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RESEARCH ARTICLE

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Bog Turtle (*Glyptemys muhlenbergii*) Wetland Habitat: an Emphasis on Soil Properties

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ABSTRACT: Bog turtles (*Glyptemys muhlenbergii*) access saturated wetland soils and move through them to thermoregulate, find cover, and hibernate. Variability in the physical properties of the soil that affects suitability for turtle use is little understood. We identified dominant soil series and measured soil organic carbon (SOC) content and particle size in the top 18 cm of surface soils from Southwestern Virginia wetlands frequently used by bog turtles and similar wetlands not known to be used. A static cone penetrometer was used to evaluate soil strength in specific locations where bog turtles were found and adjacent random areas. Soils were poorly developed alluvium with aquic soil regimes. Levels of SOC were greater in locations with more continuous surface saturation and averaged 10% in the wettest locations. Proportions of sand, silt, and clay in wetlands were consistent with loam and silt loam textures. Levels of SOC and dominant particle sizes were not different in similarly saturated areas of wetlands that were frequently used or not known to be used by bog turtles. However, some wetlands not known to be used completely lacked areas that were always saturated. Based on penetrometer data, bog turtle use was centered on low strength soils. The physical qualities of surface soils in bog turtle wetlands result from the depositional environment and hydrology. The soil information derived from this study may assist biologists to determine whether wetlands are used by bog turtles, and also establishes reference soil conditions for use during wetland restoration projects that occur within the geographic range of the bog turtle.

Index terms: drought, fen, hydric soil, penetrometer, saturation, SSURGO, Virginia

INTRODUCTION

The Federally Threatened bog turtle (*Glyptemys muhlenbergii*) is a rare species that occurs over a disjunct range separated into northern and southern populations. The southern range of the bog turtle extends from approximately Roanoke, Virginia, to Northern Georgia, primarily along the Blue Ridge Physiographic Province, but also extends into the western portion of the Piedmont Province (Herman and Tryon 1997). Throughout its range, the proportion of available wetlands used by bog turtles is low despite the fact that many wetlands in the region appear similar upon a visual inspection (S.L. Carter, unpubl. data). More detailed, quantifiable field characterizations of soil properties in bog turtle habitat may help wildlife managers recognize how the occurrence of bog turtles is related to habitat differences among available wetlands. Identifying habitat use patterns and habitat conditions that could possibly limit use by bog turtles are important steps in conserving the species, as the dynamic wetlands where the turtles occur are often altered by human activities or are experiencing natural succession.

The wetland fens used by bog turtles are characterized by groundwater supplied hydrology that results in saturation of surface soils, without deep inundation (Pitts 1978; Bury 1979; Chase et al. 1989; Buhlmann et al. 1997; Herman and Tryon 1997; Carter et al. 1999; Ernst and Lovich 2009). The bog turtle spends much of its time submerged in saturated wetland soils that provide a medium for temperature regulation, shelter from predators, and a place for hibernation. Soil conditions in bog turtle wetlands are summarized as being deep, soft, and silty mud that is saturated and contains black organic material (Chase et al. 1989; Buhlmann et al. 1997; Ernst and Lovich 2009). General studies of mountain fens or bog type wetlands in the southern range of the bog turtle indicate the presence of soils formed from alluvium with moderate accumulations of organic matter and sphagnum moss at the surface (Weakley and Shafale 1994; Stolt and Baker 1995; Moorhead et al. 2000). Some of the wetland soils may qualify as organic soils, especially in seepage areas where soils have a thicker and darker surface layer than in adjacent floodplain soils (Stolt and Baker 1995).

The texture and soil organic carbon (SOC) content of soils are physical characteristics that may be related to bog turtle use and selection of wetland habitats. Texture and SOC content are related to soil bulk density and strength, and control how soil physical properties vary when wet. Soil strength is defined as the property of the soil that causes it to resist deformation, and is increased by compaction (Brady and Weil 2008). Even at low proportions relative to other soil components, organic matter has a significant effect on soil structure, making it less dense and less easily compacted (Daum 1996; Blanco-Canqui et al. 2009). Clay is generally associated with stronger soils that are more easily compacted, while sandy soils tend to resist compaction (To and Kay 2005). Less dense, organically rich, saturated soils mixed with less cohesive granular sand and silt may provide a low strength substrate through which bog turtles can move. In Virginia, bog turtles use areas of wetlands that are closer to pockets of water and that contain deeper mud than paired random wetland areas (Carter et al. 1999). A standardized and repeatable in situ method could be useful for determining if bog turtles are selecting microhabitats with low strength soils.

