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Abstract

The magnitude and distribution of lead contamination remain unknown in wetland systems. Anthropogenic deposition of lead may be contributing to negative population-level effects in waterfowl and other organisms that depend on dynamic wetland habitats, particularly if they are unable to detect and differentiate levels of environmental contamination by lead. Detection of lead and behavioral response to elevated lead levels by waterfowl is poorly understood, but necessary to characterize the risk of lead-contaminated habitats. We measured the relationship between lead contamination of wetland soils and habitat use by mottled ducks (*Anas fulvigula*) on the Upper Texas Coast, USA. Mottled ducks have historically experienced disproportionate negative effects from lead exposure, and exhibit a unique nonmigratory life history that increases risk of exposure when inhabiting contaminated areas. We used spatial interpolation to estimate lead in wetland soils of the Texas Chenier Plain National Wildlife Refuge Complex. Soil lead levels varied across the refuge complex (0.01–1085.51 ppm), but greater lead concentrations frequently corresponded to areas with high densities of transmittered mottled ducks. We used soil lead concentration data and MaxENT species distribution models to quantify relationships among various habitat factors and locations of mottled ducks. Use of habitats with greater lead concentration increased during years of a major disturbance. Because mottled ducks use habitats with high concentrations of lead during periods of stress, have greater risk of exposure following major disturbance to the coastal marsh system, and no innate mechanism for avoiding the threat of lead exposure, we suggest the potential presence of an ecological trap of quality habitat that warrants further quantification at a population scale for mottled ducks.

Keywords Anas fulvigula · Contaminants · Ecological trap · Lead · Mottled duck · Species distribution model

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Introduction

Environmental contaminants in the contemporary era of industrialization and intense human effects on natural environments present some of the most complicated management concerns faced by modern conservationists. A large body of scientific work has focused on effects of accumulation and negative health effects of environmentally available heavy metals as these contaminants exist in diverse landscapes and ecosystems in varying quantities and forms (Davis et al. 1990; Bollhöfer and Rosman 2001; Sharma and Dubey 2005; Tomasevic et al. 2013; Haig et al. 2014). However, direct effects of the distribution of contaminants in the environment on wildlife space use are not well documented, but necessary to characterize potential risk to exposed populations.

Chronic exposure to environmental lead has a number of detrimental effects on bird species, including atrophy of organs, dysfunction in the nervous and digestive systems, reduced disease resistance, mass loss, lowered survival, and potentially increased susceptibility to harvest and predation (Bellrose 1955; Irwin and Karstad 1972; Rocke and Samuel 1991; Sanderson et al. 1992; Wobeser 1997; McCracken et al. 2000). Historically, waterfowl and other waterbird species have faced threats stemming from lead exposure from spent shot (Bellrose 1955; Pain 1996; Mateo et al. 1998). Lead contamination continues to be an important issue for wildlife conservation and habitat management despite significant efforts to reduce input from human activities and mitigate extant environmental pools (Haig et al. 2014).

Lead is particularly problematic as a long-term contaminant because it does not degrade at an appreciable rate under normal environmental conditions (Check and Marteel-Parrish 2013). That said, the degree of lead availability in the environment can be influenced by many factors, many of which are system specific. Coastal wetlands are uniquely dynamic, and experience fluctuations in temperature, salinity, inflow and outflow rates, inundation, and vegetation (Batzer and Baldwin 2012). All of these environmental factors can affect availability of lead, particularly those that affect chemical processes or mechanically disturb sediments that may contain particulate lead or solid lead (i.e., lead shot shells). In dynamic systems, wildlife may experience an increased exposure risk as a result of the occurrence of "hot spots" in selected habitats.

Evolved behaviors, specifically those involved in habitat selection for foraging and other resource acquisition, may not only be a potential pathway for lead exposure, but may also increase exposure risk in populations living in ecosystems contaminated by lead. Many waterfowl species, for instance, have experienced widespread negative individual effects with potential population-level implications, including reduced reproductive success and increased mortality, as a result of the ingestion of spent lead shot pellets (Coburn et al. 1951; Bellrose 1959; Irwin and Karstad 1972). Lead shot was deposited in wetlands and other waterfowl habitats as a result of its extensive historical use as hunting ammunition for waterfowl before a lead shot ban was finalized for webbed migratory gamebird hunting in the United States in 1991 (USFWS 2013a). However, exposure to lead from other sources via ingestion of prey and sediments contaminated by lead also contributes to negative population efforts in waterfowl populations (Bollhöfer and Rosman 2001; Fisher et al. 2006; Haig et al. 2014). Although long-term negative effects of sublethal exposure to lead on population demography may exist due to habitat selection by waterfowl, it is difficult to exclusively attribute these deleterious population responses to lead exposure or circulating environmental lead. Shorter-term responses, conversely, can be measured by observing avoidance behavior by organisms living in contaminated landscapes by comparing spatial variation in environmental contamination and associated animal space use. Measuring these responses is contingent on characterizing the type of exposure that occurs, identifying (or assuming) innate avoidance mechanisms exist, and whether the contaminant in question manifests negative effects in a measurable fashion. Assessing short-term habitat use responses to environmental lead by individuals is a key component for linking lead exposure to larger population demographic trends, which can be difficult to attribute to a specific cause.

The mottled duck (*Anas fulvigula*), a non-migratory relative of the mallard (*A. platyrhynchos*) and American black duck (*A. rubripes*), is native to the Western Gulf Coast of Texas and Louisiana, USA, and persists in highly human-altered coastal marsh ecosystems with a history of high levels of lead contamination (Fisher et al. 1986; Howes et al. 2010; McDowell et al. 2015; Riecke et al. 2015). Historical environmental surveys in Texas coastal marshes show large quantities of residual lead in the form of spent lead shot pellets (Fisher et al. 1986), with additional deposition from atmospheric sources (Bollhöfer and Rosman 2001). Despite a 1983 ban on lead shot on the Upper Texas Coast for waterfowl hunting, migratory waterbirds in this region, such as black-necked stilt (*Himantopus mexicanus*; Riecke et al. 2015), continue to experience negative health and population effects from lead exposure (Fisher et al. 1986; Moulton et al. 1988; McCracken et al. 2000; Haig et al. 2014). Mottled ducks on the Upper Texas Coast historically exhibited the greatest lead shot ingestion (proportion with lead in digestive tracts) and lead exposure (proportion with blood or bone lead levels greater than background) rates recorded for North American waterfowl (Anderson et al. 1987). Even after the 1991 federal lead shot ban for all waterfowl that reduced lead prevalence in waterfowl, lead ingestion rates for mottled ducks on the Upper Texas Coast, although reduced since prior to the lead ban, remain greater than other sites in Texas and the Central Flyway and are much elevated relative to migratory waterfowl species (Merendino et al. 2005; McDowell et al. 2015).

Elevated levels of blood lead, wing bone lead, and shot ingestion rates for mottled ducks could result from several factors. The chief hypothesis, however, is that their non-migratory life history subjects mottled ducks to a greater degree of risk from environmental exposure compared to migratory species, given that historical surveys of the Texas Coast soils have suggested variable, but relatively high levels of extant lead shot and particulate lead (Fisher et al. 1986; McDowell 2014). Furthermore, waterfowl, including mottled ducks, have not evolved an effective physiological process for depuration of lead (Haig et al. 2014). These features are exacerbated by agricultural conversion, human development, and other factors that are reducing extant mottled duck habitat on the Texas Coast (Kennish 2001, 2002; Moon 2014). Because mottled ducks ingest lead via voluntary behaviors such as grit consumption (Mateo et al. 2000; Figuerola et al. 2005), bottom-feeding for invertebrates resulting in incidental lead particle ingestion (Beyer et al. 1998; McDowell 2014), and consumption of contaminated food sources (Weis and Weis 2004; Weegman and Weegman 2007), we hypothesize that mottled ducks do not experience individual exposure events at a level sufficient to elicit an acute response, and thus do not exhibit avoidance behavior of highly contaminated areas. If this is the case, understanding spatiotemporal space use and spatial factors that influence lead presence in the environment become critical for understanding how to manage exposure to lead by mottled ducks.

