Grazing for Bog Turtle (*Glyptemys muhlenbergii*) Habitat Management: Case Study of a New York Fen

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Abstract.—Groundwater-fed wet meadows and rich fens with low, open vegetation form the core habitats of rare Bog Turtles (*Glyptemys muhlenbergii*) in the northern part of their range in North America. Under current conditions, these habitats tend to become overgrown with taller vegetation in the absence of management. In agricultural and post-agricultural landscapes, managers sometimes use livestock grazing to improve and maintain habitat quality for Bog Turtles, despite insufficient knowledge about how specific practices affect both Bog Turtles and nontarget species. To further our understanding of such effects, we present results from a single wetland complex in New York, USA, which we managed primarily with cattle grazing over four and a half growing seasons. Management effectiveness was assessed by monitoring Bog Turtle nest placement, habitat use via radio tracking, and vegetation structure and composition change in permanent plots. Nest locations varied among years, with all nests placed in grazed or recently grazed areas. Individual turtles maintained, and in some cases expanded, their ranges in grazed areas during spring and summer, although they continued to avoid one (grazed) area with apparently unsuitable soils, and increasingly used cattle exclusion areas for fall and overwintering habitat. Plant species richness and the cover of native plants and fen-indicator plants increased in grazed areas, while cover of nonnative species did not. Grazing appeared to improve Bog Turtle habitat without negatively affecting fen and other wetland vegetation at this site, and we propose several specific management recommendations based on our results.

Key Words.—fen vegetation; home range; livestock; prescribed grazing; rare species; restoration; seasonal habitat use; wetland soils

Introduction

Bog Turtles (*Glyptemys muhlenbergii*) are threatened throughout their northern range in North America in large part because of the loss, fragmentation, and degradation of their core habitats, groundwater-fed wet meadows and fens (Klemens 2001). Bog Turtles require at least a small area of habitat that is characterized by low, open vegetation underlain by soft, wet soil and includes plant structures (tussocks or hummocks) that provide raised nest sites (Klemens 2001). These habitats tend to become overgrown by tall, dense vegetation (including woody or herbaceous, native or non-native plants), a process that is encouraged by nutrient additions (Woo and Zedler 2002; Kiviat et al. 2010). To restore or maintain suitable vegetation, Bog Turtle habitats are managed at many locations in New York, New Jersey, Pennsylvania, and other states (U.S. Fish and Wildlife Service [USFWS] 2010), although there has been little detailed research on the responses of Bog Turtles to management (but see Tesauro and Ehrenfeld 2007; Sirois et al. 2014) or the effects of management on other species (Middleton et al. 2006).

Rich fens are circumneutral to basic, groundwater-fed wetlands, dominated by sedges, other graminoids, forbs, and sometimes low shrubs; they are uncommon but widespread habitats that occur in north-central and northeastern North America, northern Europe, and elsewhere (Grootjans et al. 2006). They depend on a base- and iron-rich groundwater flow that promotes base-rich conditions in the topsoil, limits nutrient cycling and nutrient availability to plants, and supports a high diversity of graminoids and forbs (Grootjans et al. 2006). In addition to supporting Bog Turtles, rich fens in the northeastern U.S. support many rare and declining plants and other animals of conservation concern (Bedford and Godwin 2003). Rich fens have the potential to be stable communities over thousands of years (Futyuma and Miller 2001; Grootjans et al. 2006), although natural disturbances such as beaver dam construction and abandonment or activities of large herbivores may also have played a role in maintenance of open wetlands for Bog Turtle habitat in prehistoric times (Kiviat 1978). Most extant rich fens in New York are small (< 2 ha; Bedford and Godwin 2003). Both fens and Bog Turtle populations were likely small historically, and Bog Turtles maintained a metapopulation structure by regular but infrequent movement among habitat patches (Shoemaker and Gibbs 2013).

Beginning with European settlement, humans have destroyed and modified North American fens and wet meadows (e.g., where agriculture or development have altered hydrology or nutrient availability) but in some cases have inadvertently maintained these habitats through low-intensity livestock grazing (Middleton et al. 2006). Fens that have been grazed by cattle and then abandoned typically become overgrown with shrubs and tall herbaceous growth within 10–20 y (Middleton 2002; Tesauro and Ehrenfeld 2007), whereas some fens that have experienced little agricultural impact can maintain herbaceous, short-statured vegetation for decades without active management (Middleton 2002; Middleton et al. 2006) except in areas where hydrology has been changed by other practices or where atmospheric N deposition is high (Grootjans et al. 2006). Thus, for fens that have already been altered by agricultural or other land uses, livestock grazing is believed to be an effective method of management (Kiviat 1978; Tesauro and Ehrenfeld 2007). Wet meadows have been managed with livestock grazing for many years in Europe, to promote diversity of vascular flora (Marion et al. 2010), maintain rare plants (Stammel et al. 2003), or improve habitat for certain birds or other animals (including European Pond Turtle, *Emys orbicularis*; Ficheux et al. 2014). In European fens, grazing promotes native plant diversity (Seer and Schrautzer 2014; Bucher et al. 2015; but see Middleton et al. 2006). Similarly, recently grazed rich fens in New York had higher plant species richness and diversity than nearby, ungrazed fens (Hajek 2014). Prescribed grazing was used with good success to restore or maintain suitable vegetation at a number of Bog Turtle sites in New Jersey (Tesauro 2001), and this practice is viewed favorably by regulatory agencies as an alternative to chemical management of vegetation (USFWS 2010).

In theory, low-intensity grazing in fens and wet meadows would limit height of herbaceous (and woody) growth, limit establishment or regeneration of woody species, favor grazing-tolerant plant species over others, and maintain a high level of plant diversity, including some rare and many other native species (livestock grazing in wet, infertile grasslands is predicted to increase diversity by enhancing colonization rates; Olff and Ritchie 1998). Grazing would also generate areas of bare, disturbed soil, and small to intermediate-sized depressions (such as hoofprints and trails) that could hold water or soft wet soil, microhabitats that appear to attract Bog Turtles (Tesauro 2001; Feaga et al. 2013), especially during the nesting season (Tesauro and Ehrenfeld 2007; pers. obs.) or for hibernation (at southern population sites; Feaga and Haas 2014). Negative effects, including additions of plant-available nitrogen to wetlands and streams, potential trampling of turtles and their nests (Ficheux et al. 2014), and soil

compaction (Middleton et al. 2006), should be limited by the low stocking rate and timing of grazing (Drewry 2006; Russell and Bisinger 2015) and likely offset by the benefits of overall habitat improvement. Bog Turtles would benefit, under this scenario, from abundant basking sites, unobstructed travel corridors, and high-quality nest sites (low vegetation and exposed soils or diversified soil microtopography); and possibly from increased prey availability or foraging ease. Measurable results of such benefits might include demographic factors (e.g., increased recruitment to different life stages), fitness measures (e.g., higher relative mass), or behavior of Bog Turtles (e.g., use of more or different areas of the wetland by the population, expansion of nesting areas, or smaller individual home ranges due to higher quality habitat). Research is needed to better understand the relationships between livestock, vegetation, and Bog Turtles, so that policy makers, regulators, and managers may tailor management approaches to local site conditions and turtle populations.

In this case study, we explored aspects of turtle behavior (seasonal habitat use, home range, and nest placement) and vegetation composition and structure across 4.5 y to see if they fit with the general concept of Bog Turtle habitat improvement through livestock grazing while maintaining fen quality for other native flora and fauna. Although our work occurred at a single site and with a relatively small number of turtles, we believe that our long acquaintance with the site, our experience with other Bog Turtle fens, and the level of detail of our observations can be used to critically evaluate cattle grazing as a Bog Turtle habitat management method, as well as provide concrete guidance to managers at other Bog Turtle sites.