The overall purpose of this investigation was to describe the soils present in wetlands used by bog turtles relative to wetlands in the same vicinity but not used by bog turtles. Of primary interest were soil conditions near the surface where bog turtles are typically found. We had several objectives that were investigated in the field and the laboratory: (1) Assess the utility of the Soil Survey Geographic Database (SSURGO) to identify soil series associated with turtle use, and to briefly interpret the taxonomic descriptions of these soil series; (2) evaluate how the level of saturation is related to the particle size distribution and SOC content in the upper 18 cm of wetlands used by bog turtles and wetlands not known to be used; and (3) investigate surface soil strength in specific locations where bog turtles are found.

STUDY AREA AND METHODS

Study Area

We conducted the majority of this investigation on 12 wetlands (the "focal study wetlands") located in Floyd and Patrick counties, Virginia. All wetlands were located in the Blue Ridge physiographic province. Precise wetland locations are not reported because of the federal and state protected status of the bog turtle and the risk of illegal collection. Each focal wetland was between 0.1 and 1.2 ha in size with a mean and median size of approximately 0.5 ha. A wetland was considered a discrete study site when it was bounded by greater than 100 m of non-wetland, was bounded by the convergence of hydrology into a stream, or was separated from another site by a road. All focal wetlands were currently, or historically, used for agriculture (primarily cattle (*Bos taurus*) grazing) within 15 years of starting of the study with exception of one wetland that supported a mature forest. Focal wetlands were irregularly shaped with multiple core areas of saturation due to variations in surface elevation and numerous seepage areas. Consistent with their current or former agricultural use, most of the focal wetlands had evidence of drainage ditches. These ditches varied in time since the last maintenance, with some showing signs of recent maintenance while others were abandoned and barely distinguishable from the surrounding undisturbed wetland.

The focal wetlands were identified a priori before the study began based on bog turtle habitat use information gathered from the Virginia Department of Game and Inland Fisheries (VDGIF) and National Park Service (NPS). Wetlands were divided into two groups of six based on whether they were known to support bog turtles ("frequently used wetlands") or not (wetlands "not known to be used"). At the end of the study, the a priori group of six wetlands not known to be used was updated to incorporate new turtle survey information that acknowledged the single occurrence of a bog turtle in two of the wetlands. The six a priori frequently used wetlands, and four remaining a priori wetlands not known to be used, make up the post hoc wetland grouping. We refer to the two a priori wetlands "not known to be used" where singular occurrences of bog turtles were recorded as "transiently used wetlands." We justify using post hoc wetland groupings and the term "transiently used wetlands" because they imply that although turtles may occasionally (transiently) use a wetland, a viable population is not supported unless sufficient numbers of individuals use the wetland on a regular basis to allow breeding and reproduction. Descriptions of the focal wetlands and a discussion of the criteria and bog turtle survey efforts used to assign bog turtle wetland use status are provided in Feaga et al. (2012), which describes the hydrologic conditions in the same 12 wetlands.

An additional 18 wetlands (the "limited study wetlands") frequently used by bog turtles were included in a narrower study of soil properties (see soil sampling section below). Six of these wetlands were located in either Carroll, Floyd, or Patrick counties, Virginia, while the remaining 12 wetlands were in either Ashe, Buncombe, or Wilkes counties, North Carolina. These 18 wetlands were located in the Blue Ridge physiographic province or the western extent of the Piedmont physiographic province and were selected based on information provided by the NPS, VDGIF, or the North Carolina Wildlife Resources Commission. Throughout this document, data and results should be assumed to originate from the previously described group of 12 Virginia "focal study wetlands" unless specifically referred to as the "limited study wetlands."

Identifying Soil Series Using SSURGO

We used SSURGO data from Floyd and Patrick counties and the Soil Data Viewer extension for ArcMap 9.2 (ESRI Redlands, CA, USA) to determine the dominant soil series present within, and in the vicinity of, the focal wetlands (Soil Survey Staff 2009). We recorded the center point of all focal wetlands using a GPS unit with approximately 4-m accuracy and created a 1-ha circular polygon (plot) around each plot. These dimensions were based upon personal experience and existing literature describing typical bog turtle wetland sizes in Virginia (Buhlmann et al. 1997). Exact wetland boundaries were not used because all of the focal wetlands were not depicted on existing resource maps (e.g., National Wetland Inventory), were highly irregular in shape, and difficult to delineate using aerial imagery. We used Soil Data Viewer to generate a report of the soil series present, the taxonomic description of the series, and the proportions of each series in each plot. Dominant soil types (by proportion) were examined for any obvious differences in drainage class, parent materials, depth to a restrictive layer, or textural class between the wetland groups with different bog turtle use status. Initial exploration revealed that the sample size was too small within the categorical groups to allow for statistical analysis.

Soil Sampling and SOC and Particle Size Analysis

We stratified sampling by the degree of wetness exhibited by each study wetland. Degree of wetness could fall into five possible categorical strata (Table 1). We defined strata based on qualitative observations made during the year prior to the July 2008 sampling (Figure 1). Severe drought conditions occurred in 2007 and 2008, and surface saturation in the focal wetlands in July 2008 was reduced to only small areas that were topographically low or where groundwater seepage occurred (Feaga et al. 2012).