To translate results of an individual area to a larger scale (e.g., management unit) or landscape, it is helpful to bolster information on the spatial location of contamination with an understanding of environmental factors that are typically linked to levels of contamination in a particular ecosystem. This can then be linked to information on space use to suggest whether environmental factors indicative of contamination are present in areas of selected habitat, indicating risk for wildlife. Modern analytical approaches, such as spatial interpolation and Species Distribution Models (SDMs), make it possible to determine the environmental factors linked to contamination and additionally draw connections to animal space use and movement (Cambardella et al. 1994; Zhang 2006; Janssen et al. 2008).

Our goals were to determine whether space use by mottled ducks overlaps with high levels of lead contamination in the environment relative to maximum values in various soil strata, indicating a lack of response to exposure risk, and, if so, which environmental factors are typically predictive of lead contamination. We assessed this by mapping environmental lead distribution through random soil samples and interpolation among samples on National Wildlife Refuges on the Upper Texas Coast. Then, we used species occurrence probability values based on radio-tagged female mottled ducks and environmental factors to (1) identify environmental factors that may indicate lead contamination and (2) assess whether mottled ducks appear to avoid lead present in their habitat on the Upper Texas Coast. We predicted that geospatial models of lead distribution might indicate elevated levels of contamination in area localized around historical hunting or shooting activities, and areas with slower soil permeability might create the conditions necessary for lead to persist longer in the environment. If mottled duck occurrence was predicted by relatively larger values of lead concentration in SDMs, we hypothesize mottled ducks do not perceive an exposure risk in their environment and may therefore be experiencing an ecological trap, the negative effects of an evolved behavior based on an undetected environmental threat related to their life history (Kokko and Sutherland 2001). If mottled ducks are exposed to an ecological trap, the persistence of environmental lead contamination will likely continue to negatively affect mottled duck populations in the future.

Methods

Study site

The Texas Chenier Plain Region is primarily coastal marsh habitat consisting chiefly of mud deposits and live oak (*Quercus virginiana*) ridges interspersed with wetlands (McBride et al. 2007). This area provides vital habitat for many species, but is particularly important for wintering and resident waterfowl (USFWS 2008). Data collection occurred on the Texas Chenier Plain National Wildlife Refuge Complex (TCPC), which included Anahuac, McFaddin, and Texas Point National Wildlife Refuges (NWR; Fig. 1). The TCPC encompasses 37,578 ha along the Gulf Coast of northeast Texas between Houston, Texas, USA, and the Texas-Louisiana, USA, border. The U.S. Fish and Wildlife Service imposed a nontoxic shot requirement during the 1978 hunting season and finalized by 1981 for these refuges in conjunction with the banning of lead ammunition on the Texas coast for waterfowl as part of the 1983 ban across the Upper Texas Coast (Moulton et al. 1988). Land acquisition to form the TCPC began in 1954, with much of the TCPC rigorously managed for migrating and wintering waterfowl via farming, grazing, hydrology manipulation, prescribed fire, and moist-soil wetland management.

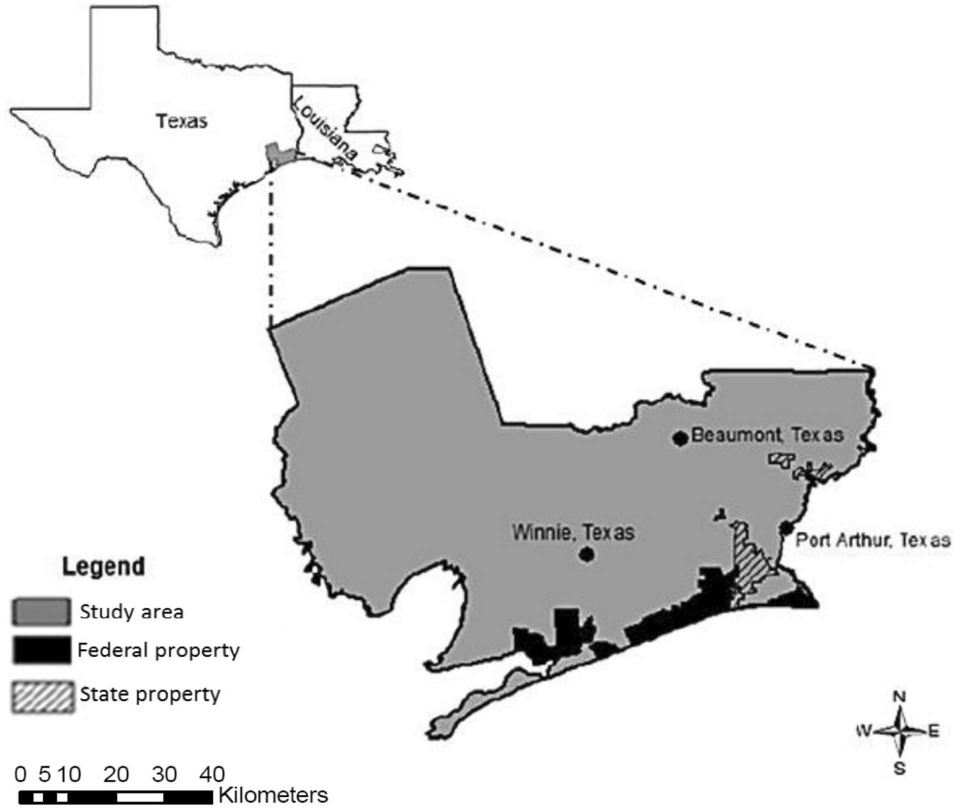

Fig. 1 Location of the study area on the Texas Chenier Plain National Wildlife Refuge Complex on the Upper Texas Gulf Coast. Lead concentrations of wetland soils and space use by mottled ducks were quantified in this vicinity during 2006–2012

The landscape of the TCPC is largely influenced by subtropical weather patterns, hydrology, and climate associated with the Gulf of Mexico. The TCPC receives, on average, 144 cm of rain per year, ranging from 52–218 cm (USFWS 2007). This region is also prone to hydrologic and other effects stemming from the landfall of tropical storms and hurricanes, which can cause significant disturbance effects on land forms and vegetation communities due to changes in salinity, sediment accumulation, and other factors (Stone et al. 1997; Turner et al. 2006; Howes et al. 2010). Dominant wetland types on both Anahuac and McFaddin NWRs include fresh, intermediate, brackish, and saline marshes (USFWS 2008; Haukos et al. 2010; McDowell 2014; Moon 2014). Vegetation communities in wetlands vary greatly based on water depth, salinity level, and tidal amplitude. Intermediate and brackish marshes are dominated by *Spartina patens*, with other species such as *Scirpus* spp., *Schoenoplectus* spp., *Typha* spp., *Distichlis* spp., *Juncus* spp., and *Paspalum* spp. intermixed (Stutzenbaker 1988; Rigby and Haukos 2015). Freshwater marshes are more diverse, and include *Alternanthera philoxeroides*, *Sesbania* spp., *Ludwigia* spp., *Nymphaea* spp., *Sagittaria* spp., *Eleocharis* spp., *Typha* spp., *Cyperus* spp., *Paspalum urvillei*, and *Panicum hemitonum* (Rigby and Haukos 2015). Topography and elevation vary little due to the geologic nature of the area (USFWS 2008).