Materials and Methods

Study area.—Our study area in New York, USA, was part of an approximately 8-ha complex of wet meadow, marsh, and rich fen habitat surrounded by young Red Cedar (*Juniperus virginiana*)-hardwood forest, farmland, and residential development, and underlain by Stockbridge marble. The entire study area (upland and wetland) appeared to be pasture in a 1936 aerial photo. Fens were fed by calcareous groundwater seepage, had soft soils and vegetation dominated by low herbs and shrubs, and included the indicator species Shrubby Cinquefoil (*Dasiphora fruticosa*), Grass-of-Parnassus (*Parnassia glauca*), Yellow Sedge (*Carex flava*), and Porcupine Sedge (*C. hystericina*). The surrounding area supports one of the largest concentrations of potential Bog Turtle habitats and known Bog Turtle populations in the region. (Because of the threat of illegal collecting, we have omitted precise locations from this paper. New York State Department of Environmental Conservation
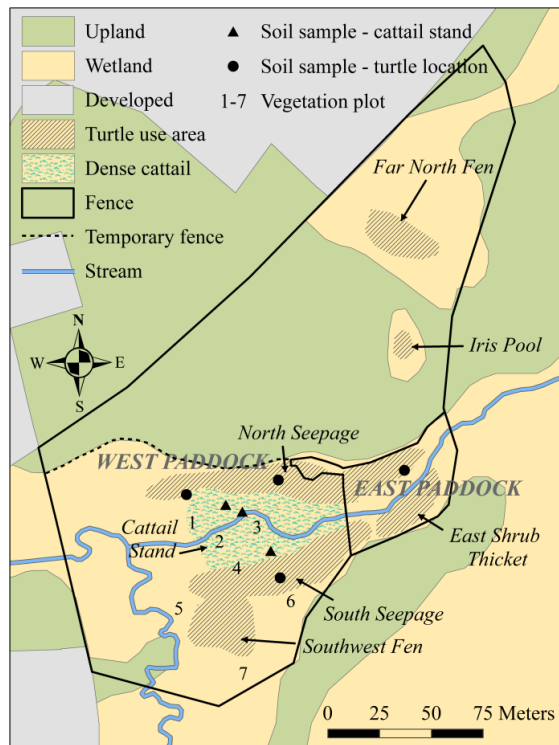
Figure 1. Bog Turtle study site in New York, USA, showing treatment paddocks (West Paddock = 3.3 ha; East Paddock = 0.2 ha), named turtle use areas, Cattail Stand, permanent vegetation survey plots, and soil sampling locations.

(NYS DEC), Region 3 Office, and United States Fish and Wildlife Service, New York Field Office, have this information.) At least three other potential Bog Turtle wetlands lie within 1 km of the study area, so the study population could be part of a larger metapopulation with regular exchange of individuals among sites (Shoemaker and Gibbs 2013). Significant residential development and a highway lie within 1 km of the site, and it is adjacent to a working dairy farm (the source of cattle used for management).

The core Bog Turtle wetland comprised about 1.6 ha, although the turtles only used part of this area. A small stream flowed from east to west through the wetland, joining a larger stream in the western part of the site. Within this core, we delineated several turtle use areas that encompassed most Bog Turtle locations throughout the study period (totaling 0.3 ha) and a dense stand of cattail mostly avoided by the turtles (Fig. 1). The Cattail Stand was an area of (in 2012) dense Broad-leaved Cattail (*Typha latifolia*) on a less organic, alluvial, soil near the east-west stream. The turtle use areas were fairly uniformly seepy, with many small rivulets and generally saturated soils. The North Seepage included a sloping fen dominated by sedges and Shrubby Cinquefoil and a flatter area of Broad-leaved Cattail, Red-osier Dogwood (*Cornus sericea*), and scattered Tussock

Sedge (*Carex stricta*). The South Seepage included a sedge fen, an area dominated by Broad-leaved Cattail, Red-osier Dogwood, and scattered Tussock Sedge, and a cattail-mixed species area. The Southwest Fen contained Sweetflag (*Acorus*) in one portion. The East Shrub Thicket was dominated by Red-osier Dogwood, with smaller amounts of Purple Loosestrife (*Lythrum salicaria*) and other tall herbs; this area was fed by a perennial spring just to the south. West of these turtle use areas was an area of drier wetland with tall forbs and shrubs. To the north of the core wetland, the marshy Iris Pool and Far North Fen with an adjoining Common Reed (*Phragmites australis australis*) stand were visited by a single radio tracked turtle. *Sphagnum* moss was limited to 1–2 m² associated with a grove of Northern White Cedar (*Thuja occidentalis*) in the South Seepage, but other mosses were locally common.

Grazing regime.—We constructed an enclosure for prescribed cattle grazing in the Bog Turtle habitat in March 2012 (Fig. 1) concurrent with cutting about 100 woody plant stems and girdling a few larger trees. Because hand-cut woody vegetation was sparse and largely outside the turtle use areas, we do not think it affected our results and we do not discuss it further. The fence enclosed 3.6 ha, with approximately 1.6 ha of potential core Bog Turtle wetland and 2 ha of young forest, shrubland, and smaller wetlands. Because cattle forage in the core Bog Turtle wetland was of low quality, we needed to include a large area of non-turtle habitat to provide adequate forage for the entire season. We divided the fenced area into West (3.3 ha, including 1.4 ha of core wetland) and East (0.2 ha, all core wetland) paddocks, with approximately half of the main (North Seepage) nesting area in each paddock. The West Paddock was the main grazing treatment area because it was large enough to provide forage for the whole growing season (Fig. 1). Each treatment year two dairy heifers were used to graze one or both of the paddocks (Fig. 2); the cows were different individuals each year. Start and end dates for grazing varied across years due to the logistical constraints of the dairy farm, and we had to adjust paddock area at times by enlarging the area for more forage, or reducing the area to intensify grazing pressure (Table 1). Stocking rate was approximately 0.6–1.4 animal units (AU)/ha in each year (one dairy heifer = one AU).

Nest surveys and protection.—We conducted nest surveys in 2012–2016 via a combination of evening searches for nesting females and visual and tactile inspection of sedge tussocks and other mounds after nesting season ended (late June to early July). Additionally, we included location data for nests found opportunistically from 2009 and 2010 (three and eight

TABLE 1. Summary of cattle grazing regime at the study site for Bog Turtles (*Glyptemys muhlenbergii*) in New York, USA, 2012–2016. Stocking rate was approximately 0.6–1.4 animal units (AU)/ha in each year. See Fig. 2 for a map of areas grazed in each year. In 2012, grazing in the East Paddock occurred for the first eight weeks (extra forage needed). In 2013, cattle were restricted to the 1.4-ha wetland part of the West Paddock (south of dashed line in Fig. 1) until the second week of July to intensify grazing, and a small (0.03-ha) area containing several turtle nests was fenced off and excluded from grazing from mid-June until the end date. In 2014, grazing in the West Paddock was restricted to the 1.4-ha wetland part of the paddock until early August.

Year	Start Date	End Date	West Paddock	East Paddock
2012	13 June	29 October	Grazed (20 weeks)	Grazed (eight weeks)
2013	29 April	17 September	Grazed (20 weeks)	Not grazed
2014	23 May	18 October	Grazed (21 weeks)	Not grazed
2015	—	—	Not grazed	Not grazed
2016	22 April	26 May	Not grazed	Grazed (five weeks)

nests, respectively), and old eggshells found early in 2009 identified the sites of two 2008 nests. One person (JT) conducted all surveys except those in 2012, which were conducted by Suzanne Macey (Macey 2015). Most nest locations were marked at discovery with GPS; a few we estimated remotely. Although the entire wetland was searched during each survey (2012–2016), the number of person-hours spent on surveys varied (approximately four person-hours spread over several days in 2013, 2015, and 2016; over 40 person-hours in 2012 and 2014), so we did not compare the number of nests found per year. We are most interested in nest locations in relation to grazed and ungrazed areas.

All intact nests were caged with an open-bottomed cube or triangular prism (12 × 12 × 12 cm) made of 6.4 mm mesh hardware cloth and secured to the top of the hummock with 15-cm metal ground staples through hardware cloth flanges (Macey 2015). These predator excluders were removed prior to hatching in August 2012 and 2013. One nest was depredated after the excluder was removed (but before hatching), so in 2014–2016, we removed excluders after hatching was completed.

Turtle tracking.—We conducted surveys in April and May of each year to capture turtles for attachment or replacement of radio transmitters. Surveys involved both visual-encounter methods and opportunistic probing in rivulets, tunnels, hummocks, and other likely places. For each turtle, we recorded sex, carapace length and width, number of scute annuli, shell wear, injuries, and overall health and appearance and gave each a unique set of marginal scute notches with a metal file (Cagle 1939). We affixed radio transmitters (Wildlife Materials, Inc., Murphysboro, Illinois, USA) to the posterior margin of the carapace using quick-drying, waterproof epoxy (WaterWeld™ Epoxy Putty, J-B Weld, Sulphur Springs, Texas, USA). Mass of the transmitter plus epoxy was approximately 5–7% of the body mass of each turtle. We released all turtles the same day at their point of capture.