We used an 8.9-cm diameter, 18-cm long bucket auger to collect at least 10 subsamples from within each categorical wetness strata available in each study wetland. We did not sample deeper than the upper 18 cm of soil because concurrent studies established that hibernating and active bog turtles are almost always found at relatively shallow depths (Feaga 2010). Subsamples were thoroughly mixed in a bucket on site and a composite sample was taken. Not all categorical wetness strata were available in each wetland. The "active ditch" stratum was only present on three wetlands frequently used by bog turtles, and the "always wet" stratum was present on eight focal wetlands. The "temporarily wet" stratum was absent on one transiently used wetland.

We air-dried composite samples, ground them, and passed them through a 2-mm sieve to remove large plant material and gravel. Soil was treated with a 50-g portion of the composite sample with 30% hydrogen peroxide to remove organic matter. Particle size was determined using the hydrometer method (Gee and Bauder 1979). We determined the percent content of SOC using combustion of an approximate 1-mg sub-sample of composite sample with a carbon nitrogen analyzer (Elementar VarioMax CNS, Hanau, Germany). We analyzed two replicate sub-samples for SOC content per composite sample, and replicate samples were averaged prior to statistical analysis to reduce analytical variability.

We tested the hypotheses that the gradient of SOC content would increase with increasing surface wetness (strata) and that SOC content would be greater in wetlands frequently used by bog turtles than in wetlands not known to be used. We also tested if particle size was different between wetland groups with different use status. Response variables of percent SOC and percent silt were evaluated for the assumption of normality of residuals and analyzed using a general linear model with fixed effects (PROC GLM, SAS institute, Cary, NC). Fixed effects were wetland use status, wetness stratum, and their interaction. Statistics were evaluated for both the a priori and post hoc wetland groupings. We determined where significant differences occurred between strata using Tukey's test for multiple comparisons. Significance was assumed at $\alpha \leq 0.05$. Only percent silt was tested statistically as the proportions of silt, sand, and clay in a soil sample were not independent.

In June 2009, we collected composite samples from the 18 limited study wetlands. Each composite sample consisted of at least 10 subsamples gathered in the wettest areas of each wetland. Subsamples were not stratified by wetness, but were effectively collected from areas of the wetland that would have qualified as "always wet" or "usually wet" in the stratified sampling scheme. At the time of sampling, we recorded the pH at the surface of each wetland by taking the average from three subsamples. All soil samples were air-dried and analyzed for SOC and particle size distribution. The purpose of sampling in the limited study wetlands was to improve our estimate of typical soil conditions in wetlands frequently used by bog turtles, provide quality control that the stratified samples taken from the 12 focal wetlands were accurate, and expand

Table 1. Criteria used to stratify wetlands before soil sampling and analysis. Strata were identified using qualitative observations of soil surface saturation recorded from June 2007 through July 2008. Hydrologic conditions in late July and August 2008 were the driest recorded during the study. Moderate to severe drought conditions occurred in 2007 and 2008.

Wetness Strata	Definition
Always wet	Remained saturated to the soil surface throughout the study, including during periods of drought. Occurred in seepage areas or topographic low spots. Bog turtles frequently used this stratum.
Usually wet	Vegetation and water table hydrology were indistinguishable from the always wet stratum during the majority of the study, but this stratum dried during the summer of 2008. Bog turtles frequently used this stratum.
Temporarily wet	Met wetland criteria (Wetland Training Institute, Inc. 1995), but only had surface saturation or water pockets during early spring or after rain events. Bog turtles crossed this stratum frequently.
Non-wetland	Did not meet wetland criteria (Wetland Training Institute, Inc. 1995). Occurred between wetland areas. Turtles were observed crossing this stratum to access saturation, but did not remain in stratum.
Active Ditch	Human-created wetland feature. Remained saturated throughout the entire study. Occurred in wetlands or small streams that had been channelized 5-10 years (estimated) prior to the study. Turtles used this stratum in all wetlands where it occurred, particularly during drought. Not present in most wetlands.

