *seven new species* of chameleons were identified (NASA website; Raxworthy 2003; Ramanujan 2004). It is possible that these spatial technologies can be used to identify and delineate additional wetland habitats for the bog turtle and assist in their protection and future viability.

The Bog Turtle, *Glyptemys muhlenbergii*

The bog turtle (Glyptemys muhlenbergii) is North America's smallest and most secretive turtle. It has an average size of 3 to 3.75 inches in straight-line carapace length with distinctive bright yellow to orange patches on its neck (Figure 3) (Herman 2003). Bog turtles were first reported in North Carolina in 1882 (Yarrow 1882) and are currently known from 21 counties (Herman 2003). Their populations are small, and can be comprised of less than 20 individuals that exist in small, disjunct patches of habitat (Buhlmann et al. 1997). To date, 140 occurrence records have been recorded, though tragically, many of these records are individual sightings of road casualties (Herman and Tryon 1997; Herman 2003).


Figure 3. The Bog Turtle, *Glyptemys muhlenbergii.*
(Photo by Dennis W. Herman)

Causes of Decline

As with other turtle species, the bog turtle is faced with two principle threats: habitat loss, due to the draining and filling of wetlands, and the illegal collection for pet trade demands. These pressures have caused a serious decline in the species' population numbers and consequently, the northern population received protection under the Endangered Species Act (1973) in 1997. However, due to a paucity of data to justify full protection, the southern population was listed as "threatened due to similarity of appearance," as it would be too difficult for law enforcement officials to make a distinction between the two populations (USFWS 1997).

Status surveys are ongoing and researchers are currently trying to determine the status of bog turtle population numbers in the Southeast. The process of identifying new and/or potential habitats is further complicated by: a habitat that is small and isolated, and the bog turtle's small physical size and secretive nature make them particularly difficult to locate and protect.

Habitat Loss

As stated previously, the Southeastern United States has lost approximately 90 percent of its mountain wetlands, which serve as crucial bog turtle habitat, primarily due to drainage for agriculture, development and construction (Natural Resources Conservation Service 2002). Small, isolated wetlands play an important role in bog turtle metapopulation dynamics as sites for occasional migration, recolonization, refugia or conservation relocation programs. The loss of these wetlands results in greater migratory distances between wetland sites thus reducing the rate of successful mating opportunities, recruitment and gene flow.

Many wetlands are privately held and have been tiled and drained over the years to put the land into more economically productive use. Researchers must use caution when trying to gain access to private property to search for bog turtles as many landowners are leery of government officials and the perceived threat of interference with their property rights. If bog turtles are found on the property, many landowners are reluctant to remove even a few acres from production due to the resulting financial impact.

Through Project Bog Turtle, the USFWS provided funds to lease bog turtle sites from landowners. Modeled after traditional rural land-lease agreements, landowners are paid to leave wetlands unaltered and to allow access to the site for research purposes. Several landowners found these leases beneficial as they were protecting an endangered species on their property without losing income in the process (Walton 2002). As a result of this program and efforts by researchers to maintain open, friendly relations, many landowners have emerged as important, enthusiastic partners in bog turtle conservation efforts.

Consumption by Humans and Pet Trade Demands

North Carolina turtle populations were dealt a harsh blow when the North Carolina Wildlife Resources Commission’s Nongame Advisory Committee reported that commercial collection and harvesting of various turtle species (predominantly aquatic species) in the state had gone from 460 turtles in 2001 to more than 23,000 in 2002. North Carolina is to be commended for having progressive legislators who sprang into action enacting new legislation that became effective July 2003 limiting the number of turtles a collector may possess to fewer than five (North Carolina G.S. 113-333).

While these measures will certainly help to restrict the number of turtles taken after the bill was passed, it will do little to mitigate the damage that has already been done. It has been suggested that the loss of even one reproducing female may have long-term consequences for the local population. The loss of thousands of turtles in a relatively short period of time may be a catastrophic impact to North Carolina's turtle populations and may be evident for many generations to come. It is now believed that the turtles taken from North Carolina were probably headed for European pet trade markets or the food markets of China (Herman pers. comm.; Altherr and Freyer 2000).

Habitat

There are two distinct populations of bog turtles separated by an apparent 250 mile disjunct: the northern population, which ranges from New York and Massachusetts south to Maryland, and the southern population, which ranges from southeastern Virginia south to northern Georgia as shown in Figure 4 (Ernst et al. 1994). Bog turtles have been located in five southeastern states: Virginia, North Carolina, South Carolina, Georgia and Tennessee. There is an ongoing effort to fully identify the existence of bog turtle habitats and the status of bog turtle populations in each state. Consequently, bog turtle presence/absence surveys are conducted in an effort to identify and protect new and potential habitat sites.

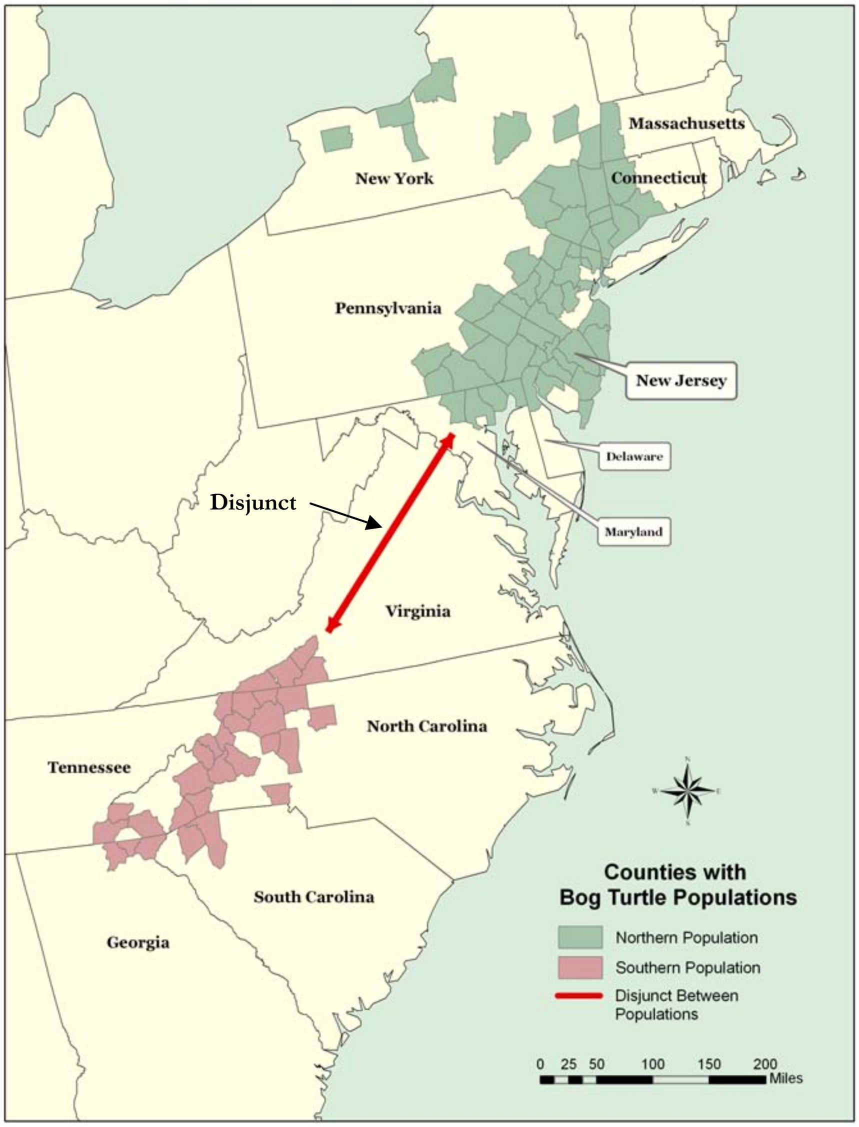


Figure 4. Geographic distribution of the bog turtle. (ESRI and NatureServe Explorer Comprehensive Species Report)

Bog turtles prefer a particular type of spring-fed wetlands referred to as *fens*. The defining characteristic of a fen is that its dominant source of wetness is groundwater seepage as opposed to significant inputs from precipitation or runoff from adjacent areas (Bedford and Goodwin 2003). Fens are also referred to as wet meadows, bogs or meadow bogs and are often found in seepage slopes (Figure 5a) or terraces along the headwaters of small or medium size streams. It is believed that groundwater flowing into these wetland sites assist in the maintenance of more constant temperatures which are cooler in summer and warmer in winter months than surrounding air and surface water temperatures (Amon et al. 2002). Frederick (1974) noted that the waters in Cedar Bog, Ohio never froze and that steam could be observed above the fen during winter months. Additionally, average maximum soil temperatures were 8.88˚ C cooler in the six warmest months than in nearby soils.

Fens are *usually* acidic and experience long-term or continual saturation which produces anaerobic conditions. Anaerobic conditions exist when available dissolved oxygen is depleted by microbiological respiration during the process of decomposing detritus and other organic materials. Once available O_2 is depleted, anaerobic conditions ensue where respiration is conducted by the chemical reduction of iron (Fe), manganese (Mn) and nitrates (N). As Fe and Mn are chemically reduced, soils take on a gleyed appearance. Gleyed soils in these fens are typically a greenish-blue with low chroma values (≤ 2).

Figure 5. Bog turtles prefer a particular type of spring-fed wetlands referred to as *fens* a) Fens are often found in seepage slopes; b) Fens are dominated by hydrophilic plant species; c) Iron compounds are reoxidized creating a rusty color; and d) Bog turtles are frequently found in wetlands located in pasture settings. (Photos by Roy Stine)

Wetland perimeters are often visually distinguishable from surrounding areas by their hydrophilic vegetation which is taller and often greener than vegetation of adjacent areas. The fens located in North Carolina are dominated by hydrophilic plant species such as sedges (*Carex* sp.) with peat mosses (*Sphagnum* sp.) as a common ground cover (Figure 5b). In unmanaged areas where succession is occurring, it is common to find red maple (*Acer rubrum*), tag alder (*Alnus serrulata*), and tulip poplar (*Liriodendron tulipifera*) (Herman 2003).