We tracked between six and eight adult turtles each year. We could not follow the same set of individuals each year due to transmitter failure and the difficulty of relocating particular turtles; however, we tracked six individuals (including two males) for 3 y, and four of those (including one male) for 5 y. We tracked turtles through most or all of the active season in 2012–2015; tracking commenced in April or May of each year and ended in October or November. In 2016, we tracked turtles from April through the end of nesting season (early July). We located turtles either approximately twice/week (2012, 2014) or once/week (2013, 2015, 2016) using an R1000 Receiver (Communication Specialists, Inc., Orange, California, USA) and a Yagi antenna (F151-3FB from AF Antronics, Inc., Urbana, Illinois, USA, or RA-23K from Telonics, Inc., Mesa, Arizona, USA). We collected coordinates of turtle locations using a 2005 GeoXT GPS unit (Trimble, Sunnyvale, California, USA) in 2012 and a GPSMAP 62 (Garmin International, Inc., Olathe, Kansas, USA) in 2013–2016. Accuracy may have differed between the two units. Tested mean error in open conditions was 0.9 m for the Trimble GeoXT (Serr et al. 2006)

TABLE 2. Number of location points (from weekly or bi-weekly radio tracking) for each Bog Turtle (*Glyptemys muhlenbergii*) in each year at study site in New York, USA.

Individual (sex)	2012 (April-Oct.)	2013 (May-Nov.)	2014 (April-Oct.)	2015 (April-Oct.)	2016 (April-July)
Turtle 1 (F)	38	25	35	24	12
Turtle 2 (M)	36	27	49	21	12
Turtle 3 (F)	29	26	52	—	—
Turtle 4 (F)	37	29	51	26	7
Turtle 5 (F)	37	26	52	26	12
Turtle 6 (M)	28	22	29	—	—
Turtle 7 (F)	37	—	51	—	—
Turtle 8 (F)	36	—	—	—	—
Turtle 9 (F)	—	—	—	18	10
Turtle 10 (F)	—	—	—	21	6
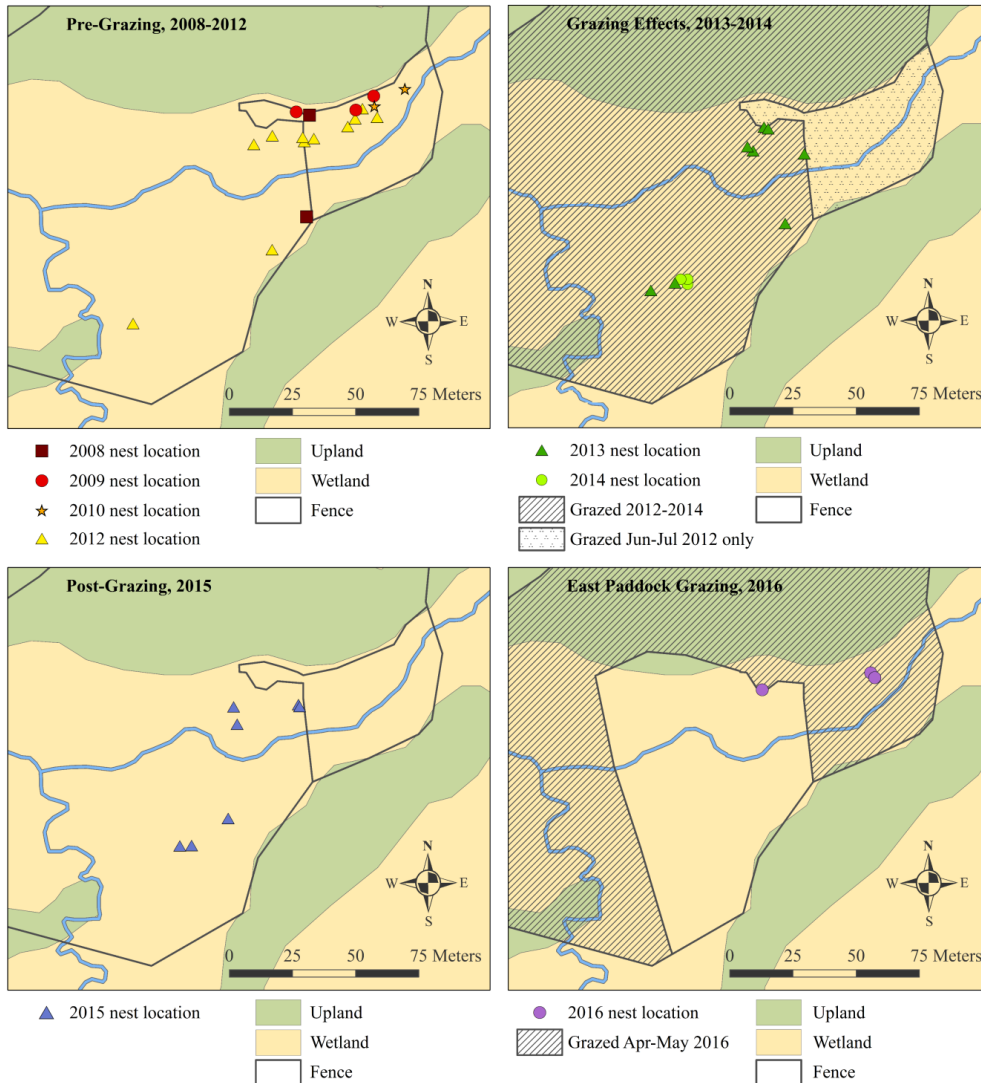
Figure 2. Locations of Bog Turtle (*Glyptemys muhlenbergii*) nests in relation to cattle-grazed areas at the study site in New York, USA. Grazing started in mid-June 2012 (well into the nesting season), and effects on vegetation were not pronounced until the following year, so we included 2012 nests in the "pre-grazing" map. For detail on grazing duration and stocking rate, see Table 1.

and 3.7 m for the GPSMAP 62 (Wing 2011); however, this 3-m difference was small relative to the differences in home range among years (e.g., 20–60 m westward expansion; see Fig. 3). The total number of location points we were able to take differed among turtles in each year (Table 2). To assess vegetation change and/ or turtle microhabitat selection, each time we located a turtle we recorded the three most dominant plant species in an approximately 1-m² plot centered on the turtle. We graphed the frequency of occurrence of the most dominant plants (first and second combined) at turtle locations across years. We performed spatial analyses with ArcMap 10.3 (Esri, Redlands, California, USA) unless otherwise stated, and all statistical and graphical analyses with Statistica 12 (Statsoft, Tulsa, Oklahoma, USA).

Home range, the area used by an individual during a period of time (such as a year), can be estimated using a sample of locations of that individual throughout the year. We estimated home range for each turtle in each year using two methods: minimum convex polygon (MCP) and kernel density estimation (KDE). MCP home range is easily calculated and interpreted and is useful for comparing values to past Bog Turtle studies; it may also be the most accurate home range area estimator for species such as Bog Turtle that use a small area or return often to the same locations (Row and Blouin-Demers 2006). Kernel density estimation uses the location points to generate a three-dimensional probability of occurrence surface. KDEs can be useful for identifying more intensively-used (core) parts of the range. With smaller sample sizes,
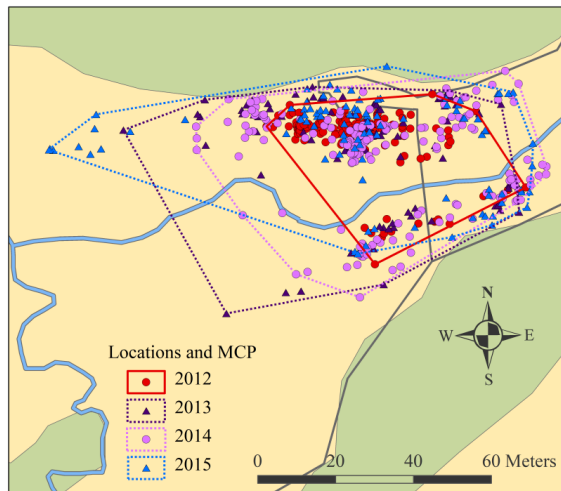
FIGURE 3. Core wetland locations (i.e., excluding 2012–2014 locations of Turtle 1 in the Far North Fen) for Turtles 1, 2, 4, and 5 (pooled), and minimum convex polygon (MCP) home range (pooled), for each year 2012–2015, at the study site for Bog Turtles (*Glyptemys muhlenbergii*) in New York, USA. Note expansion to west during the grazing period (2012–2014), and continued expansion in the north but contraction in the south after the grazing period (2015).