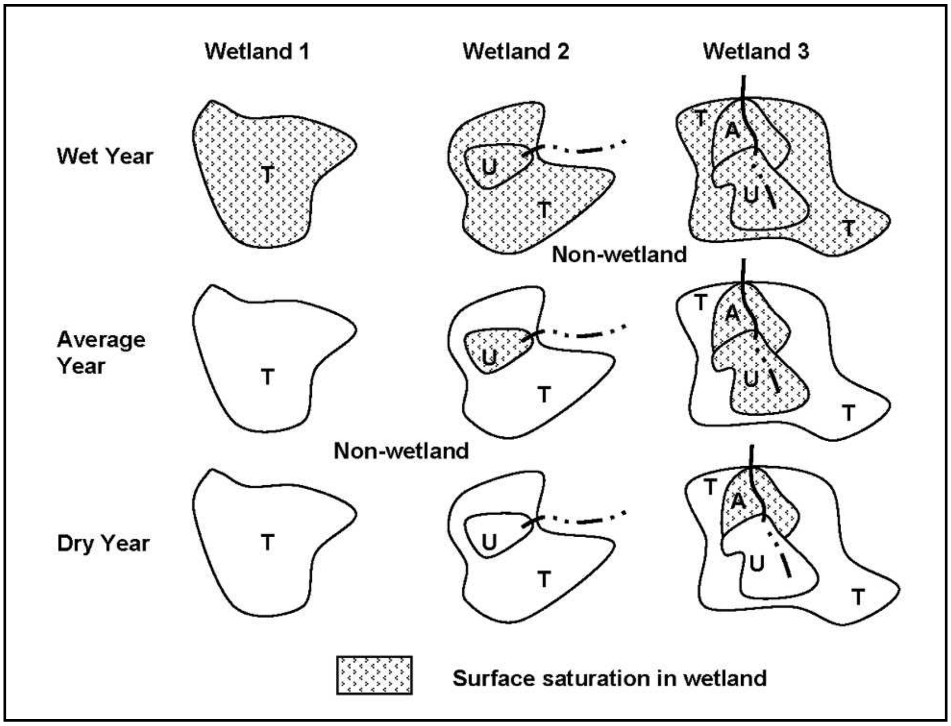

Figure 1. Schematic showing how surface saturation can vary among and within wetlands depending on yearly weather conditions. We took advantage of dry conditions in 2008 to establish wetness strata for sampling surface soil in bog turtle wetlands. Areas with an A, U, and T correspond to the "always wet," "usually wet," and "temporarily wet" strata, respectively. Not all wetness strata were present in every wetland, even when official wetland criteria were met (Wetland Training Institute, Inc. 1995). The non-wetland strata did not meet wetland criteria.

the spatial inference of our results to the North Carolina portion of the bog turtle range. Although many wetlands used by bog turtles in North Carolina are in a steeper topographical setting than those in Virginia, the parent materials and soil forming factors are similar and result in comparable soil characteristics.

Evaluating Soil Penetration Resistance at Points of Turtle Use

In June 2008, we used a digital logging static cone penetrometer (Field Scout SC900 Soil Compaction Meter, Spectrum Technologies, Inc., Plainfield, Ill.) to investigate the selection of soil strength by bog turtles. The SC900 is capable of logging the compaction of soils from 0 to 45 cm at 2.5-cm increments. To accommodate for the relatively low strength of saturated soils, we used a 20.27-mm diameter cone rather than the 12.83-mm diameter cone provided with the penetrometer (American Society of Agricultural and Biological Engineers 2004). We multiplied all cone index readings (kPa) by the scalar 0.40 to compensate for the larger cone. We measured the penetration resistance at locations used by turtles (n = 12) and at random locations (n = 12). All data were recorded by the same operator to reduce observer variance (Herrick and Jones 2002). Turtle-centered (used) locations could be any location where a bog turtle was found, as long as the turtle was not walking at the time of capture. Random locations were generated using a random compass bearing and distance between two and five meters of the turtle-centered locations. Many of the wetlands used by bog turtles are irregularly-shaped and small, so distances to random location were relatively short to ensure that paired random data were constrained to locations that met wetland criteria (Wetland Training Institute, Inc. 1995). At each measurement location, we made nine subsample penetration profiles that were taken at the center point and at 50 and 100 cm from the center in each cardinal direction. For analysis, all subsamples were averaged by depth to provide two profiles (used and random) for each turtle. We used paired t-tests to examine the hypothesis that overall soil strength between 0 and 20 cm was lower in turtle-centered areas than in random areas. We also used simple linear regression to test for an overall trend of soil strength as a function of depth and modeled the interaction (difference in slope) and intercepts of soil strength with depth at turtle-centered and random locations. Soil strength was natural log transformed before regression and interaction modeling to improve the assumption of normality of residuals.

RESULTS

Identifying Soil Series Using SSURGO

SSURGO indicated that three different hydric soils were present in the 12 focal wetlands. No apparent differences in the frequency of soil series were detected between wetlands with different turtle use status. The most common soil series present was the hydric Hatboro sandy loam (fine-loamy, mixed, active, non-acid, mesic Fluvaquentic Endoaquepts), comprising approximately 50% of the soil coverage in the focal wetlands. The other hydric series present included the Kinkora series (fine, mixed, semiactive, mesic Typic Endoaquults) and the Nikwasi series (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, nonacid, mesic Cumulic Humaquepts). The most common non-hydric soil series present in the vicinity of the wetland sites were the Ashe (coarse-loamy, mixed, active, mesic Typic Dystrudepts), Delanco (fine-loamy, mixed, semiactive, mesic Aquic Hapludults), Edneyville (coarse-loamy, mixed, active, mesic Typic Dystrudepts), and Myersville (fine-loamy, mixed, active, mesic Ultic Hapludalfs).