The TCPC and Chenier Plain historically support the greatest mottled duck breeding densities on the Texas coast (Moon 2014). The TCPC supports high quality habitat needed for the entire life cycle of mottled ducks, including intermediate marsh, which is associated with important nesting habitat and supports >70% of pair ponds selected by mottled ducks, and in association with other emergent marsh types constitute important brooding habitat (Haukos et al. 2010; Moon 2014; Rigby and Haukos 2015). Selection for quality habitats occurs year-round due to a lack of migration by mottled ducks (Moon et al. 2015).

Soil sample collection and lead content sampling

To describe potential effects of lead in the environment on mottled ducks, we created a spatially explicit dataset of the distribution of lead in soil on the TCPC. To determine locations to collect soil samples, we placed a boundary shapefile for Anahuac NWR over April 2008 LandSat imagery in ArcGIS 10.0 (ESRI 2012), where a grid of 1-km^2 "cells" were systematically overlaid on the entire refuge, resulting in a total of 187 individual cells (McDowell 2014). Twenty percent of the 187 cells were randomly selected using a random number generator, which resulted in soil sampling in 38 cells at Anahuac NWR. This approach was repeated for McFaddin NWR, where a total of 304 cells were identified and 61 were randomly selected for

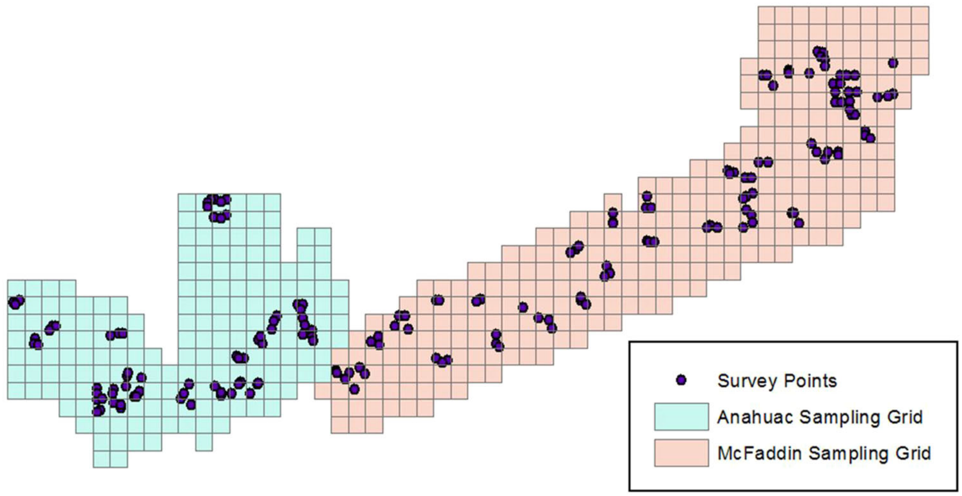

Fig. 2 Points designated for soil sampling based on a 40-ha sampling grid on Anahuac and McFaddin National Wildlife Refuges on the Upper Texas Gulf Coast. Three data points were sampled within each grid cell. For each point, soil strata **a** (0–5 cm), **b** (>5–10 cm), and **c** (>10–20 cm) were sampled via soil coring and subsequently tested for lead content during 2009–2011. These sampling points represent a stratified random sampling regime, and provided input for lead contamination analysis. Collected values were used as inputs for species distribution models (SDMs) and canonical correspondence analysis

soil sampling (Fig. 2). We overlaid each randomly selected cell with a 1-ha grid, with each grid square numbered one to 100; three of these grid squares were randomly selected for sampling within each 1-km^2 cell. When a selected 1-ha sample block occurred within an unusable site (i.e., caliche road, concrete pad, levee top, bayou, etc.), another was selected from one of the adjacent eight cells. If a usable site was not found within these eight cells, the sample point was abandoned.

A sample point was placed in the center of each selected 1-ha sample block. We collected one 30-cm soil core at the central point within each randomly selected 1-ha sample block using a stainless steel 50.8 × 51-cm hand corer (SKU: 2424-B20; WILDCO). Cores were collected and stored in disposable, transparent cellulose acetate butyrate plastic tubes. We labeled tubes with unique identifiers prior to sample collection, capped on both ends once removed, and stored in a freezer (~4 °C) until processed. A total of 183 soil cores were collected from 2010–2012 on NWRs (Anahuac: $n = 73$, McFaddin: $n = 110$).

Soil cores were dried in a 100 °C oven until dry and separated into three depth sections: of 0–5 cm (stratum A), >5–10 cm (stratum B), and >10–20 cm (stratum C). Once separated, each section was placed in individual soil sample bags, uniquely labeled, and treated as an individual sample throughout laboratory analyses. Each soil core section was digested using a method created by DigiPREP, similar to EPA 3050B (U.S. EPA 2012). Soil samples were digested with heat and dilution with hydrogen peroxide (H_2O_2), nitric acid (HNO_3), and hydrochloric acid (HCl) to achieve a final sample volume of 50 mL, then sealed. Lead concentrations (ppm) in environmental samples were estimated using AAnalyst 600 and 800 inductively coupled plasma atomic emission spectroscopy (ICP-AES) using a 1.0 ppm stock standard (see McDowell 2014 for details). The instrument was set to measure lead concentrations at a wavelength of 220.3 nm, and data recorded as ppm. Data are reported as geometric means (±geometric SD) so that no range dominated the weighting and percent changes had the same effect on the geometric mean (McDowell et al. 2015).

Interpolation of environmental lead levels

Once lead concentration was determined for each soil core ($n = 175$), we modeled predicted lead values across the TCPC landscape using ArcGIS 10.0 to interpolate values (ESRI 2012). We used the ArcGIS Geostatistical Wizard to assess relevant spatial statistics and determine the best method for interpolation. Due to the sampling design for soil surveys, certain interpolation methods were ruled out because they failed to capture spatial variation at smaller scales (e.g., clustering). We excluded ordinary kriging from model development as studies specifically designed for eventual kriging interpolation typically use a uniform sampling distribution, while this study used a random sampling distribution (Zimmerman et al. 1999). We determined that simple Inverse Distance Weighting (IDW) was a suitable technique for representing these data when fitting a surface, which had the additional advantage of methodological simplicity. IDW was suitable for our data because it has utility in representing spatial autocorrelation and working with non-uniform sampling distributions (Zimmerman et al. 1999). We created a lead content raster for each of the three soil strata across the TCPC using best fit search neighborhood settings determined in Geostatistical Wizard.

Mottled duck locations

We recorded locations and space use data from female mottled ducks from 2006–2012. Locations were collected via very-high-frequency (VHF) radio telemetry during 2006–2008 (Rigby and Haukos 2015) and via satellite telemetry during 2009–2012 (Moon et al. 2017). For VHF location data collection, trapping and handling were conducted based on guidelines contained in permits from the Texas Tech University Institutional Animal Care and Use Committee (06026-06) and USFWS. Adult female mottled ducks were captured 2006–2008 using swim-in traps and decoy traps, then tagged with 23-g Advanced Telemetry Systems A1800 backpack radio transmitters (ATS Inc., Isanti, MN; Rigby and Haukos 2012). Two randomly selected ducklings from each produced brood were additionally fitted with an A2430 transmitter attached using sutures or cyanoacrylate glue (Rigby and Haukos 2015). Duckling transmitters weighed between 1.4–1.7 g and were below the 5% of body mass threshold (Samuel and Fuller 1994). Female and brood locations were obtained via ground tracking and homing with visual confirmation every 3–4 days or, in the case of ducklings, by visual observation (Rigby and Haukos 2012, 2015).