KDEs tend to overestimate home range (especially the commonly-used 95% KDE) relative to MCPs (Row and Blouin-Demers 2006; Byer et al. 2017); both methods are negatively affected by an inconsistent sampling regime (Börger et al. 2006), which was the case with our dataset. However, our sample size was fairly large: between 21 and 52 (mean = 34) points were used in each estimate. We calculated MCP home ranges in ArcMap using the Minimum Bounding Geometry tool, with Geometry Type set to Convex_hull. We used the Geospatial Modelling Environment, v. 0.7.4 (H.L. Beyer, Spatial Ecology, LLC) to calculate kernel density (kde command, using bandwidth estimator PLUGIN and a cell size of 1). We then used the isopleth command to generate contour lines and polygons corresponding to 50% and 95% of the total KDE area, and calculated areas of those polygons in ArcMap. We assessed whether home range area differed by year (for the same set of turtles) or by individual with nonparametric tests and $\alpha = 0.1$ due to small sample sizes (n = 4, 6). We used Friedman's test for repeated measures, in which ranks depend only on the order of, in this case, home range area for each individual turtle across years. For years with significant differences, we performed Wilcoxon pairwise comparisons to see which years differed ($\alpha = 0.1$). As suggested by Gotelli and Ellison (2004), we chose not to use Bonferroni adjustments for these analyses. We ran a second set of analyses including only locations within the 1.6-ha core wetland to better assess the effect of grazing on core wetland use (this excluded use of disjunct wetland areas to the north by one turtle).

To investigate changes in seasonal habitat use across years (2012–2015), we defined three seasons of interest based on our familiarity with Bog Turtle behavior in this region: nesting season (20 May to 7 July), summer season (8 July to 19 August), and late season (20 August to 1 May). Turtles emerge from hibernacula in April. In May, gravid females seek warmth for egg development, and basking sites are distributed throughout because vegetation is still low. About two weeks before laying, females seek out nest sites (generally, sedge tussocks in short-stature vegetation). Oviposition can occur in late May to early July, depending on the year. In summer, individuals are generally active, even during droughts or periods of intense heat, but typically restrict their activity to densely vegetated or wet areas where conditions are cooler (Gemmell 1994; Morrow et al. 2001; Smith and Cherry 2016). Around late August (depending on the individual and year), turtles tend to move to the vicinity of their overwintering area. They enter hibernacula in September or October but can emerge during warm periods throughout the winter (Ernst et al. 1994; pers. obs.). For each season, we identified the proportion of locations of each turtle in the grazing treatment area (West Paddock) versus the East Paddock. We assessed whether the proportions differed across years with Friedman's tests, and, for seasons with significant differences, we performed Wilcoxon pairwise comparisons to see which years differed.

Vegetation plot sampling and flora survey.—We sampled vegetation in seven permanent, randomly placed, 5 × 5-m plots within the West Paddock grazing treatment area (Fig. 1) each July, 2012–2015. Unfortunately, we determined plot locations before turtle use areas (Fig. 1) were known, so vegetation in plots was not representative of the most-used turtle habitat. Moreover, requirements of the cattle (including forage availability), logistics of installing fencing, and the character of the site took priority in designing the study, so even though Bog Turtle habitat was present in both paddocks, vegetation composition and structure were too dissimilar for meaningful comparisons of vegetation change between the grazed and ungrazed areas. Nevertheless, these data were useful to describe vegetation change within the core wetland grazing treatment area.

One botanist (LL) led all the plot data collection. With a minimum of stepping inside the plot, we identified each plant taxon and visually estimated its cover in the plot to the nearest percentage point (Kiviat et al. 2010). We combined certain species that were difficult to distinguish in July: all asters and goldenrods except *Solidago patula*; all *Carex* except *C. stricta* plus all *Juncus* except *J. effusus* and *J. tenuis*; all grasses except *Leersia*, *Bromus ciliatus*, and *Phalaris arundinacea*;

TABLE 3. Nest and egg success rates of Bog Turtles (*Glyptemys muhlenbergii*) at a study site in New York, USA, for the study years (2012–2016) when most nests were protected, and for two previous years without nest protection. Nest search effort was inconsistent among years. Abbreviations are NEH = number of eggs hatched, NES = nest success rate, ESR = egg success rate, NJEO = number of juveniles encountered opportunistically.

Year	# Nests	# Eggs	NEH	NES	ESR	NJEO
2009	3	8	2	33%	25%	--
2010	2	7	2	50%	29%	--
2012	12	47	18	58%	38%	1
2013	8	27	13	63%	48%	4
2014	3	?	3	33%	?	2
2015	7	23	17	43%	74%	5
2016	3	15	10	100%	67%	6

and all *Polygonum* s.l. spp. except *P. sagittatum*. We measured the stretched length, to the nearest centimeter, of the three longest stems in each plot regardless of species.

We constructed several composite variables from the individual taxon data to help examine the effects of grazing on different vegetation groups. We characterized the plant taxa in the vegetation plots as native or introduced (per U.S. Department of Agriculture, National Resources Conservation Service. 2015. The PLANTS Database. Available from http://plants.usda.gov [Accessed 1 March 2015]) and summed cover values for each category for each plot (omitting a few ambiguous taxa such as *Calystegia sepium* and *Phalaris arundinacea*, which include both native and nonnative forms). We created total tall (typically > 1 m when mature) and total short (< 1 m) variables, total shrub, total sedge-rush, and total grass variables, and a taxon richness variable. We also classified each taxon as a fen species, disturbance species, or non-fen woody species (per Kiviat et al. 2010 with additional species) and summed the cover values for each of these composite variables (see Supplemental Information Table A for more complete variable definitions).

We used the nonparametric Friedman's test for repeated measures, for comparing plots among 4 y for n = 7 West Paddock plots. Individual taxon cover estimates of < 1% were rounded to 1% for analyses. For variables with significant differences by year, we performed Wilcoxon pairwise comparisons to see which years differed. We also conducted a flora survey of the whole core wetland area in each year (2012–2015). We subjectively ranked each species as abundant, common, uncommon, or rare in the core wetland in each of the three years.

Soil sampling.—We collected equal-volume soil samples at 0–15 cm depth at four turtle locations in the North and South seepages and three random locations in the central Cattail Stand in August 2016 (Fig. 1). Because soils were predominantly root-bound, we sampled in spots that were relatively root-free within approximately 0.5 m of the turtle locations and random locations. Samples were analyzed by the Cornell Nutrient Analysis Laboratory (Ithaca, New York, USA) for 26 elements, pH, organic matter (loss-on-ignition), nitrate+nitrite, and ammonium. We compared each variable for turtle locations to Cattail Stand locations using the Mann-Whitney U exact probabilities test with α = 0.10 because of the small sample size.

RESULTS

Grazing.—Although grazing period and paddock size varied among and within years, the stocking rate was approximately 0.6–1.4 dairy heifers/ha for most of the growing season (one dairy heifer = one animal unit [AU]). In 2012 and 2013, the cattle concentrated much of their grazing in the core Bog Turtle habitat, even when they had access to the northern half (young upland forest and smaller wetlands) of the West Paddock; grazing in 2014 was widespread throughout the enclosure. In 2012, we were unable to initiate grazing until mid-June (halfway through nesting season), and we did not notice a large qualitative change in wetland vegetation structure in that year; at low stocking rates it is common to see a lag in effects on vegetation (pers. obs.). Thus, for our comparisons among years, 2012 was considered a pre-grazing effects year; this was useful because our contract did not allow a full season of pre-treatment data collection. Starting in spring 2013 and continuing through the 2014 season, however, grazed areas looked substantially altered, with muddy trails and shorter vegetation structure, especially in the central dense Cattail Stand. Dogwood (*Cornus sericea* and *C. amomum*) shrubs were about half the height of those in the ungrazed East Paddock. During the (ungrazed) rest period in 2015 and 2016, grasses and sedges appeared much denser in the West Paddock, and cattails in the central stand partly regained density. Concentrated early season grazing in the East Paddock in 2016 resulted in shorter vegetation and disturbed soils in some areas prior to the nesting season.

Researcher treading was an additional source of wetland disturbance throughout the study. Weekly or semi-weekly tracking plus additional surveys for vegetation and nests resulted in several open, muddy footpaths. In 2016, we avoided these paths, and vegetation regrew so that paths were barely noticeable by early in the season.