Soil SOC and Particle Size

Levels of SOC in the focal wetlands were significantly dependent on wetness strata, but were not different between wetlands with different bog turtle use status. There was no significant interaction between turtle use status and wetness strata (Table 2). Levels of SOC increased as the degree of saturation in strata increased (Table 3).

Table 2. Results of ANOVA testing for dependence of organic carbon content and percent silt on wetland bog turtle use status, wetness stratum, and the interaction of these factors. The a priori wetland groupings were based on bog turtle wetland use status at the beginning of the study (n=6 frequently used; n=6 wetlands not known to be used), while the post hoc groupings had two transiently used wetlands that were removed from the a priori group of wetlands not known to be used after a single bog turtle was found during the study.

Property	Source of variation	*df* *	*F*	*P-value*	*F*	*P-value*
			a priori		post hoc	
%SOC	Bog turtle use status	1	0.15	0.702	0.64	0.430
	Wetness stratum	3	15.24	< 0.001	13.39	< 0.001
	Use status*Stratum	3	0.60	0.618	0.57	0.637
%Silt	Bog turtle use status	1	2.45	0.127	0.00	0.976
	Wetness stratum	3	1.39	0.263	1.78	0.174
	Use status*Stratum	3	0.88	0.461	1.30	0.295

* Error degrees of freedom in all models=35.

Average SOC content ranged from 4.7% ± 0.8% in the "temporarily wet" stratum to 10.9% ± 0.9% (± SE) in the "always wet" stratum. The active ditch stratum SOC content was 3.3% ± 0.5%, but was only present on three frequently used wetlands and, therefore, was not included in the general linear model. Tukey's multiple comparisons among strata indicated that the "always wet" and "usually wet" strata were not different from each other, but were both different than the "temporarily

Table 3. Mean soil properties in variably-wet strata of 12 wetlands grouped by bog turtle use status. The a priori wetland groupings were based on bog turtle use status at the beginning of the study (n=6 frequently used; n=6 wetlands not known to be used), while the post hoc groupings had two transiently used wetlands that were removed from the a priori group of wetlands not known to be used after a single bog turtle was found during the study.

Bog turtle use status	Wetness stratum	N	Organic carbon	Sand	Silt	Clay
			----------------- % (SE) from 0 – 18 cm -----------			
Used	Always wet	4	9.9 (1.5)	39.2 (7.5)	54.1 (6.4)	6.7 (1.6)
a priori	Usually wet	6	8.6 (1.1)	39.7 (1.8)	52.3 (2.1)	8.0 (0.6)
	Temporarily wet	6	5.0 (0.5)	49.8 (4.1)	44.0 (3.8)	6.1 (1.5)
	Non-wetland	6	3.6 (0.8) †ab	46.2 (2.8)	47.3 (2.9)	6.5 (1.5)
	Active ditch*	3	3.5 (0.33)	61.3 (4.2)	32.0 (5.5)	6.8 (1.7)
Unused	Always wet	4	11.9 (3.1)	49.6 (3.9)	42.4 (3.3)	8.0 (1.7)
a priori	Usually wet	6	7.9 (0.7)	42.6 (5.9)	50.2 (6.3)	7.2 (0.7)
	Temporarily wet	5	4.4 (0.3) †a	49.9 (4.8)	46.1 (4.6)	4.0 (1.7)
	Non-wetland	6	4.4 (0.6) †a	56.0 (5.3)	39.0 (5.0)	5.1 (1.6)
Unused	Always wet	2	9.1 (0.5)	49.5 (8.4)	43.6 (7.7)	6.9 (0.6)
post hoc	Usually wet	4	7.2 (0.7)	35.8 (6.1)	57.4 (6.5)	6.9 (1.1)
	Temporarily wet	4	4.3 (0.3)	45.7 (3.0)	50.4 (2.2)	3.9 (2.1)
	Non-wetland	4	4.5 (0.9)	49.4 (5.2)	46.0 (3.4)	4.5 (2.4)

† Indicates a significant difference (P <0.05) within wetlands with the same bog turtle use status. A difference between the identified stratum and the "always wet" stratum is indicated by an "a." A difference between the identified stratum and the "usually wet" stratum is indicated by a "b."

* The wetness stratum "active ditch" was not compared among other strata in the mixed model because it was not represented in the group of wetlands not known to be used by bog turtles.

wet" and non-wetland strata. The "temporarily wet" stratum and the non-wetland stratum were not significantly different. Comparisons indicated that SOC content in "always wet" strata were significantly higher than in non-wetland strata in both of the a priori wetland groups regardless of use status.