For satellite location data collection, female mottled ducks were captured via airboat by nightlighting and fitted with Platform Transmitter Terminal (PTT; 22-g Model 100, Microwave Telemetry Inc., Columbia, MD) telemetry units during August 2009–2011 under Bird Banding Laboratory permit #09072 and USFWS Animal Care and Use guidelines. This unit constituted <3% of body mass, which did not have a negative effect on survival (Moon et al. 2017). Data collection began 72 h after radio-tagged birds were released and continued with locations recorded ≥2 times per week until mortality, transmitter malfunction/failure, or study termination. For spatial analyses, only class 3 locations were used, which had estimated location error of <250 m (Moon et al. 2017).

During 2006–2008, 40 mottled ducks were captured and fitted with VHF radio transmitters; during 2009–2011, 92 were fitted with satellite transmitters. Number of locations of female mottled ducks from 2006–2011 were, respectively: 267, 214, 332, 147, 397, and 276. After removing locations not contained within the bounds of Anahuac and McFaddin NWRs, 1398 total locations were used to construct SDMs and partitioned based on year, life-history period, and age class. Duckling locations collected on Anahuac NWR ($n = 337$) also contributed to SDMs. Locations were categorized as breeding ($n = 1043$) or nonbreeding ($n = 557$) locations for life-history models; breeding locations were collected from both VHF and satellite locations whereas nonbreeding locations were only from satellite data because VHF telemetry studies were only conducted during the breeding season (Mar–Sept). Analyses for VHF data were confined to Anahuac NWR while satellite location were available for the entire TCPC and used in larger-scale analyses. We categorized satellite locations into breeding (May–September) and nonbreeding (October–April) seasons (Moon et al. 2017), allowing documentation of changes in habitat use between life history periods.

Species distribution modeling

Ecologists developed SDMs to evaluate relative importance of environmental factors in predicting space occupancy by a species or cursorily describing its niche (Guisan and Zimmermann 2000). SDMs are optimized to provide information about the three ecological factors deemed to be of high importance in predicting species range: (1) limiting factors for a given species, (2) occurrence of disturbances in environmental systems of natural or human origin, and (3) available resources (Guisan et al. 2002). We created SDMs by overlaying mottled duck location and space use data with lead concentration raster surfaces as well as environmental variables selected a priori to be of importance to mottled duck occurrence: the National Wetland Inventory delineation of wetland types on the TCPC (USFWS 2013b); a soil permeability index derived from the SSURGO database and associated state-level tables (NRCS 2012); a digital elevation model (DEM) from the National Elevation Dataset (NED) (courtesy of the U.S. Geological Survey); and land cover developed by USFWS at the TCPC (Moon 2014; Table 1). We used MaxENT, an open source software that allows input of a set of species locations along with various

Table 1 Input variables (data type and source) used in MaxENT models constructed to predict occurrence of mottled ducks in coastal marsh of Anahuac and McFaddin National Wildlife Refuges on the Upper Texas Coast during 2006–2012

Variable	Type	Source	Abbreviations
Soil permeability	Categorical	SSURGO	Perm_A,_B,_C
Wetland classification	Categorical	National Wetland Inventory	NWI
Elevation	Continuous	National Elevation Dataset	DEM
Land cover	Categorical	Moon 2014	LC
Lead content	Continuous	McDowell 2014	Lead_A,_B,_C

Variables affected by soil strata (0–5 cm, stratum A; >5–10 cm, stratum B; and >10–20 cm, stratum C), namely soil permeability (PERM) and lead content (LEAD), are referred to first with the variable and then with soil stratum referenced (e.g., Lead_A, Perm_A)

Table 2 Codes and definitions for variables used in a correspondence analysis to establish relationships between mottled duck locations and habitat variables on the Upper Texas Gulf Coast from 2006–2012

Variable	Descriptor	Variable	Descriptor
Perm_1	Water	LC1	Pasture
Perm_2	Very Slow	LC2	Grass
Perm_3	Moderate	LC3	Agriculture
Perm_4	Slow	LC4	Emergent wetland
Perm_5	Rapid	LC5	Water
Perm_6	Very rapid	LC6	*Spartina patens*
NWI1	Freshwater pond	LC7	Beach
NWI2	Freshwater emergent	LC8	*Phragmites australis*
NWI3	Estuarine/ deepwater marine	LC9	Forest
NWI4	Fresh forested/shrub wetland	LC10	Agriculture
NWI5	Other	LC11	No classification
NWI6	Estuarine/marine	LC12	Urban
NWI7	Lacustrine wetland	LC13	No data
NWI8	Riverine wetland	DEM	Elevation
Lead	Lead		

environmental covariates, to estimate species distribution (Phillips et al. 2012).

To create models, we partitioned location data by year, age group, and life-history period, which were used as covariates. All environmental datasets used in the analysis were clipped to the exact extent of the boundary of Anahuac and McFaddin NWRs and converted from ESRI grid files to ASCII to provide suitable input for the MaxENT program. We evaluated models using several criteria. First, model fit was assessed using the area under a Receiving Operator Characteristic (ROC) curve (AUC), which described how far the model was from making completely random predictions; AUC values closer to 1 indicate the most non-random possible fit (Hanley and McNeil 1982). Second, we examined MaxENT response curves, which estimated parameters of each environmental variable used in the model that were most important for predicting mottled duck occurrence. Third, we examined variable percent contribution and permutation importance values, which indicated the extent to which each variable contributed to creating the model for occurrence either when considered with the whole model set or as a stand-alone factor, respectively. Last, we examined the results of a jackknife test of variable importance, whereby MaxENT established the importance of variables; this was accomplished by removing the variable from the overall model and quantifying the effect on predictive strength, and also by using the variable individually to predict occurrence (Elith et al. 2011). This procedure identifies variables that have the most information not present in other variables and those variables that contain the most information by themselves (Phillips et al. 2012).

Multivariate statistical analysis

We used canonical correspondence analysis (CCA) in the Vegan package in Program R to assess relationships among habitat variables and lead concentration in the environment, which contributes to the overall analysis by providing information on how habitat variables relate to one another as well as to mottled duck habitat usage (R Development Core Team 2014). Mottled duck locations were used to sample input rasters used for MaxENT models, the results of which were used to conduct CCA. This type of ordination was well suited for combining categorical and continuous variables, and appropriate for our analyses due to the dynamic nature of the habitat input variables (Table 2).

Results

Soil lead concentrations ranged from 0.01–1085.5 ppm with a geometric mean of 18.34 ppm for all samples. A total of 516 subsample strata (top (A): $n = 178$, middle (B): $n = 172$, bottom (C): $n = 166$) were examined for the TCPC. Lead concentrations in the top layer (stratum A) ranged from 0.01–93.96 ppm with geometric mean of 20.12 ppm. Lead concentrations in the middle layer (stratum B) ranged from 6.67–1085.51 ppm with a geometric mean of 20.22 ppm, and lead concentrations in the bottom layer (stratum C) ranged from 9.16–55.85 ppm with a geometric mean of 17.43 ppm (Table 3).