Nests.—Total nests found in each year (2012–2016) ranged from 3–12; number of eggs from 15–47, and

TABLE 4. Home range summary statistics (ha) for all Bog Turtles (10) and all years (4), and for each year, at a study site in New York. Note that this was not the same set of turtles in each year (see Table 2). Abbreviations are MCP = minimum convex polygon, KDE = kernel density estimate, SD = standard deviation.

	n	Mean	Min.	Max.	SD
All Turtles; All Years					
MCP	27	0.171	0.018	0.809	0.164
95% KDE	27	0.230	0.018	1.370	0.257
50% KDE	27	0.047	0.003	0.278	0.052
By Year 2012					
MCP	8	0.128	0.018	0.330	0.109
95% KDE	8	0.134	0.018	0.334	0.100
50% KDE	8	0.023	0.003	0.059	0.018
By Year 2013					
MCP	6	0.246	0.082	0.809	0.279
95% KDE	6	0.394	0.106	1.370	0.488
50% KDE	6	0.082	0.019	0.278	0.100
By Year 2014					
MCP	7	0.210	0.108	0.509	0.138
95% KDE	7	0.244	0.092	0.559	0.156
50% KDE	7	0.049	0.013	0.092	0.027
By Year 2015					
MCP	6	0.109	0.034	0.201	0.076
95% KDE	6	0.179	0.065	0.284	0.100
50% KDE	6	0.040	0.015	0.073	0.022

eggs hatched from 3–18 (Table 3). The egg (hatching) success rate was 38% to 74%; almost all nests had predator excluders installed. In 2012, one nest was depredated following removal of the predator excluder in anticipation of hatching; in 2014, two nests were depredated before predator excluders could be placed. Two nests that were protected by excluders had the eggs removed by a small predator, perhaps a White-footed Mouse (*Peromyscus leucopus*) or shrew (e.g., *Blarina brevicauda*), which dug into the nesting tussock from a subterranean entry point and carried away the eggs. Prior to this study, we knew the locations of two nests in 2008, three nests in 2009, and eight nests in 2010; in these years we did not protect the nests, and the egg success rate was lower (Table 3).

Nest locations shifted during our study (Fig. 2). In the years before grazing treatment had affected vegetation (2008–2012), we located the 25 nests in both paddocks with more in the East Paddock. We located all 20 nests found after 2012 (grazing and post-grazing rest years) in areas grazed during the current or previous growing season. The number of juveniles (0–5 y old) encountered opportunistically generally increased as the study went on (Table 3). Before grazing treatment effects (2012), we found one juvenile in the West Paddock. During and one year after West Paddock grazing (2013–2015) we found eight juveniles (total) in the West Paddock and three in the East. During East Paddock grazing (2016), we found one juvenile in the West Paddock and five in the East. In 2013, we set up a temporary fence around the highest concentration of nests to exclude cattle and protect nests from trampling. Temporary fencing was not set up in any other year, and the 11 nests in grazed areas were not trampled.

Turtle locations.—Bog Turtles were generally active throughout the season, and we found them most often in open areas (often basking) or in shaded locations beneath dense or shrubby vegetation with a complex microtopography (such as above and belowground roots, woody stems, hummocks, and moss). The individuals we tracked had fairly small home ranges in generally the same areas each year (Supplemental Information D). All turtles stayed entirely within the core wetland except Turtle 1: she also spent considerable time in the Far North Fen (approximately 100 m from the core wetland) during the first three years of the study (two weeks in May to June in 2012, mid-August 2013 through late April 2014, and a few days during mid-June 2014).

Mean Bog Turtle home range was 0.17 ha (range, 0.02–0.81 ha; MCP) and 0.23 ha (range, 0.02–1.37 ha; 95% KDE) for all turtles and all years (Table 4). Minimum and maximum annual MCP home range for each turtle across three or four years were as follows: Turtle 1, female (0.034 ha, 0.809 ha); Turtle 2, male (0.018 ha, 0.129 ha); Turtle 3, female (0.197 ha, 0.262 ha); Turtle 4, female (0.041 ha, 0.145 ha); Turtle 5, female (0.097 ha, 0.201 ha); Turtle 6, male (0.082 ha, 0.151 ha). The three home range estimator methods yielded very similar results, so the following are MCP results only. Home range differed by turtle for six turtles in the first three years of the study ($\chi^2 = 11.76$, df = 5, $P = 0.040$). The same analysis for only the four turtles that were tracked across four years yielded no difference in home range by individual turtle ($\chi^2 = 3.90$, df = 3, $P = 0.270$). Nor did any home range estimate differ by year, either for six turtles across three years ($\chi^2 = 3.00$, df = 2, $P = 0.220$) or for four turtles across four years ($\chi^2 = 5.70$, df = 3, $P = 0.130$). For the latter case, however, use of the core wetland only (excluding use of the Far North Fen by Turtle 1) was significantly different among four years ($\chi^2 = 8.10$, df = 3, $P = 0.040$), with differences between 2012 and each of the subsequent three years ($Z = 1.83$, n = 4, $P = 0.070$ for each pair; pooled MCP home ranges for these four turtles shown in Fig. 3). We noted modest expansion into previously unused areas of the core wetland after 2012, especially in the grazed West Paddock (Fig. 3). This pattern can also be seen in several of the ranges of individual turtles (Supplemental Information D).
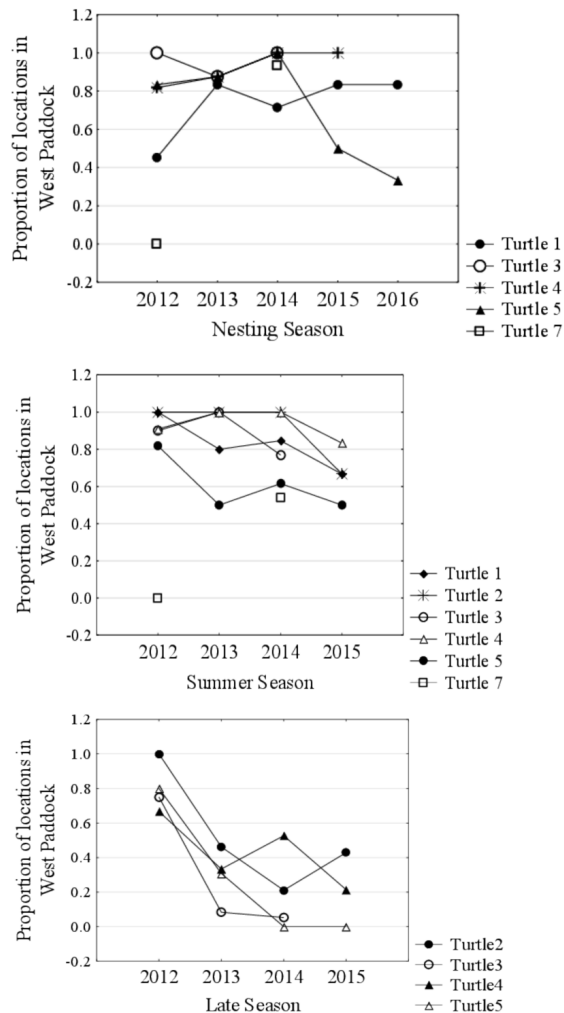
Figure 4. Proportion of locations of Bog Turtles (*Glyptemys muhlenbergii*) in the West Paddock (grazed 2012–2014) compared to the East Paddock across years, by season, at the study site in New York, USA. There was no grazing in 2015, and in 2016 the East Paddock was grazed in the spring. Turtles that used one paddock or the other exclusively, or with fewer than five locations/season, were not included.

To assess grazing effects on seasonal spatial distribution of turtles, we examined the proportion of locations in the West Paddock (grazed 2012–2014) vs. the East Paddock (grazed early in 2016) in different seasons (Fig. 4). For the nesting season, there were no significant differences among years in the proportion of locations in the West Paddock for either 2012–2014 ($\chi^2 = 3.33$, df = 2, n = 4 turtles, $P = 0.190$) or 2012–2015 ($\chi^2 = 3.75$, df = 3, n = 3 turtles, $P = 0.290$). No turtle displayed more than a slight, temporary decline in West Paddock use during the grazing period (2012–2014), and four turtles increased their use of this area during that period (Fig. 4). After grazing ceased, two turtles maintained a similar level of use, and one turtle decreased West Paddock use, spending more time in the East Paddock during and after it was grazed in 2016.

Summer season use of the West Paddock did not differ across the period 2012–2014 ($\chi^2 = 0.40$, df = 2, n = 5 turtles, $P = 0.820$) but did change during 2012–2015 ($\chi^2 = 8.03$, df = 3, n = 4 turtles, $P = 0.045$). The only significant rank differences among pairs of years were between 2012 and 2015 and 2014 and 2015 ($Z = 1.83$, n = 4 turtles, $P = 0.068$ for both; Fig. 4). Late season use of the West Paddock differed both for 2012–2014 ($\chi^2 = 6.50$, df = 2, n = 4 turtles, $P = 0.040$) and 2012–2015 ($\chi^2 = 6.93$, df = 3, n = 3 turtles, $P = 0.070$). We excluded Turtle 1 from this analysis because she overwintered in the Far North Fen in at least one year and had transmitter failure in another year. The only significant rank differences among pairs of years were between 2012 and 2013 and 2012 and 2014 ($Z = 1.83$, n = 4 turtles, $P = 0.068$ for both; Fig. 4). Six turtles overwintered in the East Paddock shrub thicket; two overwintered in the West Paddock; and two others appeared to shift their overwintering sites during the study (from West to East Paddock). Turtle 1 may have overwintered in three different locations. She used the West Paddock and Far North Fen exclusively in 2012–2014, then spent half her late season time (and overwintered) in the East Paddock in 2015.