In some sites the presence of oxidized rhizospheres may be observed. This results when specialized hydrophytic plant species transport oxygen from parenchyma cells located in leaves and stems down to the root system. As excess oxygen escapes from root tissues, iron compounds are reoxidized creating a rusty color at the root system (Figure 5c). Other plants may exhibit adventitious roots or spread their roots just below the soil surface in a zone of aeration (Mitsch and Gosselink 2000; Brady and Weil 2002).

Bog turtles are frequently found in wetlands located within pasture settings (Figure 5d). It is believed that grazing animals, such as cattle and horses, greatly assist in retaining water in these wet areas (Herman 1999). Grazers churn the mud, creating pockets that trap water that would otherwise flow out of the area, and bog turtles can sometimes be found burrowed down in these pockets. Additionally, grazers reduce vegetation that would transpirate water from the site. One management technique is to use livestock excluder fences during months with high turtle activity, usually late spring to late fall. The excluder fencing is removed to allow grazers into the site to graze and churn the mud again during late fall and through the early spring months.

Biology and Ecology

Due to a paucity of long-term studies, there is much about the bog turtle that remains unknown. Long-term studies are essential to our effective stewardship of this species as well as its continued survival in the future yet, long-term studies of this species have only begun in earnest within the past 20 years.

Bog turtles, like many other turtle species, have the potential to live very long lives, perhaps 50 years or longer. However, it is believed that few hatchlings survive to sexual maturity due to naturally occurring events such as high mortality in eggs, neonates and juveniles. Female bog turtles typically reach sexual maturity when they are approximately 7 years old and will lay an average clutch of 1 to 6 eggs with a mean of 3 eggs. While annual reproduction is possible, it is unlikely due to fluctuating food sources and infrequent encounters with a male. It is reasonable to assume that females reproduce every second or third season, or 10 to 15 times over their life span. Extrapolated over a lifetime, a female may lay an average of 30 to 45 eggs, but only a few can be expected to survive to sexual maturity (Herman 1994). Many turtle species have natal fidelity, and while it is not certain that bog turtles share this characteristic, it is possible that they do.

Turtles are sexed by external inspection: adult males have a concave plastron with a longer tail and a more posteriorly placed cloaca than females. Male turtles will not show their secondary sexual characteristics, such as a longer tail and concave plastron, until they reach about 60-mm straight carapace length. However, this feature may be difficult to recognize with the untrained eye (Herman, pers. comm.). Sex determination in young juveniles is almost impossible.

Age determination is measured by counting the annuli or number of rings within a scute. The innermost ring indicates the scute formed prior to hatching (natal scute) and is not counted. Each subsequent ring is counted as one year. Figure 6 shows a turtle whose age is estimated to be 6 years old using this method. Bog turtles lose annuli definition as they get older due to repetitive burrowing into the muddy substrate.

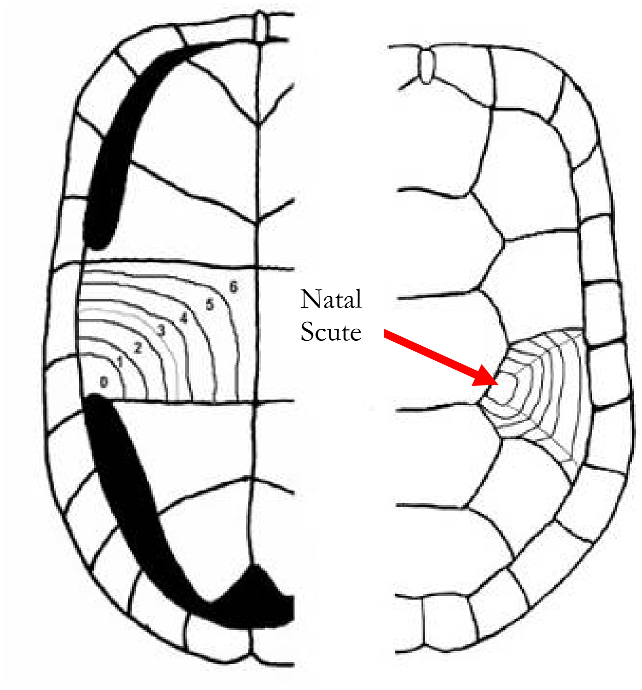


Figure 6. Age determination is measured by counting the annuli.
(Modified from Herman)

CHAPTER III

METHODS

The specific goal of this paper was to determine whether publicly available data, in the form of satellite and aerial imagery, could be used to identify and delineate known and additional bog turtle wetland habitat sites. Before assembling imagery data from all potential counties in which bog turtles may be found, it was decided to establish a proof of concept within the confines of a single county. Ashe County, North Carolina was chosen because it is accessible with only a short drive and because the County has several well-established bog turtle populations (Figure 7). Due to the confidentiality surrounding endangered species, all specific localities are omitted from this paper.

All research was coordinated with Project Bog Turtle (PBT), the North Carolina Wildlife Resources Commission (NCWRC), The Nature Conservancy (TNC), and UNCG. An Endangered Species permit was obtained from the NCWRC, the issuing authority for the USFWS Endangered Species Office. A research permit was obtained from TNC as one of the research sites was located on their property.

Dennis Herman, one of the original founders of PBT, provided the coordinates of 13 wetland sites. Six sites were known to support bog turtles and

7 appeared to be suitable habitat, but bog turtles have never been found in these locations. Herman provided a tour of the sites on 11-Aug-05 to allow visual inspection, to obtain ground reference information and to take photographs of dominant floral species.

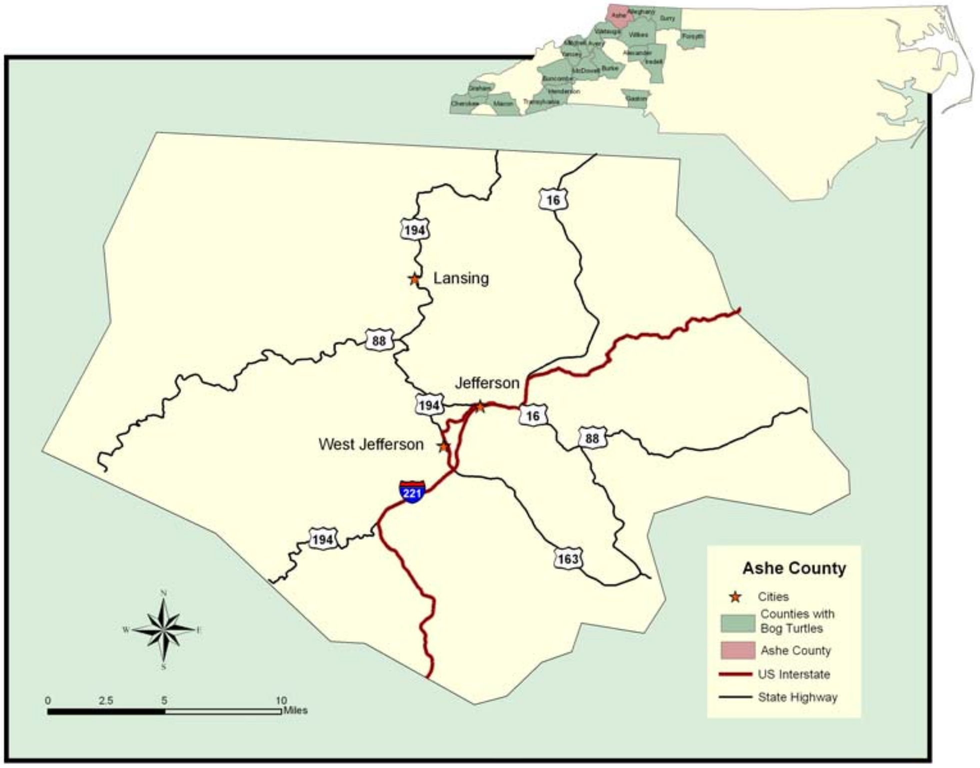


Figure 7. Ashe County, North Carolina. (ESRI and North Carolina Department of Transportation, Transportation Data)

Landowner information was obtained from PBT and verified with the Ashe County GIS tax parcel website (http://ashegis.ashecountygov.com/webgis/). Letters were sent to landowners that explained the purpose and nature of the research and requested permission to conduct research on their properties.

Information was also requested from the landowners regarding hunting practices on their property; parking preferences; whether they would like additional information on bog turtles; if they wanted to be contacted before a site visit; the preferred method and point of entry into the wetland; and since many of the sites are located in pasture settings, whether or not they had “charging bulls” on the property. Permission was granted from all 6 landowners with wetlands that currently support a bog turtle population on their property. Only 1 landowner without a known bog turtle population responded and granted permission.

Another visit was made on 08-Oct-2005 to the properties that had granted permission to delineate the wetland areas using a Trimble GeoExplorer CE global positioning system (GPS) to use as ground reference information. The Trimble unit was set to collect data using US State Plane 1983, North Carolina 3200, North American Datum 1983 (Conus), GEOID99 (Conus) coordinate system, collecting spatial reference points every 5 seconds. A minimum of 4 satellites were triangulated at all times during the collection process with a maximum of 7 satellites as shown in Table 4.

One person led while the other person walked behind holding the GPS unit. The follower was able to keep a close eye on the number of satellites locked and progression of the map drawn on the GPS screen while following the first person using direct and peripheral vision. Each perimeter was walked at a pace allowed by the terrain. In some areas creeks had to be navigated; fences were crossed; woody debris was carefully traversed; and in some areas soil saturation caused slower travel.

