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Research article

Decision support tool: Mottled duck habitat management and conservation in the Western Gulf Coast

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ABSTRACT

The Western Gulf Coast provides important habitat for migratory and resident waterfowl. The mottled duck (*Anas fulvigula*) relies on this region for all of its life-cycle events. Its relatively small population, limited worldwide range, and generally declining population trajectory has earned it a “Red” status on the Audubon WatchList and is a species of concern among state and federal agencies. The Western Gulf Coast (WGC) mottled duck population decline is believed to be primarily caused by the historical conversion and degradation of coastal wetlands and native prairie, and recent declines in cultivated rice. There is general agreement among experts that negative impacts to nesting and brood-rearing habitat are the most important threats to the WGC mottled duck population and increasing recruitment is essential to the growth and sustainability of the population.

Our goal was to use available knowledge of mottled duck nesting and brood-rearing requirements to develop a model to aid managers in targeting areas for conservation and management. We developed four spatially explicit models that: 1) identify and prioritize existing mottled duck nesting habitat for conservation (e.g., protection or maintenance); 2) identify and prioritize existing mottled duck brood-rearing habitat for conservation; 3) identify and prioritize areas for grassland establishment; and 4) identify and prioritize wetland basins for freshwater enhancement. Spatial models revealed that only 6 km^2 and 9 km^2 of nesting and brood-rearing habitat, respectively, were identified as highest priority (top 10%) for conservation in the WGC. Brood habitat was identified as potentially limiting recruitment in the Texas Mid Coast and the Laguna Madre subregions of our study area, whereas grassland habitat was potentially limiting recruitment in Chenier Plain and Mississippi River Coastal Wetlands subregions. Spatial models also revealed that there is a high density of areas of high priority for grassland establishment inland in Texas and Louisiana. Likewise, there is a high density of wetland basins of high priority for freshwater enhancement throughout coastal Louisiana and the upper Texas coast.

We used two separate measures to assess the performance of our Mottled Duck Decision Support Tool (hereafter MODU-DST) and found that it adequately identified patch suitability, as defined by our model, with ≥79% accuracy. Using data from the Cooperative Breeding Mottled Duck Survey, we also found that breeding mottled ducks were using landscapes with optimal spatial arrangement of nesting and brood-rearing habitat, which is reflected by higher mean priority rankings of nesting and brood-rearing habitat in the landscape.

1. Introduction

The Western Gulf Coast (WGC) provides valuable habitat for migratory and resident waterfowl. The mottled duck (*Anas fulvigula*) is a resident species in this region and is closely associated with coastal marsh and inland agricultural habitats, relying on these areas for all its life-cycle needs. Habitat conversion and degradation due to large-scale hydrologic alterations, urban expansion, declines in rice agriculture, and other human activities have raised concerns for the declining WGC mottled duck population. Collective evidence from available population

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data across the WGC range suggests a long-term steep decline in Texas and a stable to slightly declining trend in Louisiana (Wilson, 2007). Although other threats such as sport harvest (Raftovich et al., 2011), lead poisoning (Anderson et al., 2000; Sanderson and Bellrose, 1986), hybridization (Ford, 2015; McCracken et al., 2001), and predation (Bielefeld et al., 2010; Durham and Afton, 2003; Elsey et al., 2004; Stutzenbaker, 1988) may contribute to mottled duck population declines, loss of nesting and brood-rearing habitats is believed to be the primary cause (Wilson, 2007). Therefore, a priority for increasing the WGC mottled duck population is to increase recruitment by conserving landscapes with nesting and brood-rearing habitats in appropriate spatial configurations.

Managers and conservationists typically rely on limited resources for the protection and enhancement of habitats; thus, tools that identify areas most suitable for conservation efforts enable more efficient allocation of those resources. Decision Support Tools (DSTs) are information systems, often computer-based, that support decision-making activities (Power, 2007). In the last few decades, DSTs have become a vital component in the management of wildlife and their habitats (Bennetsen et al., 2016; Garcia and Armbruster, 1997; Kangas et al., 2000; Quinn and Hanna, 2003; Rauscher, 1999). A common drawback of historical approaches to habitat management is the inability to account for the spatial and temporal relationships between ecological variables related to a particular species (Cooperrider et al., 1986; Heinen and Cross, 1983). In recent decades, biologists have relied more heavily on ecological models for environmental decision support (Jones et al., 2016; Naugle et al., 2001; Robinson et al., 2016; Thorne et al., 2015). Ecological Decision Support Tools integrate available biological and ecological knowledge, expert opinion, and empirical data to develop tools that aid the decision-making process.

Our goal was to develop a spatially explicit DST for mottled duck habitat conservation in the WGC, prioritized for targeting conservation of nesting and brood-rearing habitat. Additionally, following the Strategic Habitat Conservation framework (Opdam et al., 2002; Schmolke et al., 2010; USFWS, 2008) we used an independent dataset to assess model performance and utility (Brooks, 1997; Schmolke et al., 2010) and inform future refinements.