Interpolation analysis demonstrated variation in soil lead concentrations across the TCPC (Fig. 3). Interpolated lead concentrations in soil stratum A were most variable, ranging from ~4–86 ppm, while lead concentrations in soil strata B and C had lower ranges, with values spanning ~8–37 ppm and ~2–44 ppm, respectively. Several areas of high lead concentrations were predicted, many of which overlap with high density mottled duck location data (Fig. 3). This is particularly evident when examining Stratum A, where particulate lead would be most directly accessible to mottled ducks during foraging. This was not the case in the lower portions of the soil column (Strata B & C), where areas of relatively high lead concentrations did not correspond to increased space use mottled duck locations (Fig. 3).

Occurrence predictions from MaxENT models varied across years and categories (e.g., age class), with ranges and environmental variables shifting temporally in importance. Tested models used all environmental factors, with location data creating iterations for breeding/non-breeding season, age class, and year (Tables 4, 5). All models demonstrated

Table 3 Soil lead concentrations (ppm) among soil strata from management units of Anahuac and McFaddin National Wildlife Refuges (NWR) 2010–2012

NWR	Management unit	*n*	Low	High	Mean	Geometric mean	Median
Anahuac	Total	214	0.01	67.56	19.35	17.76	17.71
	East unit rice fields	27	9.81	30.01	14.68	14.33	14.15
	Gator trail	9	13.01	21.31	15.34	15.14	14.61
	Middleton	27	0.01	48.79	20.61	15.39	18.58
	Shoveler Pond	9	14.04	20.31	15.78	15.63	14.64
	Alice Jackson-White	16	12.14	22.86	16.15	15.89	16.30
	West Pond	18	12.53	29.45	17.00	16.51	15.32
	Deep marsh	36	15.34	29.76	19.56	19.31	18.95
	Pace	18	6.67	67.56	21.84	19.73	19.19
	Jackson Ditch	9	15.84	25.27	20.19	19.96	20.38
	Roberts-Mueller	27	13.76	55.85	21.04	20.04	20.74
	East marsh	18	16.32	60.31	27.60	24.99	21.56
McFaddin	Total	302	5.53	1085.51	24.68	20.37	19.49
	North unit	19	9.16	37.82	17.87	16.67	17.69
	Clam Lake	9	14.24	22.08	18.02	17.85	17.71
	Mud Bayou	32	12.69	29.11	18.51	18.24	18.22
	10 Mile	18	14.05	24.64	18.67	18.44	17.33
	White’s levee	60	5.53	52.31	20.37	19.09	18.91
	Goose Gully	18	11.68	29.59	19.84	19.20	19.33
	Star Lake	50	15.39	43.71	22.98	22.33	21.69
	Pay ponds	53	12.02	93.96	23.73	22.34	21.17
	5 Mile	43	14.16	1085.51	47.38	23.30	19.91
Total		516	0.01	1085.51	22.47	19.24	18.94
	Stratum A	178	0.01	93.96	22.28	20.12	20.63
	Stratum B	172	6.67	1085.51	26.87	20.22	19.53
	Stratum C	166	9.16	55.85	18.12	17.43	17.47

Soil strata were 0–5 cm (Stratum A), >5–10 cm (Stratum B), and >10–20 cm (Stratum C). Soil lead concentrations were consistently highest in Stratum A, with the largest peak value occurring in Stratum B. Geometric means of soil lead concentration decreased as lower portions of the soil column were assessed, indicating greatest overall availability of lead in surface soils where mottled ducks are most likely to feed

AUC values ≥ 0.75, and were considered to sufficiently non-randomly predict mottled duck occurrence (Hanley and McNeil 1982). Among the most important factors in predicting mottled duck occurrence were Perm_A (organic layer permeability) and Lead_C (clay pan lead content). These results suggest that in locations where organic layer soil permeability is very slow to moderate, mottled ducks experience greater quality habitat conditions. These conditions, however, also indicate slow penetration of lead particles through the soil column (Rooney 2002). Moderate lead presence on the clay pan, Lead_C, though not likely directly accessible to mottled ducks, may present an exposure risk through phytoextraction or sediment mixing (McDowell et al. 2015). Other highly ranked variables in several models included NWI and Landcover, with response curves suggesting importance of certain landcover types related to agriculture and grass to mottled duck occurrence. This is consistent with habitat use by mottled ducks (Moon 2014).

Results from MaxENT models indicate that areas with high concentrations of lead did not consistently have high probabilities of space use by mottled ducks. Exceptions were 2009 and 2011, where Lead_A ranked high in percent contribution. Lead_A was also the most important model variable when removed as part of jackknife testing during 2009 (Table 5). Of the models that included lead layers as important environmental predictor variables based on jackknife testing, soil lead values that best predicted mottled duck occurrence were typically <20 ppm (Table 5). Results from MaxENT models did not suggest significant differences between breeding and nonbreeding season habitat selection, and lead concentration did not have high percent contributions or permutation importance in these models.

Canonical correspondence analysis including environmental variables used in modeling suggests several patterns in location/habitat factor relationships. First, Lead_A, or lead in the top soil layer, appears in the center of the ordination space (Fig. 4). Central orientation in ordination

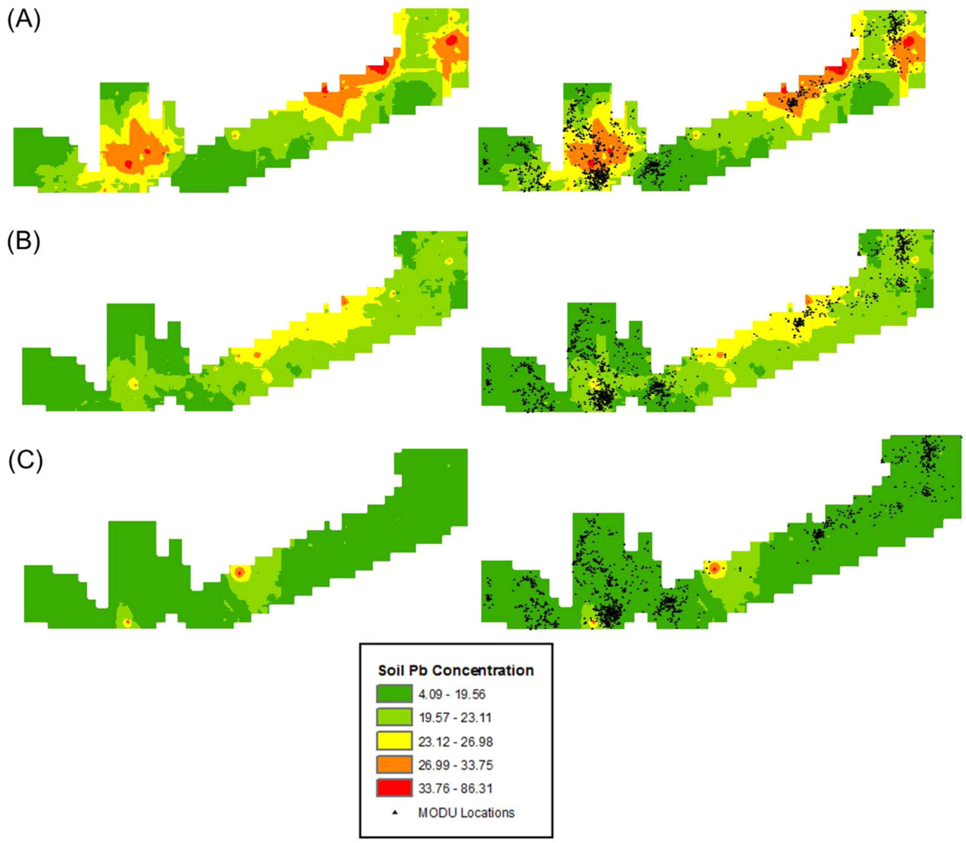

Fig. 3 Relative lead distributions on Anahuac and McFaddin National Wildlife Refuges on the Upper Texas Gulf Coast within soil strata **a** (0–5 cm), **b** (>5–10 cm), and **c** (>10–20), labeled, respectively, collected during 2009–2011. Content estimates were based on Inverse Distance Weighting interpolation of soil lead concentration levels using ArcGIS. These values represent the best currently available estimate of where "hot spots" of lead contamination occur on this landscape. Locations of female and broods from telemetry during 2006–2012 are overlaid on the right hand pane. Several areas are evident where space use by mottled ducks corresponds to areas of relatively high lead content in surface soils, the most easily accessible for direct ingestion through feeding or other means. Lead contamination levels in lower soil strata indicate that additional lead is present in the environment that may become bioavailable as a result of tidal forces, ecological disturbances (e.g., hurricanes), etc