Table 4. Data and Readings from Trimble GPS Unit

Site Name	Satellites	Min # Satellites	Max # Satellites	Precision	Time
ASHE05	3,13,16,19, 23, 25, 27	5	7	68%	12:41:32p
ASHE09	No Data				
ASHE10	No Data				
ASHE15	7,8,11,19,27,28	4	6	68%	04:00:12p
ASHE18	3,8,13,16,19,23,27	4	7	68%	02:14:00p
ASHE19	1,3,13,16,20,23,25	4	7	68%	11:25:01a
WetlandD	1,14,16,20,25,30	5	6	68%	09:23:10a

Several problems were experienced during the data collection process. Most notably was that the Trimble GPS unit would shut down without warning even though the battery icon was showing ample charge. Additionally, the unit would frequently freeze during the point collection process resulting in a straight line from the last point to the current position. Often the unit would be in the “on” or “off” mode and could not be turned on or shut down between sites. Once power to the unit was restored, it was decided to leave the unit on at all times. As a result, the data contained point omissions in some instances and multiple points collected in areas where one would be sufficient.

Upon return from Ashe County, the data held in the Trimble unit was downloaded using GPS Pathfinder Office V.2.90. Difficulties were experienced with this process as well: some files could not be downloaded and others could not be differentially corrected using the automated program functions. Differential correction was performed on available files using the base station from Conover, NC. Corrections were made to the numbers and positions of points on the available wetland polygons: multiple points in one location were deleted and lines between sites were omitted. Additional polygons were created in ArcGIS using coordinates provided by PBT and 1998 color infrared aerial images. Polygons of all 13 wetlands were combined into one shapefile in ArcGIS.

The area of each polygon was determined by identifying each vertex along the perimeter of the polygon and its relative contribution to total area as described by Jensen (2005). Table 5 shows the code name and size of each wetland in the study area with an average wetland size of 0.8111 ha.

Table 5. Name and size of each wetland in the study area.

Site Code	Area in Hectares
Ashe 10	0.3024
Ashe 15	1.9884
Ashe 18	3.5943
Ashe 19	1.3413
Ashe 5	0.3155
Ashe 9	0.3911
Wet BB	0.0320
Wet C	0.2631
Wet D	0.3692
Wet DA1	1.0744
Wet DA2	0.1835
Wet S	0.3247
Wet T	0.3646
Average Size:	0.8111

Remotely Sensed Data

For this research project Landsat 7 ETM+ images and Color-Infrared (CIR) Digital Orthophotography Quarter Quadrangle (DOQQ) aerial photographs were used for a portion of Ashe

County where the predominance of the bog turtle habitats occur. The Landsat 7 ETM+ was obtained from the image collection at UNCG. The CIR images were downloaded from North Carolina Department of Transportation (NC DOT) (www.ncdot.org/it/gis/).

Weather data were requested from the NC State Climate Office (www.nc-climate.ncsu.edu) for the Jefferson Station (ID 314496) for the time period that both images were taken. The CIR images were taken between January and March 1998, and the Landsat 7 ETM+ was taken May 3, 2003. Climagraphs of these two periods are shown in Figure 8. The first 5 months of 1998 received 35.72 inches of precipitation, while the same time period in 2003 received only 23.10 inches. It is possible that wetland areas are more pronounced in the 1998 images due to increased baseflow and groundwater recharge in wetland areas.

CIR images have 1 meter resolution. The spectral range of the CIR imagery is approximately 500-600 nm (green), 600-700 nm (red), and 700-900 nm (near-infrared). CIR near-infrared (NIR) wavelengths lack ultra-violet and blue wavelengths which results in a color-infrared image. Green, healthy vegetation has a high reflectance of NIR wavelengths and appears as bright red; red objects with very low NIR reflection appear green (such as conifers); green objects with very low NIR reflection appear blue; and blue objects with very low near-infrared reflection appear black (such as water). The spectral reflectance of soil is strongly correlated with moisture content: high moisture content results in lower reflectance.

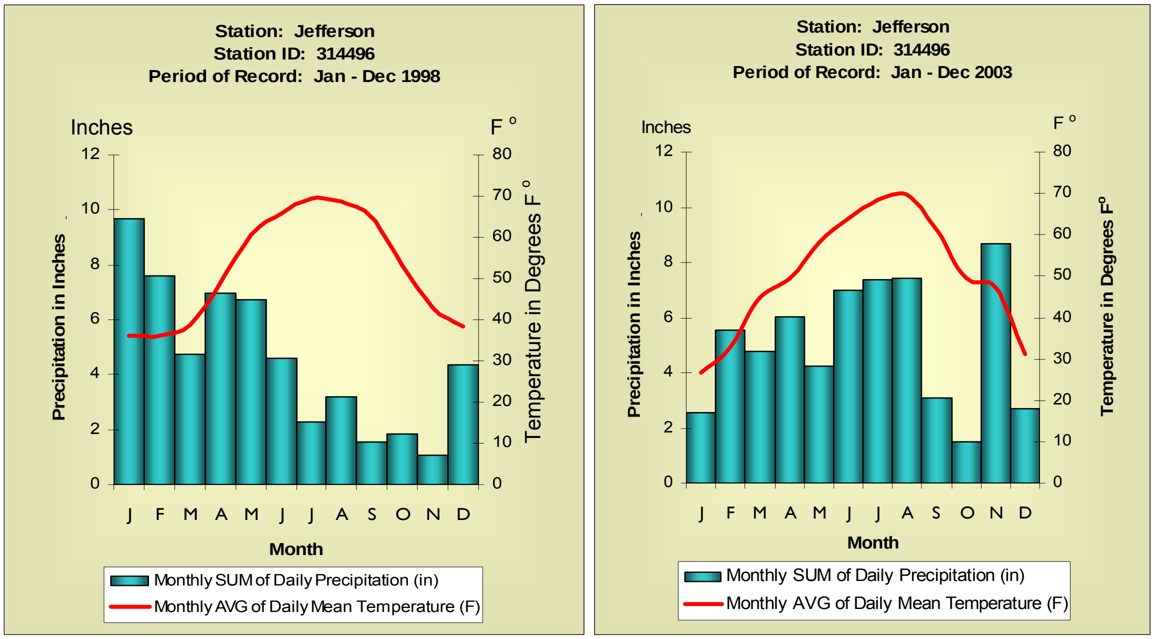


Figure 8. Ashe County Climagraphs for 1998 and 2003.

Landsat 7 EMT+ imagery captures data in eight spectral “bands” from a narrow range of the electromagnetic spectrum (Table 6). The bands are stored in raster grid data formats with cell values based upon the spectral reflectance (brightness) value of each pixel. The first three bands (1, 2 and 3) represent blue, green and red of the visible portion of the spectrum; band 4 represents the near infrared (NIR) portion; and bands 5 and 7 represent mid- and mid/short infrared. These 6 bands capture data at a resolution of 28.5 meters. Band 6 measures heat emitted from the Earth’s surface and consists of two bands: 6.1 at 60 meter resolution and 6.2 at 120 meter resolution. Band 8 is a panchromatic band that captures images at 15 meter resolution.

Table 6. Landsat 7 ETM+ eight spectral bands (USGS website).

Spectral Band	Spectral Range (μ)	Resolution	Application
1. Visible Blue	.45 - .52	30 meter	Water penetration, bathymetry and sediment load mapping. Also useful for differentiation of soil from vegetation, and deciduous from coniferous flora.
2. Visible Green	.52 - .61	30 meter	Designed to measure visible green reflectance peak of vegetation for vigor assessment. Also used to map sediment concentration in turbid waters, and is higher for ferrous iron rich rock compared to ferric iron.
3. Visible Red	.63 - .69	30 meter	A chlorophyll absorption band important for vegetation discrimination. It is higher for rocks and soils rich in iron, especially ferric iron.
4. Near Infrared	.78 - .90	30 meter	Useful for determining healthy vegetation resulting in a characteristic 'red-edge' between bands 3 and 4 and for delineation of water bodies.
5. Mid-Infrared	1.55 - 1.75	30 meter	Indicative of vegetation moisture content and soil moisture. Contained water absorbs, resulting in lower values. Dry material results in relatively higher values.
6. Thermal IR	10.40 - 12.50	60 and 120 meter	Used for thermal mapping. Useful for heat intensity, vegetation and crop stress analysis and locating thermal pollution.
7. Mid/Short IR	2.090 - 2.350	30 meter	Designed to measure hydrothermally altered rocks associated with mineral deposits.
8. Panchromatic	.520 - .900	15 meter	Data is acquired over the visible green to near infra-red portion of the spectrum.

The next step was to co-reference the images to a standard map projection (North Carolina State Plane, NAD 1983) so that all pixels were in their correct planimetric (*x*-, *y*-) locations. This was accomplished using ERDAS (1997) software and an image-to-image registration. A minimum of 50 ground control points were obtained with a root mean square (RMS) error of 0.096 using nearest neighbor logic.

A subset of the Landsat 7 ETM+ image and the CIR aerial photographs were used for a portion of Ashe County where the wetlands occurred. A Wallis Adaptive Filter was used on the Landsat 7 image to adjust the contrast (ERDAS 1997) and an Atmospheric Correction (ATCOR) was applied to reduce atmospheric haze (Jensen 2005). Univariate statistics (minimum, maximum, mean, and standard deviation) shown in Tables 7—8 and Figures 9—10 did not denote any unusual geometric or radiometric anomalies. Multivariate statistics were used to measure between-band covariance and correlation among the bands. Histograms revealed Gaussian or bi-modal trends for all bands in the Landsat 7 and CIR images.