Vegetation and flora.—Several key vegetation plot variables changed across years (2012–2015) in the grazing treatment area (West Paddock). Cover of the following groups showed a significant (positive) change among years (results from Friedman test, all n = 7, all df = 3): total short vegetation ($\chi^2 = 14.39$, df = 3, $P = 0.002$), total grass cover ($\chi^2 = 10.32$, df = 3, $P = 0.016$), *Carex-Juncus* cover ($\chi^2 = 12.69$, df = 3, $P = 0.005$), total native species cover ($\chi^2 = 11.23$, df = 3, $P = 0.011$), and total fen species cover ($\chi^2 = 11.39$, df = 3, $P = 0.010$). Results from pairwise comparisons showed that most of these groups had similar cover from 2012 to 2014 and then increased significantly in 2015 (Supplemental Information Fig. A1). Mean length of the three longest plants per plot did not change ($\chi^2 = 5.35$, df = 3, $P = 0.130$). Taxon richness also showed a positive change, particularly in 2015 ($\chi^2 = 7.90$, df = 3, $P = 0.048$). Total introduced species ($\chi^2 = 2.74$, df = 3, $P = 0.430$) and total disturbance species ($\chi^2 = 1.61$, df = 3, $P = 0.650$) did not change significantly. Median rank cover of *Lythrum salicaria* stayed about the same ($\chi^2 = 5.42$, df = 3, $P = 0.140$), but the variance decreased greatly in 2014 and 2015. *Typha latifolia* changed across years ($\chi^2 = 12.07$, df = 3, $P = 0.007$), with a large decrease in cover after 2012 (Supplemental Information Fig. A2).

Dominant plants recorded at each turtle location also shifted across years (Fig. 5). After the first year, turtles were located in sedge-dominated microsites less often. The proportion of Broad-leaved Cattail- and Red-osier Dogwood-dominated locations declined in the third year of grazing and the first (non-grazed) rest year. The
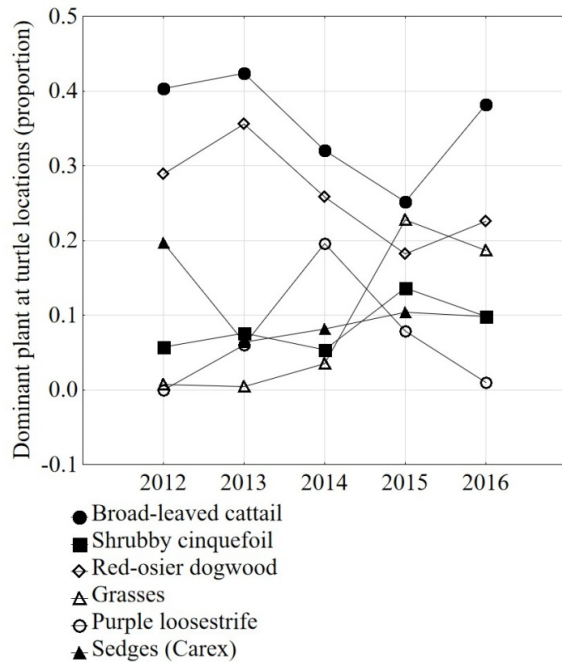
FIGURE 5. Six plant species representing the first and second most dominant plants recorded at each turtle location point at the study site for Bog Turtles (*Glyptemys muhlenbergii*) in New York, USA (both paddocks), shown in relative proportion to each other for each year. The West Paddock was grazed 2012–2014, and not grazed 2015–2016; the East Paddock was grazed in spring 2012 and spring 2016.

rest year also saw an increase in grass-dominated turtle locations.

Overall, the vascular flora was diverse (210 species) and the species list remained essentially the same through our study (Supplemental Information B). We found a large population of the New York-rare Hidden Spikemoss (*Selaginella eclipes*), a fen specialist, in the better quality sedge-Shrubby Cinquefoil areas, both grazed and ungrazed. Its abundance did not appear to be affected by grazing at our site.

Soils.—Soil analysis revealed sharp differences between turtle use areas and the central Cattail Stand, even with our small sample sizes (all non-overlapping values, $U = 0.0$, $P = 0.057$ for all). Turtle use areas had higher concentrations of many elements, including calcium, iron, magnesium, and sulfur; higher organic matter; and higher phosphorus and ammonium. Soils in the Cattail Stand had higher dry bulk density and higher nitrate+nitrite levels (Supplemental Information C).

DISCUSSION

Grazing effects on turtles.—The most dramatic and likely effect of grazing was seen in Bog Turtle nest site selection. In years prior to the grazing management project, no nests were found in the West Paddock grazing treatment area in the North or South Seepages (nest search effort in those years was lower in the Southwest Fen). Grazing commenced on 13 June 2012, about halfway into the nesting season, so it is unlikely to have changed vegetation enough to have influenced nest site selection in that year. Nests in 2012 were distributed evenly between the East and West paddocks. When shorter vegetation and small areas of disturbed soil characterized the West Paddock during the grazing years of 2013 and 2014, all nests were located there. All nests were again located in the West Paddock in 2015, the rest year, suggesting that grazing through the fall of the previous year kept the habitat open enough to promote nesting the following spring. In 2016, spring grazing occurred in the East Paddock, and two of the three nests found in that year were in the East Paddock (one was along the fenceline). The West Paddock, after 1.5 y with no grazing, may have been too overgrown. Researcher footpaths also seemed to play a role in nest site selection. In 2013–2015, two to three nests each year were sited along a well-defined footpath in the Southwest Fen. All paths in the West Paddock were avoided in 2016; they grew in, and no nests were found in that area in 2016. Fidelity to nest sites has been documented in Bog Turtles, both to the same nesting area and occasionally to the same hummock (Whitlock 2002; Macey 2015; Zappalorti et al. 2016). Although nests in this study were not linked to specific females, our results suggest that nest site selection may be quite plastic when habitat conditions change.

We note that the probability of nest detection was likely higher in grazed than ungrazed areas; also, because nest monitoring was not the primary focus of this project, nest survey time was not quantified or equal (between years or grazed/ungrazed areas). These factors could have increased the detection of nests in grazed areas. However, dense regrowth of vegetation in the West Paddock during the rest year likely equalized detection probabilities in the two paddocks; in that year all nests were nonetheless found in the West Paddock.

Small areas of disturbed soil such as hoofprints, cattle trails, and human footpaths appear to be important components of nest-site selection in Bog Turtles. In an analysis of microhabitat and vegetation surrounding Bog Turtle nests in New York, the most important factors for nest site selection appeared to be proximity (within 0.5 m) to open water or exposed, saturated soil, greater cover of sedges and other graminoids, and lower cover of woody plants, forbs, and ferns (Macey 2015). Massachusetts nest sites were generally on unshaded hummocks > 10 cm above water level and within 0.5 m of water (Whitlock 2002). Less canopy cover to the west and south and greater distance from woody vegetation were important factors in nest site selection for Bog Turtles in New Jersey and Pennsylvania (Zappalorti et

al. 2016). Temperature is likely an important factor in nest site selection for Bog Turtle as it is for other turtles (Hughes et al. 2009), and exposed soils would tend to warm more quickly in spring.

Predator excluders appeared to be important for protecting nests from depredation by common predators like skunks and raccoons, although they did not protect nests from an unidentified, smaller, burrowing predator. We found the highest numbers of juveniles in the final 2 y of the study, suggesting that nest protection and/or nesting habitat management increased recruitment. This could also have been an artifact of increased detection probability after grazing, although many juveniles were found despite dense grasses during the rest year (2015). We observed no damage to turtles or nests from the cattle. Few nests were found in 2014 and 2016 (three in each year). Although search effort varied across years, 2014 was a high-effort year; four nearby Bog Turtle sites produced even fewer nests in that year (pers. obs.), suggesting a weather-related effect. Total rainfall in June (nesting season) was about half the normal amount in both 2014 and 2016, which could have affected nesting (Supplemental Information E).