Overall, the 12 focal wetlands (all three wetland strata and bog turtle use statuses) qualified as a loam texture and contained 45%, 48%, and 7% of sand, silt, and clay, respectively. Statistically, the amount of silt was not different among wetland strata, nor was it different between wetlands grouped by bog turtle use status (Tables 2 and 3). Nonetheless, the non-wetland areas in the vicinity of the focal wetlands contained somewhat more sand, and qualified as a sandy loam texture with 51%, 43%, and 6% of sand, silt, and clay, respectively. Statistical results comparing percent silt content were consistent for both a priori and post hoc wetland groupings.

Average SOC content (8.7% ± 0.9%) in the 18 limited study wetlands was within the bounds of the values measured in the "always wet" and "usually wet" strata in the 12 intensively sampled focal wetlands. The average sand, silt, and clay contents in the limited study group were 39%, 50%, and 11%, respectively, giving an overall silt loam texture class. The average pH (± SE) of the limited study group was 5.9 ± 0.1.

Soil Penetration Resistance at Points of Turtle Use

The penetration resistance profiles at turtle-centered locations were visually and statistically different than profiles at random wetland locations (Figure 2). For depths between 0 and 20 cm, the average penetration resistance (± SE) at 12 turtle locations was 133 kPa ± 40 kPa compared to 252 kPa ± 52 kPa for random locations. Soil strength was lower at turtle-centered locations than at paired random locations (df = 11, t = -1.94, P = 0.04). Linear regression and interaction analysis of the relationship of soil strength to depth at turtle-centered and random locations revealed that soil strength increased with depths between 0-20 cm for both locations (df = 1,209, t = 2.68, P = 0.008). A significant interaction (slope difference) was present between depth and turtle-centered or random location (df = 1,209, t = 2.03, P = 0.044). Soil strength was relatively high on the surface at random locations and increased moderately with depth, while soil strength was low at the surface and increased more rapidly at turtle-centered locations. Soil strength at the surface (the intercept) was lower at turtle-centered locations than at random locations (df = 1,209, t = -4.60, P < 0.001).

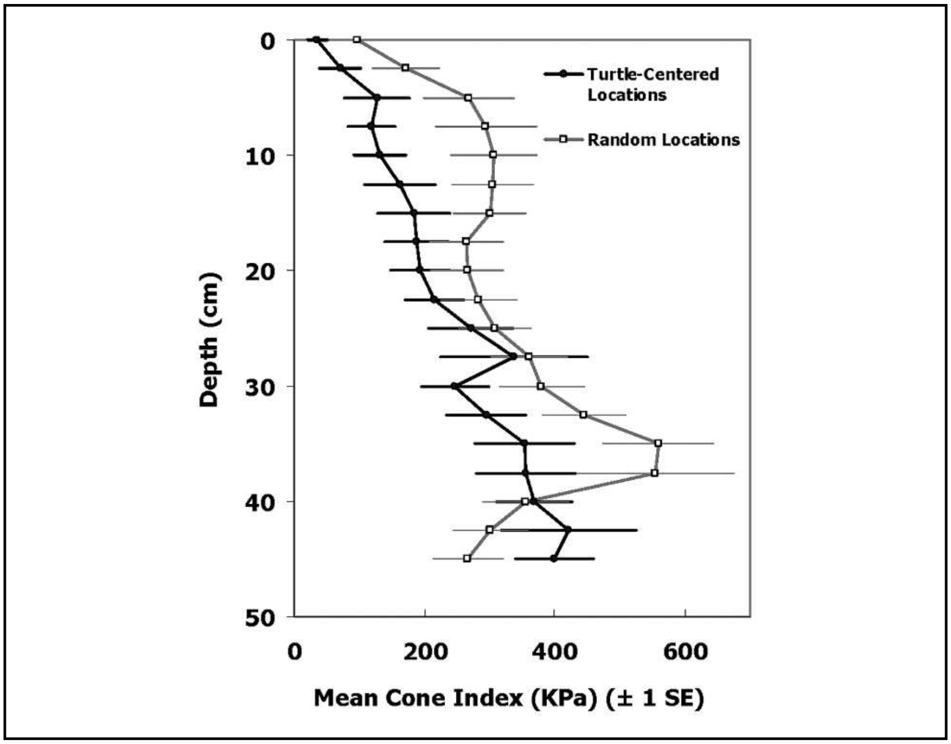

Figure 2. Mean penetrometer cone index values (kPa) with depth for bog turtle-centered (n=12) and paired random locations. Random locations were anywhere within a two to five meter radius of the turtle-centered locations. Random locations met wetland criteria (Wetland Training Institute, Inc. 1995).