space indicated that Lead_A was associated to a degree with all environmental variables, and suggests some concentration of lead in the upper soil stratum at all surveyed locations. Lead_B and Lead_C, however, although they were correlated, did not show significant linkages with most other habitat variables. One factor weakly associated with lead in lower portions of the soil column was Perm_4 (very slow soil permeability), which could suggest greater retention of lead in soils that drain more slowly. Last, NWI and landcover values related to agricultural practices on-refuge (LC3 and LC10 [agriculture]), wetland types unsuitable for mottled ducks (NWI4 [Freshwater forested/shrub wetlands] and NWI8 [riverine wetlands]), and moderate soil permeability (PERM_3) were clustered and oriented orthogonally from any vectors for lead content. Low association of agriculture with lead content at any level suggests that agricultural areas on-refuge as well as the aforementioned wetland types have little relation to environmental lead concentration, and was corroborated by relatively low lead levels on agricultural fields located in the northern portion of Anahuac NWR (Fig. 3, Table 5).

Discussion

Widespread deposition of lead from various sources before legislation and policies were enacted to reduce lead exposure of wildlife and their wetland habitats continues to manifest as lead contamination among trophic levels on the TCPC (McDowell et al. 2015). This contamination includes areas with environmental lead levels that could cause acute exposure events under certain scenarios for mottled ducks and other wildlife. However, lead is not uniformly distributed on the TCPC landscape, likely because of natural factors such as large-scale disturbances (e.g., hurricanes, intense drought), sediment transport, and tidal forces as well as human factors including industrial development and concentrated historical hunting activities (Fisher et al. 1986;

Table 4 Results from MaxENT species distribution models predicting intensity of use by mottled ducks based on all location data, specific years, breeding/non-breeding season, and duckling locations on the Upper Texas Gulf Coast during 2006–2012

		NWI		Landcover		DEM		Perm_A		Perm_B	
Model	AUC	%	P.I.	%	P.I.	%	P.I.	%	P.I.	%	P.I.
All	0.75	8.0	2.8	19.5	6.1	8.0	5.1	29.4	43.8	3.0	14.0
2006	0.94	31.6	2.5	13.2	6.3	2.3	1.8	17.1	41.9	0.4	1.2
2007	0.94	11.6	1.1	20.4	1.7	5.1	3.1	30	50.4	0.1	0.6
2008	0.90	4.7	1.5	15.2	5.4	6.1	5.2	44.1	57.2	0.1	0.3
2009	0.78	6.6	1.6	15.2	8.3	7.5	2.9	16.2	32.2	1.6	10.1
2010	0.75	9.4	5.0	10.9	4.7	5.5	4.1	12.2	30.4	9.9	21.5
2011	0.76	15.5	9.3	4.2	2.8	4.5	5.6	2.6	14.8	1.2	7.2
Breed	0.74	11.2	5.4	5.9	2.8	12.7	6.8	6.7	26.4	4.0	16.0
NB	0.75	10.6	6.3	10.9	6.1	4.2	4.0	11.0	28.0	7.9	20.5
Duckling	0.93	0.9	0.3	20.5	4.8	6.9	5.4	33.7	56.3	0.2	0.2

		Perm_C		Lead_A		Lead_B		Lead_C	
Model	AUC	%	P.I.	%	P.I.	%	P.I.	%	P.I.
All	0.75	6.7	3.0	6.5	1.7	9.0	12.8	10.0	10.8
2006	0.94	0.2	0.7	23.5	25.3	8.5	16.0	3.3	4.3
2007	0.94	6.9	9.8	4.5	9.9	18.7	18.2	2.7	5.2
2008	0.90	9.7	6.8	4.5	5.0	10.0	12.9	5.7	5.8
2009	0.78	1.1	2.0	20.3	19.9	5.9	5.2	25.6	17.8
2010	0.75	6.9	1.9	4.0	2.0	15.2	14.5	26.0	16.0
2011	0.76	23.3	4.7	17.2	10.0	13.9	21.7	17.5	23.9
Breed	0.74	13.8	4.8	4.9	3.5	18.3	17.9	22.4	16.4
NB	0.75	11.4	2.1	4.2	3.7	16.6	15.8	23.2	13.6
Duckling	0.93	6.6	6.3	5.8	4.3	9.6	7.5	15.8	14.8

The area under the curve (AUC) values provide estimates of the relative distance of how far models are from random predictions (non-random closer to 1). Percent contributions (%) indicate the amount each variable contributes to building each prediction model and permutation importance (P.I.) gives the result of a permutation test of variable importance using model training presence data (both values are percentages averaged over all model runs). Highest values for percent contribution are highlighted in gray. The high rank of Perm_A in several models suggests that in locations where organic layer soil permeability is very slow to moderate mottled ducks experience greater quality habitat conditions. These conditions, however, also indicate slow penetration of lead particles through the soil column, which can create additional lead availability for mottled ducks as a result of phytoextraction or sediment mixing

NB non-breeding, *AUC* area under receiver operating characteristic curve, *%* variable percent contribution to model, *P.I.* permutation importance, *NWI* National Wetland Inventory, *DEM* digital elevation model, *Perm* soil permeability, *Lead* soil lead content

Turner et al. 2006; Tomasevic et al. 2013). Our work identified several patterns stemming from these factors, and identified certain high risk areas (i.e., areas with a relatively high degree of environmental lead contamination) that could be primary targets for remediation and management given observed high levels of environmental lead.

Despite a lack of uniform spatial distribution, analysis of lead levels in marsh soils of TCPC reveals patterns relevant to mottled duck conservation and ecology. First, greater variability of lead levels and greater maximum values were observed in the top stratum of the soil column relative to lower strata, but we found few compelling relationships with specific environmental factors that could be driving lead concentrations in the top stratum of the soil layer. This is likely due to the increased susceptibility to multiple forces (e.g., wind, wave action, etc.) that transport particulate lead across larger geographic areas in the top portion of the soil column (Allen et al. 1980). Second, the range of lead levels in lower strata of the soil column was narrower relative to the top stratum and analyses revealed a relationship between lead content and permeability values of the dominant soil type. Specifically, lead concentrations were greater across all strata in soils that drain more slowly.