Nest success rates were 33–100% in 2012–2016 (33–50% in 2009–2010 without predator excluders) and egg success rates were 38–74% (25–29% in 2009–2010; Table 3). In a larger study of nest success (nine sites across four years, including our site), overall nest success was 72% with excluders and 38% without; egg success was 38% with excluders and 30% without (Macey 2015). Nest success across three years at two Massachusetts sites ranged from 6% to 100%, and egg success from 4% to 78% (Whitlock 2002). Nest predators were birds, raccoons, ants, and a mustelid, but predominantly small mammals. At two Maryland sites in two years, nest success was 0% and 0% at one site and 31% and 50% at another, and egg success was 11% and 46% at the latter site. Small mammal and insect predation were the main causes of nest failure (Byer et al. 2018).

Nesting season use of the grazed West Paddock (proportion of radio tracked locations for the same set of turtles) remained similar across the three years it was grazed. In the subsequent ungrazed year, two turtles maintained similar use and one greatly decreased use of the West Paddock. Use of West Paddock in the summer season also remained similar across the three grazing years, with a small but significant decline in the ungrazed year. Late-season habitat use, however, shifted significantly away from the grazing treatment area after 2012. Some hibernacula were located in the East Shrub Thicket in 2012, and two other turtles may have shifted their hibernacula to that area in 2013 and 2014. Roots of woody plants and mammal burrows are favored sites for hibernacula (Pittman and Dorcas 2009;

Shoemaker 2011; Feaga and Haas 2014), and cattle trampling could destroy such microsites. Moreover, turtles spent more late-season time in the East Paddock in 2013–2015 compared to 2012. This shift may be due to the preference of turtles for shady sites with complex microtopography when not basking or may simply reflect the increased dependence on that area for overwintering (as turtles often move to overwintering areas as early as August).

Bog Turtles at our site had MCP home range areas (0.02–0.81 ha) within the ranges reported in the literature. Home range area varied more by individual than by year (for six turtles across three years). Mean MCP home range (all turtles, all years) at our site was 0.17 ha. Smaller to similar mean home ranges have been found in Maryland (0.03, 0.08, 0.13, and 0.17 ha; Morrow et al. 2001; Byer et al. 2017), New York (0.07 ha; Shoemaker 2011), and North Carolina (0.08, 0.16 ha; Pittman and Dorcas 2009), and larger means in Massachusetts (0.46, 0.68, 0.73 ha; Whitlock 2002; Sirois et al. 2014), North Carolina (0.77, 0.81 ha; Smith and Cherry 2016), Virginia (0.91 ha; Feaga 2010), and Pennsylvania (1.28 ha; Ernst 1977).

Use of the core wetland expanded in area for the four turtles we followed across four years. Differences between 2012 (the first year of grazing) and all subsequent years were particularly marked. These modest expansions could be a result of improved habitat quality due to cattle grazing. After the first year of grazing, larger areas of the wetland had the short vegetation and small soil disturbances that Bog Turtles prefer, offering more choice of habitat. However, improvements in habitat quality may also have the opposite effect on home range size. Sirois et al. (2014) found that several Bog Turtles at another northern population site began to use restored areas of the wetland after invasive plant removal, and females had smaller home ranges after restoration. Similarly, Morrow et al. (2001) attributed a dramatic increase in home range area after 17 y to decreased habitat quality from the expansion of Multiflora Rose (*Rosa multiflora*) and other nonnative, invasive plants after cessation of grazing at a Maryland site. The turtles at their site with the largest home ranges were those that moved seasonally among different wetlands, as Turtle 1 did at our site. Turtle 1 spent considerable time at the northern wetlands during 2012–2014 but did not leave the core wetland in 2015 or early 2016. Large movements caused by insufficient resources would pose an energetic disadvantage, but we suggest that the turtles at our New York site, with their smaller home range increases, were taking advantage of newly suitable areas without incurring such costs.

We examined total monthly precipitation and monthly mean and mean maximum temperature data from the nearest weather station (Supplemental Information

E), three weather variables that could influence Bog Turtle habitat use, home range size, or nesting location. Morrow et al. (2001) found that Bog Turtles had smaller home ranges during a hot, dry summer as they restricted their activity to tunnels and wetter areas. Mean and maximum temperatures were uniform among years during the turtle active season (April-October). Higher than normal rainfall occurred in June and August 2013, July 2014, and June 2015. Lower than normal rainfall occurred in June and September 2014 and June 2016. We did not find any evident change in timing of movements or extent of habitat use by turtles in relation to months of higher or lower than normal rainfall.

Grazing effects on vegetation.—Vegetation structure and composition as measured in the vegetation plots changed over the years (2012–2015) in the grazing treatment area (West Paddock). Because we could not compare vegetation plots between grazed and ungrazed areas, significant changes in West Paddock cover should be interpreted as only potentially due to grazing effects. The following plant groups remained similar in cover from 2012–2014 and then increased in 2015, after grazing ceased: total short vegetation, grasses (which also increased in 2013), *Carex-Juncus*, total native species, and total fen species. Grazing and trampling may have kept these species in check without decreasing their cover, and the cessation of this disturbance may have resulted in their expansion. Taxon richness followed the same pattern, which could reflect colonizers taking advantage of the recently disturbed soil (we noticed a surge in seedling abundance in 2015). Importantly, total introduced species and total disturbance species remained about the same, indicating that grazing at this stocking rate (0.6–1.4 AU/ha/growing season) in our study area did not favor these undesirable groups. Cattails, which we specifically hoped to reduce, had significantly lower cover after 2012. High Purple Loosestrife cover at the beginning of the study in some plots decreased to around the median level at the end of the study (perhaps due to damage by biocontrol beetles, *Galerucella* spp., grazing, or expansion of grazing-tolerant species). Tussock Sedge, an important component of Bog Turtle habitat, was not well-represented in the plots but did not appear to decrease in grazed areas. In Midwestern U.S. wet meadows, Tussock Sedge tended to persist with light grazing, but under higher grazing pressure it was replaced by grasses (Costello 1936). A larger number of vegetation plots, a more complex design of the grazing paddocks, and paired control plots (with similar vegetation) in ungrazed paddocks would have improved our ability to track changes in vegetation, but our research design was constrained by the logistics of managing the cattle and the scope of this project. Our visual observations

of vegetation change agreed with the statistical changes in vegetation variables, and visual assessment did not reveal similar changes in ungrazed areas either within or outside the core habitat.

We would expect the dominant plant taxa at turtle locations to either follow trends in vegetation cover across the site or shift independently of overall cover as turtles select different parts of the wetland or particular plant species (for their cover or associated invertebrate food resources, for instance; Gemmell 1994). Cattail and grasses at turtle locations followed the West Paddock trends in abundance, suggesting that turtles were not choosing or avoiding these plants. A sharp decline in sedges at turtle locations after 2012 might be explained by the expansion by turtles from fen areas into other parts of the wetland. This observation could explain the increase in Purple Loosestrife-dominated locations as well; loosestrife locations could also have been selected if grazing resulted in shorter plants. Purple Loosestrife was twice as tall in ungrazed vs. grazed Bog Turtle wetlands in a New Jersey, USA, site (Tesauro and Ehrenfeld 2007). Overall, these six dominant plant taxa were represented more evenly at turtle locations by the first rest year after three years of grazing, compared to very low proportions of grass and Purple Loosestrife and high proportions of cattail and dogwood in the first grazing treatment year.

Soils.—Although Bog Turtles at our study site expanded into new areas of the wetland during the years of grazing, they continued to avoid the central Cattail Stand except for a very few, brief forays. This contradicted our initial expectations: if the turtles were only avoiding dense, tall vegetation, they should have increased their use of this area once the cattail was noticeably thinned by grazing and trampling. After grazing had reduced the thatch and standing biomass of plants throughout the wetland, we noticed that soils appeared very different in the Cattail Stand (siltier, firmer) compared with areas the turtles frequented (more organic, softer). Soils in the turtle use areas had a higher organic matter content, higher concentrations of minerals associated with groundwater and rich fens (calcium, magnesium, iron), and lower nitrate+nitrite levels than soils in the Cattail Stand.