DISCUSSION

Soil Series and Taxonomy

Hydric soils in the focal wetlands were primarily of the order Inceptisol due to the lack of structure and clay development in the subsoil. The most abundant soil in the study area, the hydric Hatboro series (fine-loamy, mixed, active, nonacid, mesic Fluvaquentic Endoaquepts), was saturated throughout the profile from water originating from below the surface (Endo), as opposed to a perched water table originating from surface runoff. The Hatboro soil is formed under conditions of flooding, and has very little development with exception to organic matter accumulation at the surface (dark epipedon). The floodplain position of the Hatboro soil is consistent with the sandy loam surface material characterizing most of the focal wetlands. Further, an increase in gravel and cobble material with depth indicates that fluvial deposition is characteristic of the Hatboro series. The process of soil formation by flooding does not imply that flooding is frequent on bog turtle wetlands. A study by Weakley and Schafale (1994) of wetlands in the Blue Ridge of North Carolina, some of which contained bog turtles, found that many of the wetlands did not exhibit hydrology with flowing surface water, but that the soils consisted of coarse alluvial materials deposited from historical flooding. The Nikwasi series (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, nonacid, mesic Cumulic Humaquepts) had a thick, dark epipedon from peat accumulation. The most common non-wetland soils in the vicinity of the focal wetlands were loamy soils with developed clay layers below the surface. These soils had variable base saturation and formed from residuum and colluvium.

SOC and Mineral Soil Texture in Bog Turtle Wetlands

Based on particle size distribution analysis, soils were primarily sandy loam or silt loam textures. These mineral textures did not differ significantly among wetness strata, although the wetter strata appeared to contain a greater proportion of silt and less sand than the drier and non-wetland strata. This pattern is common in alluvial soils (Stolt et al. 2001). The sand and silt likely originated as sediment that was imported from non-wetland areas.

Soil organic carbon content of surface soils was generally below the threshold to qualify the surface soil as organic material (present in all Histosols). This was despite the fact that many areas of the focal wetlands were always wet. When no clay is present, the threshold for organic material is 12% SOC. We found average clay contents between 5% and 11%, resulting in an approximate 13% SOC threshold for organic material (Soil Survey Staff 2006). Most of the surface soils sampled in this study were below this threshold, with a mean SOC content (± SE) of 9.9% ± 1.5%. Only the surface soils of the forested wetland with a closed canopy, a large quantity of leaf litter inputs, continuous saturation, and abundant sphagnum moss were thick enough and contained enough SOC (21%) to qualify as a histic epipedon. Soils in this wetland were mapped as the Nikwasi series. Elevated SOC levels have been observed in similar closed canopied wetlands in the Blue Ridge Mountains of North Carolina (e.g., Reynolds et al. 2007).

Surface soils in the "always wet" and "usually wet" areas of the focal wetlands (5% to 12%) classified as mucky modified mineral soils (> 5% SOC when no clay is present) (Soil Survey Staff 2006). Within the focal wetlands, SOC content was somewhat variable, even within the same wetness strata. There are several factors that can cause SOC content to vary within a wetland. It is possible that the large range of SOC content was due to non-uniform coverage of sphagnum moss. Areas containing abundant sphagnum moss are known to greatly increase the SOC content of soil (Thompson et al. 2007). Sphagnum moss decomposes slowly relative to other types of wetland plants, resulting in SOC accumulation (Moore et al. 2007). Vertical hydrologic gradients can be variable within groundwater-driven wetlands, resulting in local seepage areas that maintain surface saturation. Seepage areas have been found to increase organic accumulation in the Blue Ridge of Virginia (Stolt and Baker 1995). Finally, livestock activity may also facilitate the accumulation of organic matter by pushing living plant parts deeper into the soil where decomposition rates are slower (Moore et al. 2007). Highly variable SOC contents between 2% and 21% were found in the surface horizons of four different fens in the Blue Ridge province of North Carolina (Moorhead et al. 2000). The high variability in SOC in that study was attributed to geomorphic setting, with sloped areas having less SOC than flat areas. Another factor in the wetland variability seen in the North Carolina study by Moorhead et al. (2000) was the long-term human activity including livestock grazing that occurred in the study area. Agricultural land uses were also characteristic of our 12 study sites.

Linking Soil Conditions with Bog Turtle Use

Bog turtles were found in locations with significantly lower strength soils than nearby random wetland areas, and the pattern of soil strength with depth differed in turtle-centered and random locations. Turtle-centered locations had relatively low strength soils at the surface with a steady increase in soil strength down to 20 cm, while random locations had relatively higher strength soils at the top 15 cm. As bog turtles are most frequently found at the top of the soil profile, the relatively higher strength soils in random locations would make it difficult for turtles to submerge themselves. Soil strength at bog turtle-centered areas was less than 200 KPa through the 20-cm depth compared to strengths of up to 306 KPa for random locations. This outcome was likely due to the lack of large alluvium and presence of deeper soils at random locations relative to turtle-centered locations. Coarse materials are difficult to penetrate and can represent discontinuities in soil deposition sequences (Shanley et al. 2003). In the wetlands we investigated, the low soil strength areas used by turtles may coincide with topographic low spots where fine sediments have accumulated over large alluvium, such as in a former stream bed. Stolt et al. (2001) also found that fine particles settled on the surface of topographic low spots. Very wet areas would also be expected to have lower penetration resistances because at high water contents, soil physical qualities are more similar to materials in the liquid state (Brady and Weil 2008).