Table 7. Univariate Statistics for Landsat 7 ETM+ Image

Band	Minimum	Maximum	Mean	Standard Deviation	Columns	Rows	Cell Size	Highest Frequency
1	0	255	38.93	32.21	8,797	7,861	28.5	4,229,789
2	0	255	30.13	25.57	8,797	7,861	28.5	4,139,152
3	0	255	25.95	24.21	8,797	7,861	28.5	3,265,538
4	0	255	42.18	36.13	8,797	7,861	28.5	1,346,298
5	0	255	42.96	40.07	8,797	7,861	28.5	1,001,086
6.1	0	208	78.10	63.63	4,399	3,931	57.0	1,175,647
6.2	0	255	88.64	72.42	4,399	3,931	57.0	658,499
7	0	255	22.51	22.99	8,797	7,861	28.5	2,177,112
8	0	255	31.06	26.63	17,594	15,722	14.3	6,605,988

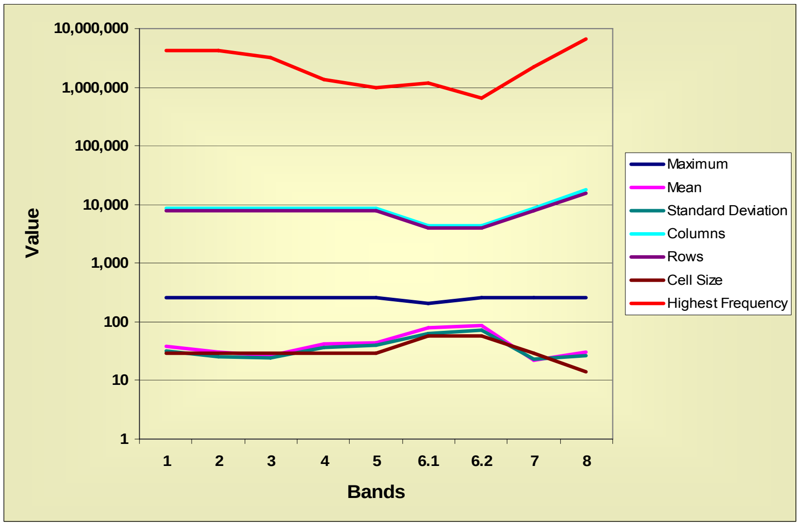


Figure 9. Univariate statistics for Landsat 7 ETM + image.

Table 8. Univariate statistics for CIR image.

Band	Minimum	Maximum	Mean	Standard Deviation	Columns	Rows	Cell Size
Red	0	255	108.01	62.92	7424	2127	3.281
Green	0	255	108.26	60.12	7424	2127	3.281
Blue	0	255	77.17	49.54	7424	2127	3.281

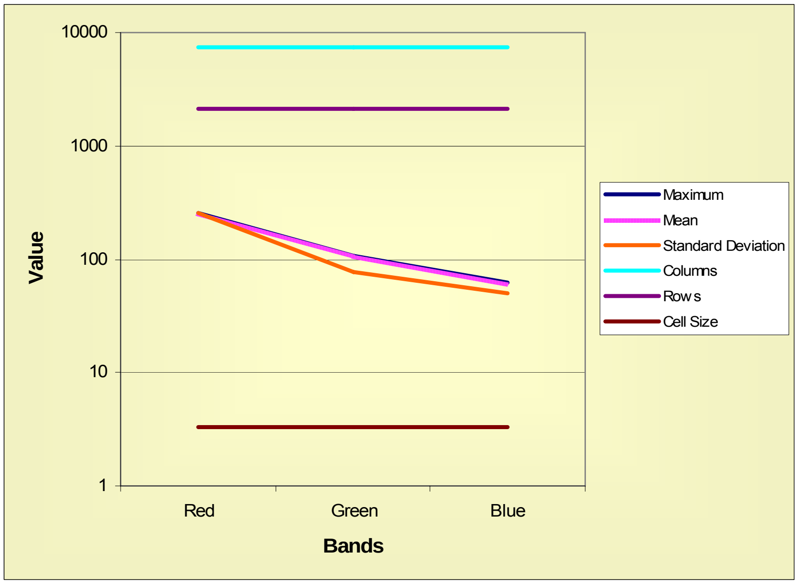


Figure 10. Univariate statistics for CIR image.

Band ratioing was used to eliminate environmental conditions such as slope, aspect, solar angle or intensity of shadows. This was accomplished by creating a new variable after dividing the brightness values of one band that had a high reflectance by the brightness values of another band with low reflectance or brightness values. Ratio values within the range 1/255 to 1 were assigned values between 1 and 128 and ratio values from 1 to 255 were assigned values within the range 128 to 255.

ERDAS Imagine is a GIS software application that allows the user to create a composite by selecting any 3 bands to display the image. Bands 1, 2 and 3 represent a true color of the image. However, by selecting bands that represent portions of the electromagnetic spectrum in the infrared range (beyond the visible range), it is possible to create a composite image that can be used to extract information that is unavailable to the naked eye.

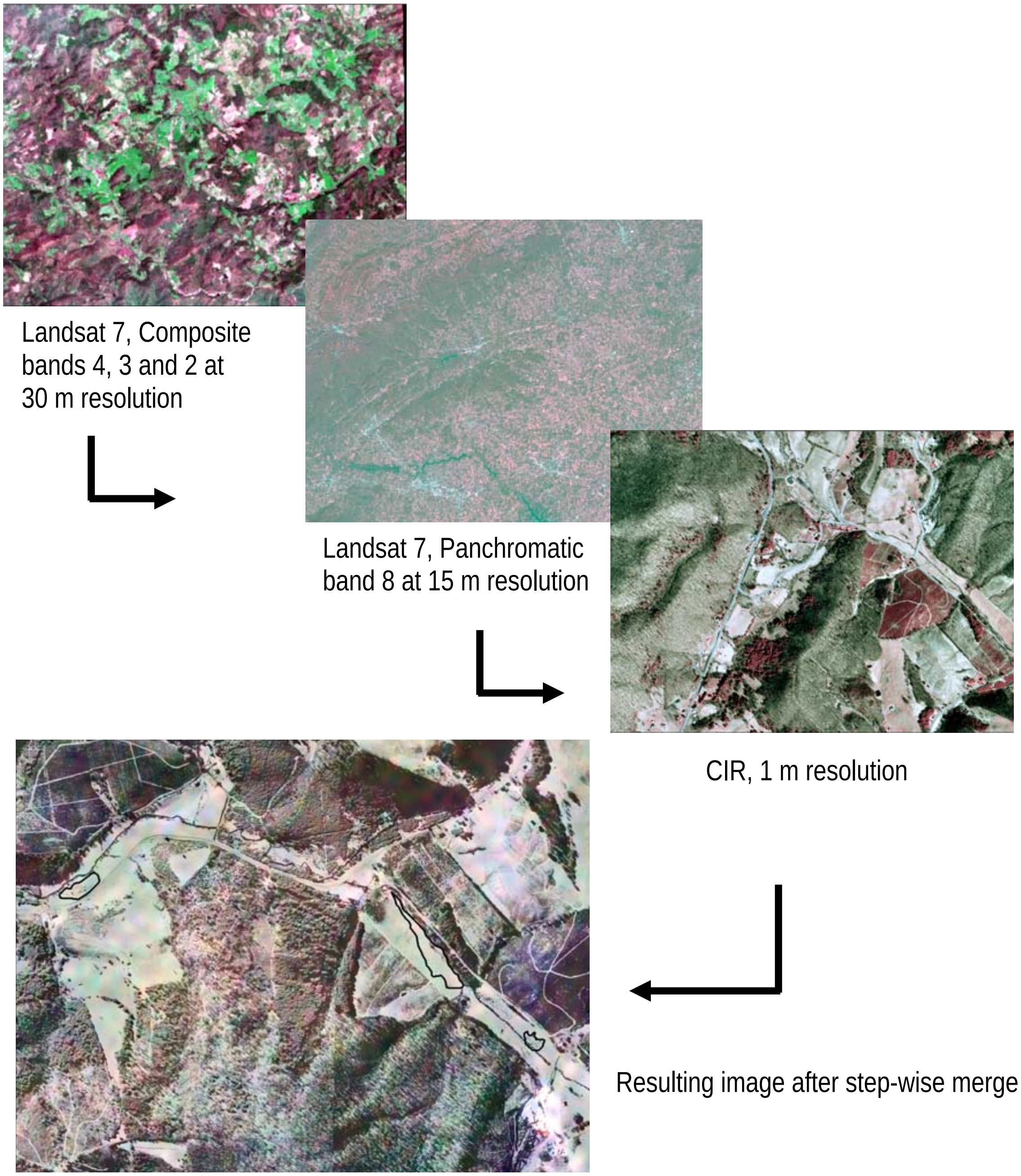
Multispectral image classification is a process where individual pixels are assigned to a class based upon their respective brightness values. These classes then represent categories of data that share similar spectral reflectance values and hence environmental characteristics. The classification process can be executed with user-defined classes and is thus called a “supervised” classification. In the supervised classification process, the user can identify and organize certain known classes, such as roads, water bodies or forests; or the user can select “areas of interest” (AOIs) and have the program find other areas of similar spectral values. Alternatively, an “unsupervised” classification can be generated in which the user sets the maximum number of classes and iterations, and the program assigns pixels to classes based on similar spectral brightness values.

To begin the analysis, bands 4, 3 and 2 of the Landsat 7 image were chosen as these bands respond to brightness, greenness and wetness (moisture content) on the landscape. The three bands of the CIR images represent green, red and near infra-red portion of the spectrum. The images were enhanced using the Normalized Difference Vegetative Index (NDVI) to calculate the ratio between reflectivity in the red band (Landsat 7 band 3 and CIR band 3) and the near infrared band (Landsat 7 band 4 and CIR band 4) as these two bands are most affected by the density and absorption of chlorophyll in vegetation as well as vegetative discrimination. This was accomplished by an algorithm which transforms raw image data in these bands into a new image based upon the formula: NDVI = (NIR – red) / (NIR + red). The images produced in this manner provided information on vegetation vigor, density and health.