Although results from our ordination analysis did not suggest a strong relationship between soil type and lead concentration, this was consistent with previous work that discovered that lead particles, as well as whole lead shot pellets, may suspend in the soil column on top of a clay pan

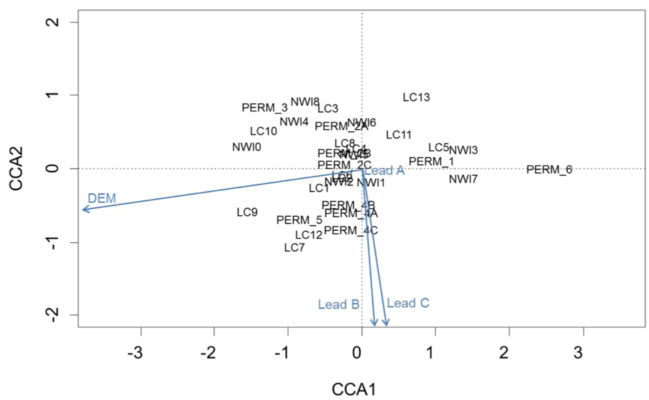

Fig. 4 Results from canonical correspondence analysis (CCA) using mottled duck locations and habitat variables selected a priori as important for determining mottled duck occurrence on the Upper Texas Gulf Coast for 2006–2012. Continuous variables are indicated as vectors, while values for categorical variables are indicated in black text. See Table 2 for definitions of variables from their acronyms. Vectors for variables "DEM," "Lead_B," and "Lead_C" extend beyond ordination space, and are truncated for ease of display. Lead_A, or lead in the top soil layer, appears in the center of the ordination space, indicating an association with all environmental variables and moderate surficial contamination at all survey locations. Lead_B and Lead_C did not show significant linkages with most environmental variables, with the exception of Perm_4 (very slow soil permeability)

Table 5 Results of jackknife tests of variable importance for MaxENT models based on all location data, specific years, breeding/non-breeding season, and duckling locations for mottled ducks on the Upper Texas Gulf Coast from 2006–2011

Model	High % contribution	With only variable	Response curve high	Without variable	Response curve high
All	Perm_A	Perm_A	Very slow	Perm_A	Very slow
2006	NWI	NWI	Estuarine wetland	Land_cov	Agriculture/ water
2007	Perm_A	Perm_A	Moderate	Lead_B	21.5 ppm
2008	Perm_A	Perm_A	Moderate	Perm_A	Moderate
2009	Lead_C	Lead_C	16 ppm	Lead_A	17 ppm
2010	Lead_C	Lead_C	14 ppm	Perm_A	Very slow
2011	Perm_C	Lead_B	25 ppm	Perm_C	Slow
Breeding	Lead_C	Lead_C	15 ppm	Lead_C	15 ppm
Non-breeding	Lead_C	Lead_C	14 ppm	Perm_A	Very slow
Duckling	Perm_A	Perm_A	Moderate	Land_cov	Agriculture

Jackknife tests examine model performance by measuring the predictive power of variables both by testing them alone and then by testing the model without them. For each variable deemed important from these two procedures, the high value from the respective response curve is indicated. The variable with the highest percent contribution value from each model is indicated for comparison. These diagnostic results, in conjunction with those provided by percent contribution and permutation importance, suggest the variables with the greatest impact on overall model performance. Notably, Lead_A had the greatest impact on model results when removed during 2009. Of the models that included lead layers as important environmental predictor variables based on jackknife testing, soil lead values that best predicted mottled duck occurrence were typically <20 ppm, indicating that during the years where lead was a predictor exposure levels were elevated but not acutely toxic

Perm soil permeability, *Lead* soil lead content, *NWI* National Wetland Inventory, *Land_cov* landcover classification, within soil stratum A (0–5 cm), stratum B (>5–10 cm), and stratum C (>10–20 cm)

due to the compaction of these small soil particle types, which are present on the TCPC (Nelson and Fink 1978; Longcore et al. 1982). The density of intact lead shot pellets remaining in this ecosystem was estimated at >60,000 based on extrapolation from two intact lead shot pellets (McDowell 2014). However, because the sampling design was intended to characterize soil lead concentrations across the TCPC landscape where the use of lead shot has been banned since 1985, it was not unexpected to find few intact shot. By focusing on areas with relatively high soil lead concentrations, future sampling can be designed to more accurately measure density of intact lead shot available for ingestion by mottled ducks. More importantly, lead content analysis, which accounts for all forms of lead in the environment, suggests lead exists in particulate form across the TCPC, including at high levels in some areas. The EPA standard for background lead concentration is 50 ppm. Of the 183 samples collected on the Complex, eight were above the 50-ppm threshold. These 8 samples were spread across 6 separate units on the Complex (Fig. 3). Five Mile Cut on McFaddin NWR had a lead concentration of 1085.57 ppm, ≥20 times the background threshold. This area has historically been hunted for waterfowl and as such would have been an area of high lead shot deposition. Likewise, the remaining five units were historically intensively hunted areas; thus, increased lead shot deposition could be expected, resulting in continued elevated soil lead concentrations.

Based on mottled duck locations relative to interpolated lead levels across the TCPC, space use by mottled ducks frequently coincided with areas of high environmental lead contamination, particularly in the organic layer. Levels of lead content in soils were elevated in the organic layer in certain locations and, although lead throughout the soil column is potentially accessible to wildlife through various mechanisms, particulate lead or lead shot in the organic layer is of greatest direct concern for mottled duck (and other waterfowl) conservation. Mottled ducks may be exposed to lead from this portion of the soil column when they feed on invertebrates or ingest sediment or lead shot pellets for gizzard grit (Mateo et al. 1998, 2000). Environmental factors can influence the extent to which lead is mobilized in the environment; increased salinity and reduced water presence can result in increased degradation and potential "pools" of lead as available water retreats (Rooney 2002), soil characteristics (e.g., decreased pH) can cause increased lead breakdown (Jørgensen and Willems 1987), and tidal mixing with finer sediment soils, often observed on the TCPC, can result in increased lead availability (Uhlig 1971). Changes in any of these factors causing more lead to become available could increase direct ingestion rates on a temporal and spatial scale that makes management challenging.

Given the variable, but common nature of the lead contamination often above background levels on the TCPC, mottled ducks continue to be exposed to lead in this ecosystem at levels much greater than for other congeneric migratory waterfowl. Organisms with lead concentrations ≥20 ppm are considered to be exposed above background levels (Pain 1996). Merchant et al. (1991) used wing bones to measure long-term exposure to lead for mottled ducks collected during 1987–1988 and reported average lead concentrations of 52.1, 36.0, and 33.6 ppm in Texas, Louisiana, and Florida, USA, respectively. Merchant et al.'s (1991) overall average of 44.2 ppm did not differ from 43.1 ppm average concentration reported by Stendell et al. (1979) for 1972–1973. Average lead concentrations in wing bones of mottled ducks declined by the 1998–1999 (mean concentration 16.6 ppm in Texas and Louisiana; Merendino et al. 2005) and 2006–2007 (mean concentrations of 18.8 and 11.6 ppm for Anahuac and McFaddin National Wildlife Refuges on the Upper Texas Coast, respectively; M. Merchant, McNeese State University, unpublished data) hunting seasons. Wing bone lead concentrations ≥20 ppm in Texas and Louisiana was found in 28 and 22% of after-hatch-year and hatch-year mottled ducks, respectively; 27.9 and 16.8% of individuals on Anahuac and McFaddin National Wildlife Refuges, respectively, exhibited concentrations >20 ppm indicating continued exposure to lead despite multi-decade ban on use of lead shot (Merendino et al. 2005; M. Merchant, McNeese State University, unpublished data). Furthermore, from 1998–2002, lead ingestion rates by mottled ducks averaged 14.1%, which exceeded ingestion rates for waterfowl prior to the lead shot ban (Merendino et al. 2005).