A notable exception of bog turtles selecting for lower strength soils occurred during the most severe portion of the drought in 2007 and 2008. At this time, the proportion of area saturated decreased in the focal wetlands (Feaga et al. 2012); and turtles could only access soils within the deepest livestock hoof prints or in the coarser-textured, shallow sediment at the bottom of ditches ("active ditch" stratum) and small streams. Ditch use was not common during the non-drought portions of the study when the "usually wet" and "temporarily wet" strata were saturated. Other research has documented bog turtle use of streams and ditches during dry periods (Pittman and Dorcas 2009; Feaga 2010).

One of the focal wetlands with the highest turtle density had soils with relatively little SOC. In this wetland, the "always wet" and "usually wet" strata had SOC contents of 5.3% and 4.4%, respectively. This wetland was ditched sometime prior to 1995 when surveys for bog turtles began. Saturation was present in the majority of the ditches throughout the study. Silt and clay sediments settled in the ditches because water velocity was negligible and ditch flow did not increase greatly during storm events. The soft sediments allowed turtles to cover themselves in mud and move through it in the same manner as observed on more organically-rich wetlands where bog turtles are present. The influence of hydrology on bog turtles was also observed on two bog turtle used wetlands where the "always wet" stratum was absent. These two wetlands contained ditches that were used by bog turtles frequently when the wetlands were driest, but infrequently during normal conditions. In some wetlands, the presence of inundated ditches may provide an alternative saturated habitat to organically rich soil areas ("always wet" stratum) as long as the "usually wet" stratum remains saturated during all but the worst droughts. Although bog turtles were observed using inundated ditches as refugia during drought, it is important to point out the net negative effects that wetland ditching can have on bog turtles and their habitat. First, the mechanical disturbances associated with the ditching process can cause direct mortality of turtles. Second, total saturated surface area is reduced when wetland hydrology is conveyed to ditches. When the availability of surface saturation is reduced, turtles may be forced to cover relatively long distances to reach alternative saturated areas, exposing themselves to risks such as predators (Roe and Georges 2008). Third, wetland activities that lower the water table or concentrate flow through channels have been shown to reduce SOC contents of wetland soils through increased decomposition of organic matter and dissolved SOC losses (Strack et al. 2008). High SOC and surface saturation are associated with abundant sphagnum moss (Moore et al. 2007). Given the correlation with sphagnum moss and SOC content, elevated decomposition of sphagnum through drying could be detrimental to bog turtles because the moss has been linked to high-quality bog turtle nesting habitats in Virginia (Mitchell 1994).

Management implications

Soil conditions are important to bog turtles because both the soil medium itself and the vegetation it supports are important to activities such as thermoregulation, predator avoidance, hibernation, and nesting. Considering the prevalent use by bog turtles of low strength soils, it follows that maintaining and monitoring their availability in wetland habitats is important to the species. Soil organic carbon accumulation at the surface, a secondary outcome of nearly continuous saturated conditions, may be important for the maintenance of low strength soils. Wetland managers focusing on bog turtles should be trained to recognize changes (on the order of years to decades) in surface saturation as a part of their typical habitat monitoring.

Wetland drying and associated changes to soils can be related to hydrology, drought, or even climate change. Ditching, pond building, and road building are human activities that can cause changes to hydrology and soil conditions, and can also result in direct mortality of bog turtles because of the use of heavy equipment. The creation of new ditches and the installation of buried tiles to drain wetlands are activities regulated by federal wetland laws. Although controversial, the maintenance of existing drainage features on active agricultural operations is loosely regulated and is a standard management practice on many farms. The maintenance of existing drainage systems, and to a lesser degree the illegal creation of new drainage features, continues to occur in some wetlands of the Virginia Blue Ridge.

In contrast to rigid enforcement of wetland laws, which is often perceived as aggressive toward landowners and also difficult to achieve in large geographic areas, education and cooperation with landowners are the primary means by which managers can limit direct hydrologic impacts to bog turtle wetlands in Virginia. Often, farm management strategies that better conserve wetland areas are actually valued by landowners because they can reduce erosion, provide pasture areas during drought, and result in improved treatment of nutrient-rich waters. Many landowners are quite willing to participate in natural resource protection programs such as those administered by the Natural Resources Conservation Service. These programs can provide technical and financial incentives so that landowners can more efficiently manage the production aspect of their land while simultaneously focusing on management of target wildlife species like the bog turtle.

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