The wetland polygon layer created in ArcGIS was loaded into ERDAS and used to identify areas of interest (AOIs) as training data for supervised classifications on both the Landsat 7 (bands 4, 3 and 2) and CIR images. Bands 4, 3 and 2 of the Landsat 7 and the three available bands in the CIR images were analyzed to determine if a spectral signature could be distinguished for hydrophilic vegetation commonly found in wetlands. In both processes 50 classes were identified using training data and *a priori* knowledge gained during site visits. A maximum of 100 iterations was used with a convergence threshold of 0.98. The maximum likelihood classification system was used to assign brightness values to each cell (pixel) which classified the cell according to the dominant characteristic. The "percentage" classification took into account various characteristics on the landscape and assigned a cell value based on an average of the percentages.

Another analysis was run using bands 7, 4 and 3 and then bands 5, 4 and 2 to create a shortwave infra-red composite, as reflectance in this spectral range is primarily a function of moisture content and can be used to discriminate vegetation types. Landsat 7 bands 2, 3 and 7 were analyzed to determine whether a spectral signature could be distinguished for "bog iron" or other ferrous material commonly associated with redoximorphic soils found in wetland areas. Landsat 7 band 6.1 was analyzed to determine whether a thermal trend occurred in the spring-fed fens.

To increase the resolution and extract the maximum amount of data possible, a step-wise merge was performed on a subset of the Landsat 7 and CIR images. The Landsat 7 image with bands 4, 3, 2 at 30 meter resolution was merged with the Landsat 7 band 8 panchromatic image at 15 meter resolution. This image was then merged with the CIR subset image at 1 meter resolution as shown in Figure 11.



Landsat 7, Composite bands 4, 3 and 2 at 30 m resolution

Landsat 7, Panchromatic band 8 at 15 m resolution

CIR, 1 m resolution

Resulting image after step-wise merge

Figure 11. Stepwise Merge

An unsupervised classification of the images was performed which limited the amount of introduced error based on unfamiliarity with distinct vegetative composition in the landscape contained within the images. An upper limit of 75 classes was selected and 100 iterations were allowed using the Iterative Self-Organizing Data analysis technique (ISODATA) algorithm with a convergence threshold of 0.98. Once the unsupervised classification process was complete, clearly identifiable classes such as roads, urban settings, residential areas and water bodies, were identified and properly labeled. Ground referenced data and the CIR images assisted in the identification of mono crops and forested areas. Signature separability was used to determine the statistical distance between signatures using a Euclidean distance measurement. Signature classes that overlapped significantly were merged or deleted.

Increased magnification of each wetland provided the identification of brightness values for each pixel. Only those pixels which were ≥ 50 percent contained by the wetland polygons were used in this analysis. Out of the 13 wetlands, only 31 percent (*n* = 4) were represented by more than 5 pixels (Figure

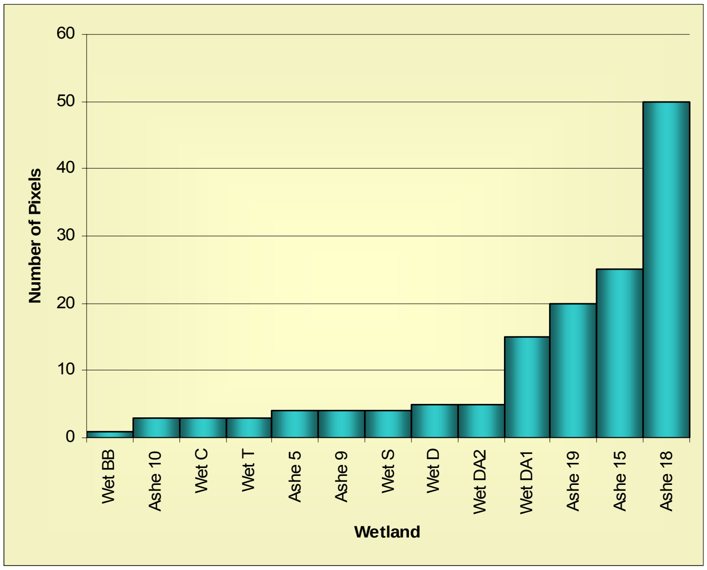


Figure 12. Number of pixels per wetland. The wetland polygon layer was used to identify pixels from an unsupervised classification on Landsat 7, 30 meter imagery. Total pixels: *n* = 142.

12). The results of the unsupervised classification were analyzed to determine whether a unique brightness value or combination of values were present in all the wetlands. In reviewing the classification results for the 13 wetlands, it was determined that the 142 pixels fell into 37 different classes as shown in Figure 13. A comparison of the wetlands that currently support bog turtles and those wetlands that do not, showed several class similarities. However, the frequency of occurrence for the 37 classes was highly variable as shown in Table 10.

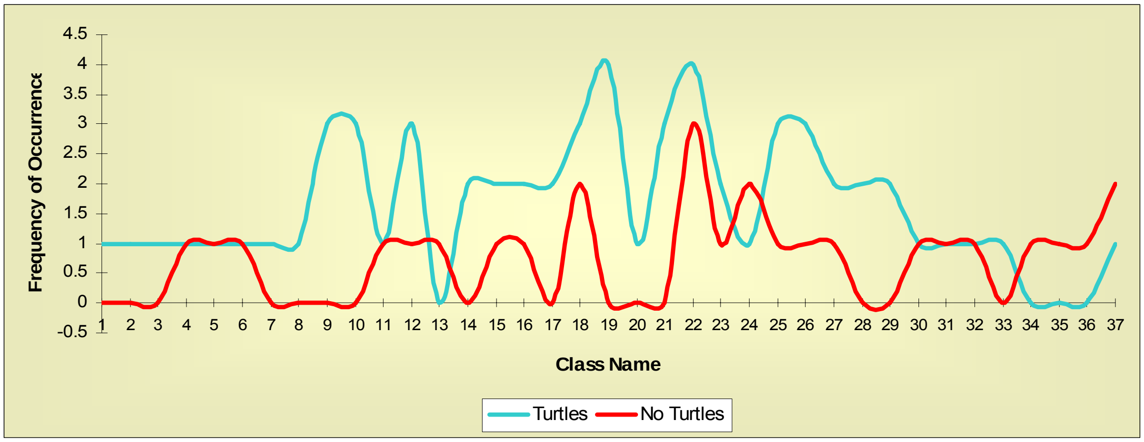


Figure 13. Class frequency between wetland sites with and without bog turtles.
(Pixel *n* = 142; Class Frequency *n* = 37)

Table 9. Number of brightness value classes between wetland sites with bog turtles and wetland sites without bog turtles.

Wetland Code Name	Total # Pixels	% of Total	Total # Classes
Ashe 10	3	2.11%	3
Ashe 15	25	17.61%	17
Ashe 18	50	35.21%	19
Ashe 19	20	14.08%	14
Ashe 5	4	2.82%	3
Ashe 9	4	2.82%	4
Total with Turtles	106	75.00%	
Wet BB	1	0.70%	1
Wet C	3	2.11%	3
Wet D	5	3.52%	4
Wet DA1	15	10.56%	10
Wet DA2	5	3.52%	2
Wet S	4	2.82%	2
Wet T	3	2.11%	3
Total without Turtles	36	25.00%	
Total Pixels	142	100.00%	

In order to obtain larger training data sites with a homogenous landscape, a shapefile was obtained from the USFWS' National Wetland Inventory (NWI) website (http://www.nwi.fws.gov/downloads.htm). A comparison of the shapefile obtained from the USFWS revealed that only 50 percent of the wetlands in this study were included in the National Wetland Inventory. NWI polygons used as training sites for a

Table 10. Frequency of Class Occurrence (*n* = 87)

Number of Classes	Frequency of Occurrence:
11 Classes	1
12 Classes	2
8 Classes	3
4 Classes	4
1 Class	5
1 Class	7
Total # Classes:	37

supervised classification yielded similar results as was found with the study area wetland polygons. Brightness values having the highest frequency of occurrence (classes 19, 22, 25 and 26) were selected to locate other areas across the landscape that would be similar in composition.

A number of image enhancements were used. These enhancements as shown in Figure 14 included: a) anomaly enhancement; b) unsupervised classification of stepwise merge image; c) Wallis Adaptive filter; d) ATCOR haze reduction with ferrous enhancement; e) ATCOR haze reduction with iron enhancement; f) ATCOR haze reduction with wetland unsupervised classification values highlighted in red; g) texture enhancement; h) Tasseled Cap using principal components; i) CIR unsupervised classification; j) Tasseled Cap after ATCOR haze reduction; k) natural color enhancement; and l) NDVI after ATCOR haze reduction.

Subsequent to these classification processes, a subset of the CIR imagery was used for an area that contained only 3 wetlands that were in close proximity to each other. An upper limit of 75 classes was selected and 100 iterations were allowed using the ISODATA algorithm with a convergence threshold of 0.98. The wetland polygon layer created in ArcGIS was used as an overlay.