Indeed, mottled duck frequency of occurrence in areas with known lead contamination, and elevated wing-bone and blood lead concentrations indicate that a relatively large proportion of the mottled duck population on the TCPC has been historically and currently remain exposed to lead (Merchant et al. 1991; Merendino et al. 2005; McDowell et al. 2015). Recent work testing blood lead levels in mottled ducks showed levels have decreased from pre-shot ban values, but lead levels remain elevated above background (McDowell et al. 2015). Of additional concern, contemporary lead levels in mottled ducks continue to exceed that reported in migratory waterfowl prior to the ban of the use of lead shot for waterfowl hunting. Given the apparent few available lead shot in the environment, the route of exposure of mottled ducks to lead is uncertain and may not primarily be the result of direct ingestion of lead shot (McDowell et al. 2015). Other potential pathways include lead that is a byproduct of fossil fuel production and combustion (Tomasevic et al. 2013), deposition of lead shot in agricultural fields due to hunting of mourning doves (*Zenaida macroura*, Schulz et al. 2002), and atmospheric deposition in coastal wetlands (Bollhöfer and Rosman 2001). Lead from these sources can enter the coastal marsh food web when absorbed or extracted by sediment, plants, or invertebrates.

Aside from direct ingestion of lead, plants and invertebrate food sources must be considered as an exposure pathway. McDowell et al. (2015) observed increased blood lead levels in mottled ducks during winter, suggesting a potential linkage between winter food sources and lead exposure. Through the process of phytoextraction, plants can assimilate lead from the surrounding soil into their tissues (Weis and Weis 2004). This likely also affects invertebrates in contaminated environments due to their consumption of contaminated plant life (Spehar et al. 1978). Mottled ducks exhibit a shift in diet from almost exclusively invertebrates during the breeding season to a predominately vegetation-based diet during winter after reproduction and molting are complete, which corresponded to the increase in blood lead levels (McDowell et al. 2015). Because mottled ducks exhibit elevated blood lead in the nonbreeding season, it can be inferred that vegetative food sources may provide increased risk for lead exposure (Eagles-Smith et al. 2009).

Perhaps partially because of the variety of potential exposure pathways for lead and apparent lack of acute exposure events, which would be represented by avoidance behavior of highly contaminated areas, our results suggest that mottled ducks on the TCPC currently do not typically avoid lead contamination in their environment as indicated by ongoing space use in areas with relatively high levels of soil lead. If mottled ducks were actively responding to lead contamination in their environment, we would expect a shift in or avoidance of contaminated habitat or in the habitat factors driving mottled duck occurrence. In contrast, the habitat/range transition between breeding and nonbreeding seasons (Stutzenbaker 1988), the shift most evident in movement data in other migratory species, did not manifest in our data. Being non-migratory, mottled ducks are constantly exposed to lead in contaminated environments should they select them, meaning repeated small exposure events over time could result in long-term chronic exposure and measureable deleterious effects.

Additionally, although mottled duck movements do not indicate a habitat shift based on any discrete exposure event or differential seasonal exposure risk that manifests concretely as elevated blood lead, our models do suggest that risk of lead exposure for mottled ducks on the Upper Texas Coast may increase during periods of intensive ecological disturbance. On the Upper Texas coast, the most commonly experienced large scale ecological disturbances affecting tidal wetlands are hurricanes and drought. Lead in the top portion of the soil column was ranked relatively high in models describing space use during years 2006, 2009, and 2011, all of which were years directly following major ecological disturbances that affected the Upper Texas Coast including two hurricanes (Rita and Ike) and prolonged periods of severe drought. There are many plausible explanations as to why habitat use or level of lead exposure might change after intense disturbances. One is that populations of mottled ducks may be forced into using habitat with greater levels of lead if habitats that are normally selected are dramatically altered during the course of a disturbance event, and thus become unavailable for use. Drought may reduce wetland availability and quality of other habitats used by mottled ducks, causing salinity to increase by concentrating solutes, which could increase the rate of lead particle mobilization (Moon 2014; Moon et al. 2017). Recent analyses also suggest the lowest survival ever recorded for mottled ducks was as a result of drought conditions (Moon et al. 2017). In addition to increasing mottled ducks exposure to lead, hurricanes cause massive amounts of sediment movement (Turner et al. 2006), catastrophic changes and destruction of plant communities (Bhattacharjee et al. 2007), and long-term changes in soil chemistry and wetland structure (Blood et al. 1991; Stone et al. 1997; Howes et al. 2010). This could cause changes in mottled duck food resources in certain areas and force mottled ducks into lower quality habitats that may not be selected for under "normal" conditions. Given that hurricanes and drought are relatively common occurrences along the Texas Coast (Stockton and Meko 1975; Keim et al. 2007), there may even be interaction dynamics between disturbances and availability of lead in coastal marshes. For example, increased breakdown of lead during drought events followed by dramatic mixing of sediments during hurricanes could mobilize lead that had descended in the soil column because of cracks formed by desiccation.

Severe ecological disturbances create ecological stressors for mottled ducks due to their lack of response to lead exposure as an increasing threat following intensive disturbance. If cues for habitat selection by mottled ducks within contaminated landscapes do not include perception of lead concentrations, the opportunity for the occurrence of an ecological trap is created, wherein organisms fail to adapt or alter behaviors due to an unperceived threat and experience negative population effects as a result (Kokko and Sutherland 2001; Schlaepfer et al. 2002). Although we have not quantified population effects necessary to determine the presence of an ecological trap for this species caused by environmental lead contamination, which might manifest as reduced fitness, negative population demographic trajectories, or in other ways, mottled ducks on the Upper Texas Coast fit many of the criteria (Bellrose 1959; McCracken et al. 2000; Kokko and Sutherland 2001; Golden et al. 2016). First, they appear to have failed to detect an ecosystem threat. This, combined with their non-migratory life history, put them at higher risk for exposure given that they live in a relatively highly contaminated habitat. Second, mottled ducks live in a dynamic landscape where the level of risk for lead exposure at a given geographic location may change based on numerous environmental conditions that unpredictably fluctuates. Finally, their evolved feeding behaviors directly expose them to lead in the soil column in the layer where concentrations are greatest. These negative effects are corroborated by ongoing observations of continued ingestion of lead shot and increased blood lead content across sex and age classes (McDowell et al. 2015). These conditions suggest potential ongoing negative population effects that could reduce local population viability resulting from the negative health effects of long-term lead exposure. The risk mottled ducks face from this threat is further intensified by the lack of a life history mechanism for dispersal, absence of long-distance movements of any kind, and record low survival rates documented during years with ecological disturbances (Moon et al. 2017). Indeed, estimated densities of mottled ducks on the Texas Gulf Coast have been declining since the late 1990s and are currently at their lowest recorded density. As population numbers continue to decline, the likelihood increases that smaller scale impacts from lead exposure could manifest as a negative population-level effect. Even if mottled ducks detected lead at a localized site with particularly severe contamination, the obligate use of geographically proximal habitats increases the likelihood of simply dispersing to another contaminated location if a region is experiencing widespread contamination, as is the Upper Texas Coast (Stutzenbaker 1988; Moon 2014). Though the threat seems static under "normal" conditions, our models indicate that the risk of lead exposure are increased during periods of ecological stress. Abrupt and dramatic shifts in habitat conditions could also contribute to sudden increases or changes in lead content in the environment by promoting degradation or dredging up lead held on the clay pan. Effects of any potential ecological trap face by mottled ducks due to lead exposure on the Upper Texas Coast could be further elucidated by the identification of population level trends and vital rates directly attributable to lead levels. However, management strategies to limit the risk of lead exposure on the Upper Texas Coast would be beneficial as part of an integrated conservation approach for mottled ducks.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Informed consent Informed consent was obtained from all individual participants included in the study.

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