Mean soil organic matter in the turtle use areas at our site (20.5%) was lower than that found in several Bog Turtle sites in Connecticut, USA, (36.8%, Warner 1988), within the range of that found at two Massachusetts, USA, sites (12.5 and 26.6%; Morgan 2008), and higher than means from Bog Turtle sites in the southeastern USA: 11.2% in South Carolina/Georgia (Stratman et al. 2016) and 9.9% in Virginia (Feaga et al. 2013). Rich fens in New York, USA, can vary widely in organic matter content (11–85%) and summer water table depth

(0 to < -50 cm; Kiviat et al. 2010) but Bog Turtles may require some minimum level of each for successful overwintering (Feaga and Haas 2014). New York rich fens with higher organic matter content and higher summer water tables also supported fewer disturbance-associated plant species (Kiviat et al. 2010). The high levels of calcium, magnesium, and iron in the turtle use areas of our site are indicative of a constant discharge of mineral-rich groundwater. Maintaining this flow is critical for maintenance of the low nutrient availability that promotes fen plant composition and structure (Boomer and Bedford 2008). Higher iron levels in the turtle use areas may inhibit some of the non-fen plants (Snowden and Wheeler 1993).

Soils in the Cattail Stand appear to be recent (of the last few decades) alluvium, the result of silty, nutrient-enriched sediment deposited along the small stream, presumably from surrounding agricultural and residential land uses. We noted highly eroded areas upstream. Sediment deposition in Midwestern fens is associated with lower organic matter content, higher bulk density, and lower plant species richness; increases in Hybrid Cattail (*Typha × glauca*) and Reed Canary Grass (*Phalaris arundinacea*); and decreases in Tussock Sedge (*Carex stricta*), tussock microtopography, and native plant abundance and diversity (Werner and Zedler 2002). The higher nitrate+nitrite concentration measured in the Cattail Stand may help explain the presence of dense cattail (see Woo and Zedler 2002). Bog Turtles may avoid such areas due to the absence of hummocks and other varied microtopography and the presence of low-organic matter soils (likely more difficult for burrowing). We conclude that grazing management alone will not improve Bog Turtle habitat in areas with such soils. However, if Tussock Sedge could be established after cattail was thinned by grazing, some habitat values could be restored. Planted Tussock Sedge plugs can form hummocks up to 10 cm high in two growing seasons (with no competition from other plants; Lawrence and Zedler 2011). *Carex stricta* tussocks and other hummocks formed by plants are an important component of Bog Turtle habitat and are used for nesting, basking (Klemens 2001), and as refuges from high temperature and low humidity (Morrow et al. 2001b). These tussocks made up the highest percentage cover within 12 cm of Bog Turtles at two Maryland wetlands during the mating, nesting, post-nesting, and hibernation seasons (Morrow et al. 2001b).

Although we did not measure soil characteristics in response to grazing, the effect of grazing on soils is an important consideration. In general, livestock have a detrimental effect on pasture soils through compaction (higher bulk density, decreased penetrability) and addition of plant-available N. Compaction has been shown to increase regardless of stocking rate in several studies (Russell and Bisinger 2015), or else to increase with stocking rate (even at the low rates proposed for Bog Turtle wetlands; Schmaltz et al. 2013). Compaction is worst in wet soils, although high soil organic matter provides some protection (Russell and Bisinger 2015). Surface soils can recover during non-grazing periods of as little as a few weeks to a few months or years, depending on soil type and severity of compaction (Drewry 2006). Although it may take years for soils to return to their pre-grazing state, significant recovery can occur in the 4–12-mo range, with better recovery over summer than over winter. A low to moderate stocking rate and rotational stocking management can help soils recover from trampling (Russell and Bisinger 2015) and is likely to increase plant diversity in the nutrient-limited wetlands on which Bog Turtles depend (Olff and Richie 1998; Török et al. 2014).

Grazing management recommendations.—Our stocking rate was approximately 0.6–1.4 AU/ha/growing season, lower than the stocking rate (1.85 AU/ha) recommended by the USFWS (2010) for Bog Turtle habitat restoration, and considerably lower than that recommended for a European fen (approximately 3 AU/ha; Seer and Schrautzer 2014). Because forage was poor in both the wetland and upland areas of our site, low stocking rates worked well. Grassier, more open sites can support the maximum stocking rate recommended by the USFWS. Forage quality, livestock type, vegetation management objectives, weather, and other factors all influence the stocking rate needed to achieve the desired effect, and the stocking density has to be actively managed throughout the season as conditions change. In some fens, less frequent or less intense (or even no) grazing may be sufficient to maintain short vegetation and small patches of bare soil.

Although many management decisions will be site-specific, we can offer some general recommendations. First, sites for grazing management should be prioritized by feasibility of livestock management, such as proximity to a farm willing to participate (in addition to Bog Turtle habitat and population considerations). Installing fences and transporting and caring for livestock are demanding tasks, and successful long-term grazing management will require a system where set-up and maintenance are not too difficult. Second, preliminary data collection should be used to plan for successful grazing management. One season of tracking a small set (four to eight) of adult turtles (e.g., every two weeks) and a nest survey would help identify seasonal use areas, nesting areas, and hibernaculum locations. Measuring soil bulk density, organic matter content, and selected elements (nitrate, Ca, Mg, Fe) in different locations throughout the wetland would help identify areas that may or may not be amenable to restoration by grazing alone.

Third, grazing should be planned to maximize nesting habitat improvements. Bog Turtles at our site shifted their nesting locations to areas with shorter vegetation and small, dispersed areas of disturbed soils (in areas with appropriate soils and hydrology). Nest protection should also be considered, as it can improve hatching rates and probably recruitment to the larger juvenile stages. Fourth, to benefit late season and overwintering habitat, some areas with known hibernacula, woody vegetation, complex microtopography, and saturated soils should be excluded from grazing year-round. Grazing exclusion areas are particularly important in sites where turtles use groundwater tunnels, which are vulnerable to collapse by cattle treading. Finally, stocking rate, paddock location, and grazing schedule should be planned to minimize negative effects on soils, surface waters, and fen vegetation. Such measures include using the minimum stocking rate effective for habitat management; allowing all grazed areas the maximum feasible recovery time between grazing events, ideally 6–12 mo including summer, to allow soils to recover; excluding high-quality fen areas; excluding livestock from the wetland during the wettest times, to the extent feasible (e.g., very early spring), because trampling causes more damage to wetter soils (either seasonally or spatially); and excluding livestock from streams or other surface waters, where feasible, to prevent nutrient additions and eutrophication both onsite and downstream.

Conclusions.—Many of our observations support the concept of grazing for Bog Turtle habitat management. Grazing (0.6–1.4 dairy heifers/ha/growing season, over 3 y) limited the height of vegetation (as measured by the percent cover of short species), maintained taxon richness during grazing and increased richness in the rest year following grazing, maintained native plants and fen-associated plants during grazing and increased cover of these groups in the following rest year, did not affect abundance of a rare plant, and did not increase the cover of nonnative or disturbance-associated species. Grazing (as well as researcher footpaths) resulted in small areas of disturbed soil, which turtles sought out during the nesting season. We did not measure nitrate or ammonium additions to the wetland or soil properties such as compaction, penetrability, or hydraulic conductivity that are likely negative consequences of any livestock introduction; however, these consequences did not have apparent negative effects on vegetation composition, structure, or diversity over the time period studied, indicating that the timing and intensity of grazing may have been adequate for wetland protection. Neither did we encounter any evidence of injured turtles or trampled nests during the study.

Bog Turtles appeared to benefit from the combination of grazing and nest protection at this site. Turtles chose nest sites almost exclusively in grazed areas (including 1 y post-grazing). Successful nesting occurred in every year, and the highest numbers of juveniles were encountered in the last 2 y of the study. Some turtles increased the amount of time they spent in grazed areas during the nesting season, and expanded their home ranges within those areas. Moreover, two unexpected results can expand our concept of grazing management. First, turtles appeared to favor cattle exclusion areas after late August, perhaps looking for more shaded conditions and microsites provided by woody and tall herbaceous species. Although most hibernacula were already located in these areas, turtles spent a greater proportion of time there after the initial year of our study. Additionally, two turtles may have shifted their hibernacula away from the grazed area. Livestock exclusion areas appear to be an important component of Bog Turtle habitat management. Second, grazing did not improve Bog Turtle habitat in an area where soils were recently deposited with fine sediment with low organic matter content. We conclude that grazing may be a helpful tool for Bog Turtle habitat management in areas with suitable soils and hydrology, provided that some Bog Turtle overwintering habitat is made inaccessible to livestock (year-round) and that the grazing regime is planned and adaptively managed with wetland, soil, and water protection goals in mind. Our study examined one site, but forage quality, desirable stocking rate and timing of grazing, and positive and negative effects of grazing are likely to vary considerably among Bog Turtle wetlands. For this reason, we want to stress the importance of further research in conjunction with future management activities.

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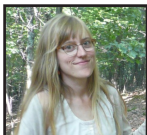
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