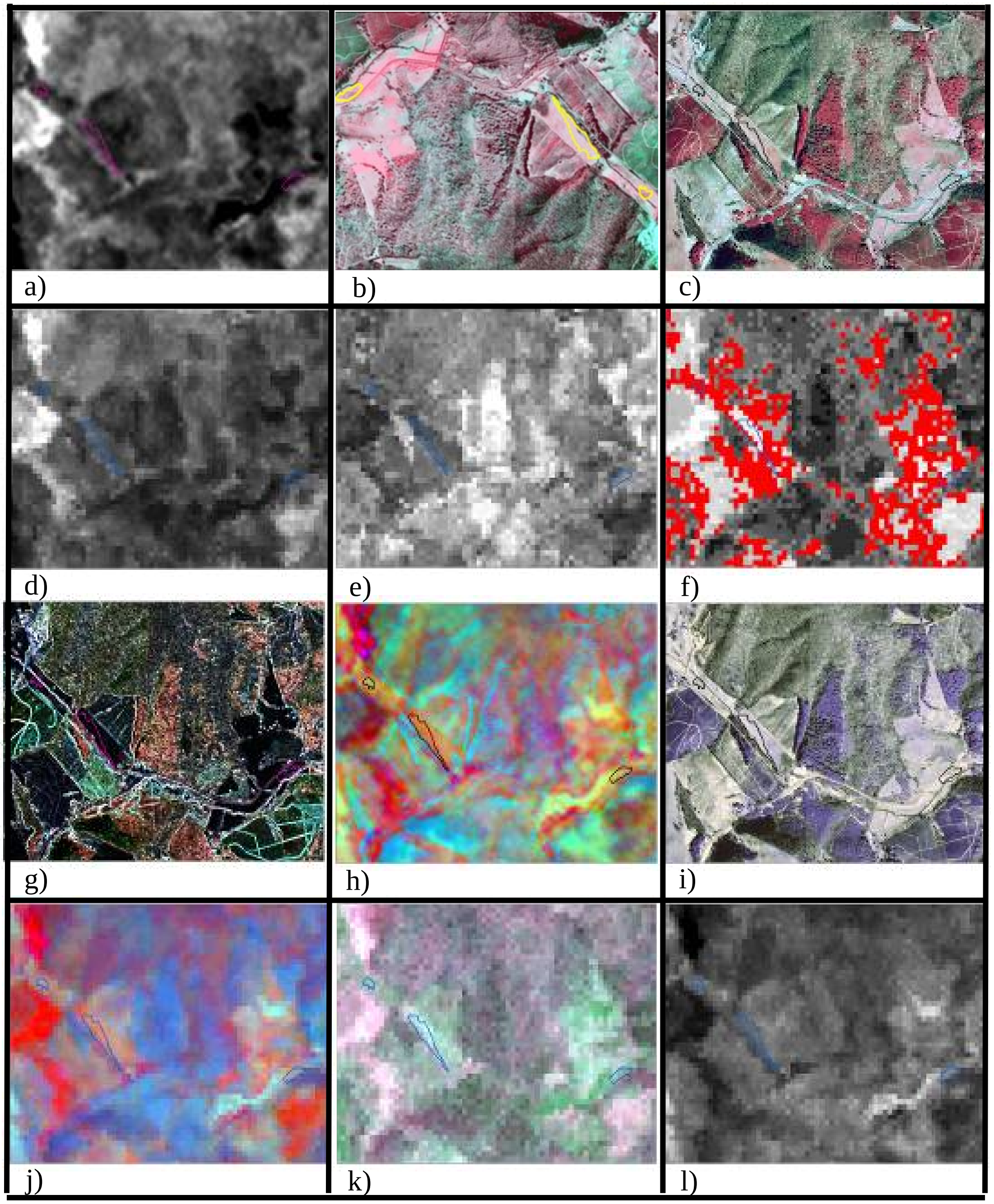


Figure 14. Image enhancements and analyses performed: a) anomaly enhanced image b) unsupervised classification of step-wise merge image c) Wallis Adaptive filter; d) ATCOR haze reduction with ferrous enhancement; e) ATCOR haze reduction with iron enhancement; f) ATCOR haze reduction with wetland unsupervised classification values highlighted in red; g) texture enhanced; h) Tasseled Cap using principal components; i) CIR unsupervised classification; j) Tasseled Cap after ATCOR haze reduction; k) Natural color enhancement; l) NDVI after ATCOR haze reduction.

CHAPTER IV

RESULTS

Bog turtles prefer a particular type of spring-fed wetlands referred to as *fens*. The fens located in North Carolina are dominated by hydrophilic plant species such as sedges (*Carex* sp.) with peat mosses (*Sphagnum* sp.) as a common ground cover. In unmanaged areas where succession is occurring, it is common to find red maple (*Acer rubrum*), tag alder (*Alnus serrulata*) and tulip poplar (*Liriodendron tulipifera*) (Herman 2003). The presence of oxidized rhizospheres can be observed in some sites. Bog turtles are frequently found in wetlands located within pasture settings where grazers reduce vegetation that would otherwise transpire water from the site. Some wetlands were frequently mowed thus eliminating the presence of woody vegetation; other wetlands were grazed by livestock; and some wetland areas were experiencing a degree of successional transition. One wetland had been mined as a rock quarry. These individual habitat characteristics resulted in a mosaic of biological and environmental conditions across the landscape.

The wetlands in this study were small; only 4 were represented by more than 5 pixels. The maximum likelihood classification system used to assign brightness values to each pixel classified the cell according to the dominant characteristic. The “percentage” classification took into account various characteristics on the landscape and assigned a cell value based on an average of the percentages. The pixels were assigned to 37 different class frequencies due to the mosaic of landscape features. Due to the low resolution of the Landsat 7 image (30 meters), the analysis didn't return a consistent signature when using the maximum likelihood method. Using the unsupervised classification and the classes that had the highest frequency of occurrence (classes 19, 22, 25 and 26) an effort was made to determine where other areas with similar brightness values occurred across the landscape. Yet, because the percentage method returned an average of the characteristics, the resulting cell brightness values could also be found abundantly across the landscape.

When analyzing the Landsat 7 thermal band 6.1, no correlation was found between areas of high spectral reflectance (indicating a source of heat) and the wetland polygons. This was probably due to the spatial resolution of 60 meters and comparatively small wetlands. Landsat 7 bands 2, 3 and 7 were analyzed to determine whether a spectral signature could be distinguished for "bog iron" or other ferrous material commonly associated with redoximorphic soils found in wetland areas. No distinct signature was obtained from this method which again may be attributable to the low spatial resolution of 30 meters.

Regardless of which band combinations were used in either the Landsat 7 ETM+ or the CIR images, it was impossible to obtain a spectral signal that was consistent across the landscape. In an effort to reduce the spatial area until specific signatures could be isolated, a small subset was obtained from each image composite for an area that contained only 3 of the wetlands.

The CIR subset containing 3 wetland images with the unsupervised classification showed the most promising results. As Figure 15 shows, one of the wetlands (a) was quite distinguishable and another one was somewhat discernable (b); yet, the last one wasn't detectable—even though they were located in close proximity to each other. Upon closer inspection of the CIR images downloaded for analysis, a variety of spectral "noise" was observed as shown in Figure 16.

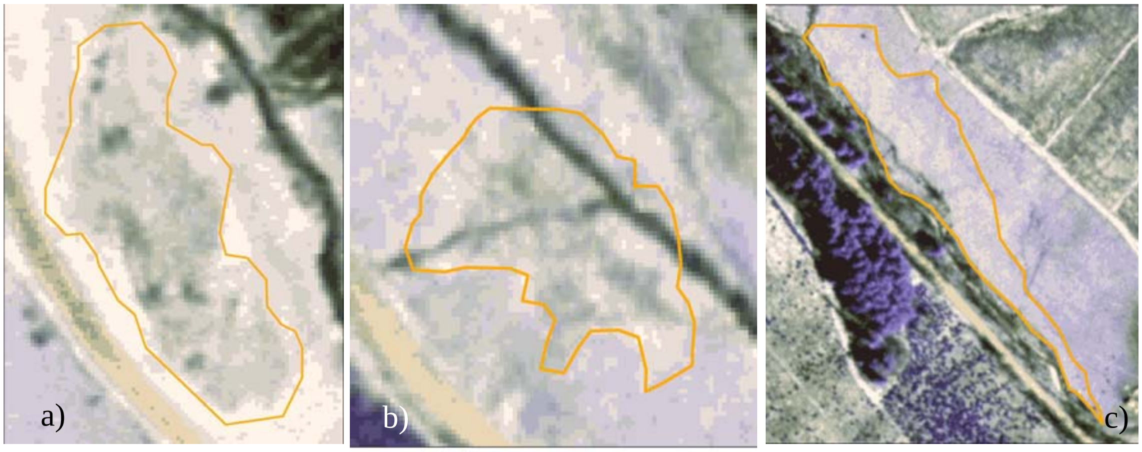


Figure 15. In this unsupervised classification with a wetland polygon overlay, wetland a) was easily distinguishable; b) was somewhat distinguishable; yet c) wasn't detectable.

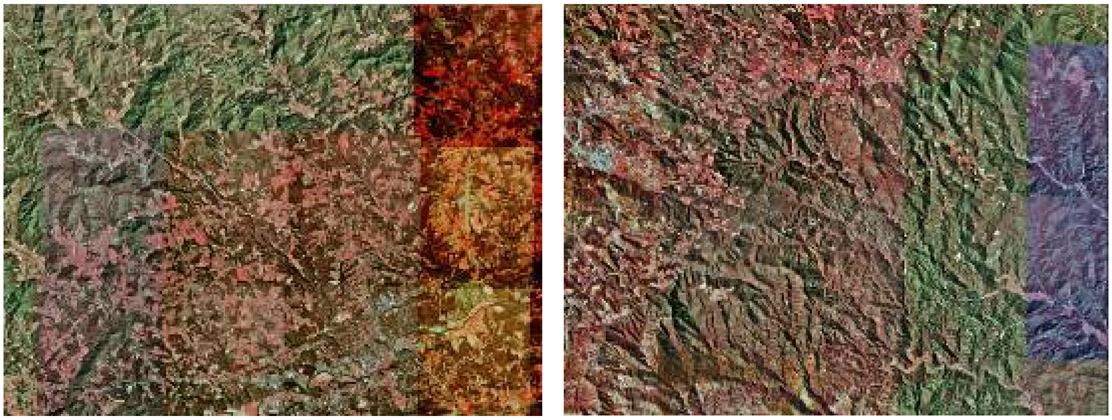


Figure 16. CIR images available for download contain spectral “noise.”

These CIR images are available for free download from various websites such as North Carolina Department of Transportation (www.ncdot.org/it/gis/), NC OneMap (www.nconemap. net/), GeoCommunity (www.geocomm.com/) and the US Geological Survey (www.cr.usgs.gov/products/aerial/doq.html). Additionally, upon closer inspection of the images used in Figure 15, it was discovered that two images had been merged as a mosaic but they clearly contain temporal distortions as shown in Figure 17. This means that the two images were taken at different times of the day as shadows can be seen on the left side of the image. These color distortions were responsible for

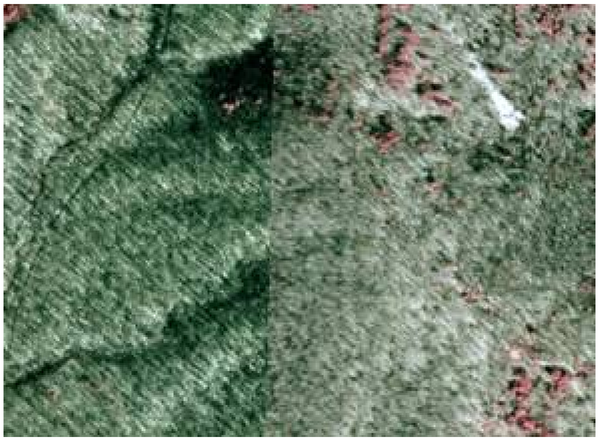


Figure 17. This image contains temporal distortions as shadows that can be seen on the left side.

returning inconsistent signatures across the landscape. While it is technically possible to develop an algorithm to balance the spectral values, it is not within the scope of this paper.

CHAPTER V

CONCLUSION

The results of this study indicate that publicly available data may not be suitable for detecting small, isolated wetlands due to heterogeneous landscape features, low spatial resolution and poor data quality. While some of the wetlands will be easy to identify using these spectral signatures, none of the enhancements or classification methods used in this research yielded adequate results to allow consistent analysis across the landscape. Consequently, a distinctive spectral signature for the wetlands as a group or others across the landscape was not detectable.

Yet, despite the difficulties encountered during the classification process, there *were* some promising results. One explanation for the lack of consistency in obtaining a spectral signature involves the quality of the CIR images. Of all the methods employed in this project, the unsupervised classification on a CIR provided the best results: one of the wetlands was readily discernable and stood out in the CIR image and another wetland was somewhat detectable. This particular CIR subset was of better quality than most of the CIR images downloaded for analysis. These results show that when high quality, high spatial resolution images are available, a distinct signature can be obtained. Research of this nature will certainly require high quality, high resolution data across the landscape in order to accurately delineate and identify wetland areas.

This project is on-going and future plans are to pursue these additional possibilities. It would be most beneficial to acquire high resolution, quality data to analyze spectral signatures that are representative of small, isolated wetlands. Ikonos imagery can be obtained at a scale of 4 meters and QuickBird imagery has a scale of 2.44—2.88 meters. This would result in much smaller pixel sizes and as a result of the finer resolution, a greater chance in detecting spectral signatures specific to bog turtle habitats.

An alternative would be to obtain hyperspectral data. Unlike Landsat 7 ETM+ with 8 bands, hyperspectral imagery is typically composed of 100—200 spectral bands and has a spatial resolution of 1—10 meters. The reflectance values of vegetation within wetland areas can be obtained using a portable spectroradiometer and these values can then be matched up with values in the hyperspectral image across the landscape.

It should also be noted that seasonality plays an important role when determining *when* to obtain satellite or aerial imagery. For most remote sensing applications, it is more beneficial to obtain the imagery during the “leaf off,” fall/winter seasons of the year to gain the best spectral and visual perspective of the landscape. Leaf canopy of deciduous trees can block visual perspectives and spectral reflectance from the landscape beneath. To successfully delineate wetlands using remote sensing, it may be more beneficial to obtain imagery just prior to the “greening-up” season when wetland vegetation is regaining its vigor. Alternatively, it may be possible to distinguish wetlands across the landscape during periods of drought. Wetlands may retain moisture longer than surrounding vegetation and it may be easier to distinguish these wet areas on the imagery towards the end of summer after a sustained period of drought.

Ancillary data, such as hydrography, soils, climate, precipitation, aspect and slope, will also be incorporated into future studies. With the use of high quality, high spectral data, it may be possible to implement remote sensing technologies to isolate soil chemical properties that would help explain why bog turtles occur in some wetlands, but not in others.

REFERENCES

Akçakaya, H. R. 1996. Linking GIS with Models. A paper presented at the Third International Conference on Integrating GIS and Environmental Modeling, at Santa Fe, New Mexico, on January 23, 1996.

Altherr, S. and D. Freyer. 2000. Asian turtles are threatened by extinction. Turtle and Tortoise Newsletter, 1:7-11.

Amon, J. P., C. A. Thompson, Q. J. Carpenter, and J. Miner. 2002. Temperate zone fens of the glaciated midwestern USA. *Wetlands,* 22:301–317.

Ashe County GIS tax parcel website: http://ashegis.ashecountygov.com/webgis/.

Aspinall, R. J. 1995. Geographic information systems: their use for environmental management and nature conservation. *Parks* 5, p. 20–31.

Bedford, B. L. and K. S. Godwin. 2003. Fens of the United States: Distribution, characteristics and scientific versus legal isolation. *Wetlands*, Vol. 23, No. 3, p. 608–629.

Behler, J. 2000. Letter from the IUCN Tortoise and Freshwater Turtle Specialist Group. Turtle and Tortoise Newsletter, 2000, 1:4-5

Brady, N. C. and R. R. Weil. 2002. The Nature and Properties of Soil. 13th Edition. Prentice Hall, Upper Saddle River, NJ.

Buhlmann, J. A., M. G. Rollins, S. M. Roble, and J. C. Mitchell. 1997. New approaches for the conservation of bog turtles, *Clemmys muhlenbergii*, in Virginia. *In:* J.V. Abbena (ed.) Proceedings: Conservation, Restoration, and Management of Tortoises and Turtles—An International Conference. SUNY, Purchase, NY.

Chen, G. -J., and A. T. Peterson. 2000. A new technique for predicting distribution of terrestrial vertebrates using inferential modeling. *Zool. Res*. 21, 231–237.

Cheng, I. 1995. Sea turtles at Dungsha Tao, South China Sea. Marine Turtle Newsletter Vol. 70, 13-14.

Committee on Sea Turtle Conservation, National Research Council, 1990. *Decline of the sea turtles*. National Academy Press. 259 p.

Davidson, O. G. 2001. *Fire in the Turtle House: The green sea turtle and the fate of the ocean.* Public Affairs. New York, NY.

Davis, F. W., D. M. Stoms, J. E. Estes, J. Scepan and J. M. Scott. 1990. An information systems approach to the preservation of biological diversity. *International Journal of Geographic Information Systems* 4, pp. 55–78.

Dean, K. 2005. Seri leatherback release ceremony: Renewing spiritual and ecological traditions. Marine Turtle Newsletter 108:27.

ERDAS. 1997. *ERDAS Field Guide*. Atlanta, Georgia.

Ernst, C. H., J. E. Lovich, and R. W. Barbour. 1994. Turtles of the United States and Canada. Smithsonian Inst. Press, Washington, DC. 578 p.

Environmental Systems Research Institute (ESRI) Data & Maps. (2002). Redlands, CA.

Fisher, P. 2000. Excerpts pertaining to turtles from the November 18, 1999 USFWS Federal Register announcement: The United States' Final Submission for April CITES Conference. *In*: Turtle and Tortoise Newsletter, 1:12-13.

Frederick, C. M. 1974. A natural history survey of the vascular flora of Cedar Bog, Champaign County, Ohio. *Ohio Journal of Science* 74:65–116.

GeoCommunity: http://www.geocomm.com/.

Gibbons, J. W., D. E. Scott, T. J. Ryan, K. A. Buhlmann, T. D. Tuberville, B. S. Metts, J. L. Greene, T. Mills, Y. Leiden, S. Poppy, and C. T. Winne. 2000. The global decline of reptiles, déjà vu amphibians. *BioScience* Vol. 50; No. 8: 653- 666.

Hanski, I. and D. Simberloff. 1997. The metapopulation approach, its history, conceptual domain, and application to conservation. *In*: Hanski, I. and Gilpin, M. (eds), *Metapopulation biology. Ecology, genetics, and evolution*. Academic Press, p. 5-/26.

Herman, D. W. 1994. The bog turtle, *Clemmys muhlenbergii,* in North Carolina. An action plan for its conservation and management. Report submitted to the North Carolina Resources Commission. 156 p.

Herman, D. W. 1999. The impacts of livestock grazing on bog turtle habitat in the piedmont and mountains of the Southeast. Report submitted to US Natural Resources Conservation Service, Wetlands Science Institute.

Herman, D. W. and B. W. Tryon. 1997. Land use, development, and natural succession and their effects on bog turtle habitat in the southeastern United States. p. 364-371. *In* J. Van Abbema (ed.), Proceedings: Conservation, Restoration, and Management of Tortoises and Turtles—An International Conference. July 1993, State University of New York, Purchase. New York Turtle and Tortoise Society, New York.

Herman, D. W. 2003. Status of the bog turtle, *Clemmys muhlenbergii,* Schoepff, in the Southern United States. Project Bog Turtle's final report to the U.S. Fish and Wildlife Service on the 1996—2002 status survey conducted under Grant Agreement #1448-0004-96-9126.

Jackson, J. B. et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638.

Jensen, John R. 2005. *Introductory Digital Image Processing, 3rd Ed*., Upper Saddle River, NJ: Prentice Hall, 526 p.

Levins, R. 1969. Some demographic and genetic consequences of environmental heterogeneity for biological control. *Bulletin of the Entomological Society of America*, 15: 237-240.

Lovich, J.E. 1994. Biodiversity and zoogeography of non-marine turtles in Southeast Asia. p. 381-391 *in* S.K. Majumdar, F.J. Brenner, J.E. Lovich, J.F. Schalles, and E.W. Miller, eds. *Biological diversity: problems and challenges*. Pennsylvania Academy of Science, Easton, PA. In press.

Lovich, J. E., R. A. Mittermeier, P. C. H. Pritchard, A. G. J. Rhodin, and J. W. Gibbons. 2000. Powdermill Conference: Trouble for the world's turtles. Turtle and Tortoise Newsletter, 1:16-17.

Luiijf, W. 1997. CITES and the tortoise and turtle trade. *In*: J. Van Abbema (ed.), Proceedings: Conservation, Restoration, and Management of Tortoises and Turtles—An International Conference, p. 125—134. July

1993, State University of New York, Purchase. New York Turtle and Tortoise Society, New York.

MacArthur, R. J. and E. O. Wilson. 1967. *The theory of island biogeography*. Princeton University Press, Princeton, NJ.

Marsh, W. 1991. *Landscape planning, environmental applications, 2nd Edition*. New York: John Wiley & Sons.

McCord, W. 2000 Current review on China food market/turtle crisis. Turtle and Tortoise Newsletter, 1:13-14.

Mitsch, W.J. and J.G. Gosselink. 2000. The value of wetlands: importance of scale and landscape setting. *Ecological Economics* 35: 25-33.

NASA. Uncovering Chameleons. A case study based upon the work of Raxworthy et al (2003). Located at: http://earthobservatory.nasa.gov/Study/Chameleons/chameleons3.html.

Natural Resources Conservation Service. 2002. *Habitat Notes: Meadow Bogs.*

NatureServe: http://www.natureserve.org/.

NC OneMap: www.nconemap.net/.

North Carolina Department of Transportation website: www.ncdot.org/it/gis/.

North Carolina General Assembly website: www.ncga.state.nc.us/.

North Carolina State Climate Office: www.nc-climate.ncsu.edu/.

Peterson, A. T., D. R. B. Stockwell, D. A. Kluza. 2002. Distributional prediction based on ecological niche modeling of primary occurrence data. *In*: Scott, J.M., Heglund, P.J., Morrison, M.L., Haufler, J.B., Raphael, M.G., Wall, W.A., Samson, F.B. (Eds.), *Predicting Species Occurrences: Issues of Accuracy and Scale*. Island Press, Washington, DC, p. 617–623.

Primack, R. B. 1995. *A Primer of Conservation Biology*. Sinauer Associates, Sunderland, Massachusetts.

Ramanujan, K. 2004. New Tools for Conservation. NASA website located at: http://earthobservatory.nasa.gov/Study/Conservation/.

Raxworthy, C. J., E. Martinez-Meyer, N. Horning, R. A Nussbaum, G. E. Schneider, M. A. Ortega-Huerta, and A. T. Peterson. 2003. Predicting distributions of known and unknown reptile species in Madagascar. *Nature*, 426, 837-841.

Rhodin, A. G. J. 2000. Publisher's Editorial: Turtle Survival Crisis. Turtle and Tortoise Newsletter, 1:2-3.

Rushton, S. P., S. J. Ormerod and G. Kerby. 2004. New paradigms for modeling species distributions? *Journal of Applied Ecology*. Vol: 41, 193–200.

Salzberg, A. 1998. The Chinese turtle problem. *Reptilia*.

Schele, L., D. Freidel, and J. Parker. 1993. *Maya Cosmos: Three Thousand Years on the Shaman's Path.* William Morrow and Company. New York, NY. 543 p.

Scott, J. M., T. H. Tear, and F. W. Davis. 1996. Gap Analysis: a landscape approach to biodiversity planning. *American Society for Photogrammetry and Remote Sensing*, Bethesda, MD.

Turner, W., S. Spector, N. Gardner, M. Fladeland, E. Sterling and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. *TRENDS in Ecology and Evolution* Vol.18 No.6.

US Fish and Wildlife Service. 1997. Final rule to list the northern population of the bog turtle as threatened and the southern population as threatened due to similarity of appearance. Federal Register 62 (213): 59605-59623.

US Fish and Wildlife Service's Endangered Species Website. Available at: http://endangered.fws.gov/.

US Fish and Wildlife Service National Wetland Inventory website: //www.nwi.fws.gov/downloads.htm.

US Fish and Wildlife Service. 1973. Endangered Species Act and Amendments. Entire document can be found at: http://endangered.fws. gov/ esa.html.

US Food and Drug Administration: Ban on Interstate and Intrastate Sales and Distribution. Sec 170.100 Turtles. Retrieved June 14, 2005 from the U.S. Food and Drug Administration web site: http://www.fda.gov/ora/compliance_ref/cpgcpggenl/cpg170-100.html.

U.S. Geological Survey GIS data: http://edcwww.cr.usgs.gov/products/aerial/doq.html.

USGS Landsat ETM+ website: http://erg.usgs.gov/isb/pubs/factsheets/fs02303.html

Venkataraman, A. B., N. V. Kumar, S. Varma and R. Sukumar. 2002. Conservation of a flagship species: Prioritizing Asian Elephant (*Elephas maximus*) conservation units in southern India. *Current Science*, Vol. 82, No. 8.

Vogiatzakis, I. N. 2003. GIS-based Modeling and Ecology: A Review of Tools and Methods. Geographical Paper No. 170. Department of Geography, The University of Reading, Reading.

Walton, E. M. 2002. Field Techniques for Bog Turtle Research in North Carolina. E.M. Walton, Greensboro, NC. 68 p.

Williams, T. 1999. The terrible turtle trade. National Audubon Society. Volume 101:2.

Yarrow, H. C. 1882. Checklist of North American reptiles and batrachia, with catalogue of specimens in the U.S. National Museum. Bull. U.S. Nat. Mus. 24:36.

APPENDIX

Websites Accessed (July 2005) for Table 3
Taxonomic List for Turtles of the US

State Name	Website
ALABAMA	http://www.outdooralabama.com/watchable-wildlife/regulations/endangered-county.cfm
ALASKA	http://www.wildlife.alaska.gov/index.cfm?adfg=endangered.main
ARIZONA	http://azgfd.com/w_c/edits/hdms_abstracts_reptiles.shtml
ARKANSAS	http://www.naturalheritage.com/program/element-search/default.asp
CALIFORNIA	http://www.dfg.ca.gov/hcpb/species/t_e_spp/tereptil/tereptla.shtml
COLORADO	http://wildlife.state.co.us/WildlifeSpecies/SpeciesOfConcern/Reptiles/
CONNECTICUT	http://dep.state.ct.us/cgnhs/nddb/species.htm
DELAWARE	http://www.dnrec.state.de.us/nhp/information/CWCSList.asp#Reptiles
FLORIDA	http://myfwc.com/imperiledspecies/
GEORGIA	http://georgiawildlife.dnr.state.ga.us/content/protectedreptiles.asp
HAWAII	http://www.state.hi.us/dlnr/dofaw/cwcs/Conservation_need.htm
IDAHO	http://fishandgame.idaho.gov/cms/tech/CDC/animals/herps.cfm
ILLINOIS	http://dnr.state.il.us/orc/Wildliferesources/theplan/herptiles.asp
INDIANA	http://www.in.gov/dnr/fishwild/endangered/e-list.htm
IOWA	http://www.iowadnr.com/other/threatened.html
KANSAS	http://www.kdwp.state.ks.us/news/other_services/threatened_and_endangered_species
KENTUCKY	http://fw.ky.gov/navigation.asp?cid=338
LOUISIANA	http://www.wlf.state.la.us/apps/netgear/index.asp?cn=lawlf&pid=693
MAINE	http://www.maine.gov/ifw/wildlife/etweb/index.htm
MARYLAND	http://www.dnr.state.md.us/wildlife/espaa.asp
MASSACHUSETTS	http://www.mass.gov/dfwele/dfw/nhesp/nhrare.htm
MICHIGAN	http://www.michigan.gov/dnr/0,1607,7-153-10370_12141_12168---,00.html
MINNESOTA	http://www.dnr.state.mn.us/ets/index.html
MISSISSIPPI	http://www.mdwfp.com/Level2/cwcs/Final/Appendix%208.pdf
MISSOURI	http://mdc.mo.gov/nathis/endangered/
MONTANA	http://fwp.mt.gov/wildthings/tande/default.html
NEBRASKA	http://www.ngpc.state.ne.us/wildlife/programs/nongame/list.asp
NEVADA	http://heritage.nv.gov/animlbig.htm
NEW HAMPSHIRE	http://www.wildlife.state.nh.us/Wildlife/Nongame/endangered_list.htm
NEW JERSEY	http://www.state.nj.us/dep/fgw/ensphome.htm
NEW MEXICO	http://www.wildlife.state.nm.us/conservation/threatened_endangered_species/index.htm
NEW YORK	http://www.dec.state.ny.us/website/dfwmr/wildlife/endspec/
NORTH CAROLINA	http://www.ncwildlife.org/fs_index_07_conservation.htm
NORTH DAKOTA	http://gf.nd.gov/conservation/levels-list.html
OHIO	http://www.ohiodnr.com/endangered/endangered4.htm
OKLAHOMA	http://www.wildlifedepartment.com/endanger.htm
OREGON	http://www.dfw.state.or.us/threatened_endangered/t_e.html
PENNSYLVANIA	http://www.dcnr.state.pa.us/wrcf/contents.aspx

State Name	Website
RHODE ISLAND	http://www.dem.ri.gov/programs/bnatres/fishwild/pdf/swgapps.pdf
SOUTH CAROLINA	http://www.dnr.sc.gov/pls/heritage/county_species.select_county_map
SOUTH DAKOTA	http://www.northern.edu/natsource/endang1.htm
TENNESSEE	http://www.state.tn.us/twra/nongmain.html
TEXAS	http://www.tpwd.state.tx.us/huntwild/wild/species/?c=endangered
UTAH	http://dwrcdc.nr.utah.gov/ucdc/
VERMONT	http://www.vtfishandwildlife.com/wildlife_nongame.cfm
VIRGINIA	http://www.dgif.state.va.us/wildlife/va_wildlife/index.html
WASHINGTON	http://wdfw.wa.gov/wlm/diversty/soc/concern.htm
WEST VIRGINIA	http://www.wvdnr.gov/wildlife/endangered.shtm
WISCONSIN	http://dnr.wi.gov/org/land/er/herps/
WYOMING	http://gf.state.wy.us/wildlife/CompConvStrategy/index.asp