Our specific objectives were to: 1) use recommendations in the Gulf Coast Joint Venture (GCJV) Mottled Duck Conservation Plan (Wilson, 2007) and input from regional stakeholders as the basis for a DST to inform delivery of conservation actions to establish, enhance, and protect/maintain coastal marshes, inland wetlands, and grasslands to positively impact key reproductive rates for WGC mottled ducks; 2) use the DST to generate spatial priorities for specific conservation actions of interest (establishment, enhancement, and protection/maintenance), with model outcomes based on target biological objectives (e.g., nest success and brood survival); and 3) assess the performance of the DST in identifying suitable habitat patches, and its ability to effectively prioritize patches.

2. Methods

2.1. Study area

Mottled ducks are managed as two distinct populations, one in peninsular Florida (Johnson et al., 1991) and the other in the WGC, which stretches from the eastern coast of Tamaulipas, Mexico into coastal Alabama (Baldassarre, 2014; Sincock et al., 1964; Stutzenbaker, 1988). Our focus was on the WGC population. Within this region we restricted the study area to Texas and Louisiana because > 99% of the GCJV population target for WGC mottled ducks occurs in these states (Wilson, 2007).

The WGC, inclusive of the Texas and Louisiana coasts (Fig. 1), stretches over 1200 km along the Gulf of Mexico and is bordered by about 12,000 km of shoreline (GSHHG, 2017; Wessel and Smith, 1996). Climate varies greatly across this region, as precipitation decreases from 1590 mm/year along the Louisiana coast, to 1390 mm/year along the upper Texas coast, to a low of 640 mm/year along the lower Texas coast (Chabreck et al., 1989; Stutzenbaker and Weller, 1989). Throughout the WGC, summers are generally hot (mean high 33 °C and mean low 24 °C; NOAA, 2011) and humid, and winters are mild (mean high 18 °C and mean low 8 °C; NOAA, 2011). The WGC is also affected by periodic tropical storm activity, which can impact vital waterfowl habitats (Couvillion et al., 2011). Agriculture consists primarily of sorghum, corn, cotton, and rice cultivation (USDA, 2014a,b). Nesting and brood-rearing habitat characteristics in the coastal marsh and agricultural landscapes differ in their structure and spatial arrangement, as well as their utility to mottled ducks (Wilson, 2007). The majority of agricultural and pasture lands occur adjacent to and inland from coastal marshes. To accommodate these differences, we identified nesting habitats in coastal zones differently than in inland (i.e., agricultural) zones. We defined the coastal zone as the combined extent of the Texas-Louisiana Coastal Marshes, Mid-Coast Barrier Islands and Coastal Marshes, Texas-Louisiana Coastal Marshes, and the Deltaic Coastal Marshes and Barrier Islands Level IV Eco-regions (U.S. Environmental Protection Agency, 2013). We further restricted development of the DST to the mottled duck range in Texas and Louisiana as described by Wilson (2007), which corresponds roughly to the geographic extent of GCJV Initiative Areas in these states (Fig. 1).

2.2. Currently available nesting and brood-rearing habitat model

We convened a comprehensive stakeholder meeting prior to initiation of model development to discuss the objectives of the development process, the appropriate biological parameters and their thresholds to include in the models, and to present a preliminary concept of the DST. Attendees included biologists, resource managers, Joint Venture staff, and academic researchers that work with mottled ducks and their habitats. Attendees provided vital feedback through open discussions and a questionnaire for the development of the DST. Regular meetings to report progress and obtain feedback were made with Gulf Coast Joint Venture and Gulf Coast Prairie Landscape Conservation Cooperative staff throughout the project.

Our model was parameterized using patch and landscape variables deemed critical for identifying currently available mottled duck nesting and brood-rearing habitat. Variables that affect mottled duck nest success and brood survival were chosen through review of appropriate literature and discussions with waterfowl habitat managers, mottled duck researchers, and other conservation stakeholders in the WGC. Vegetation type (Boryan et al., 2011), patch size, patch shape, and distance to nearest brood-rearing habitat were considered essential in identifying nesting habitat for mottled ducks (Table 1). The process for identifying nesting habitat in the coastal and inland zones was similar, with a few changes to variable thresholds to accommodate ecological and land use differences between the two landscapes. In coastal zones of Texas and Louisiana, mottled ducks nest primarily in dense stands of cordgrass (*Spartina* spp.), but will also utilize other tall grasses (Finger et al., 2003; Holbrook et al., 2000; Stutzenbaker, 1988; Walters et al., 2001). In inland areas, mottled ducks nest in idle fields and pastures (Durham and Afton, 2003). Successful nests are typically associated with higher plant diversity and vegetation density (Durham and Afton, 2003). Like most ground-nesting ducks, mottled ducks rely on vegetation structure around the nest to provide security from nest depredation. All spatial model building and analysis was conducted in ArcGIS software (ESRI, 2011). We used a step by step process and several models to identify nesting habitat in the inland and coastal zones that met all of the requirements and thresholds for suitability (Table 1; see Appendices A–F in Krainyk and Ballard, 2014 for more detail) and then converted the spatial layer into raster format for subsequent prioritization.

During the brood-rearing period, mottled ducks require low salinity, vegetated, relatively shallow wetlands in close proximity to nesting

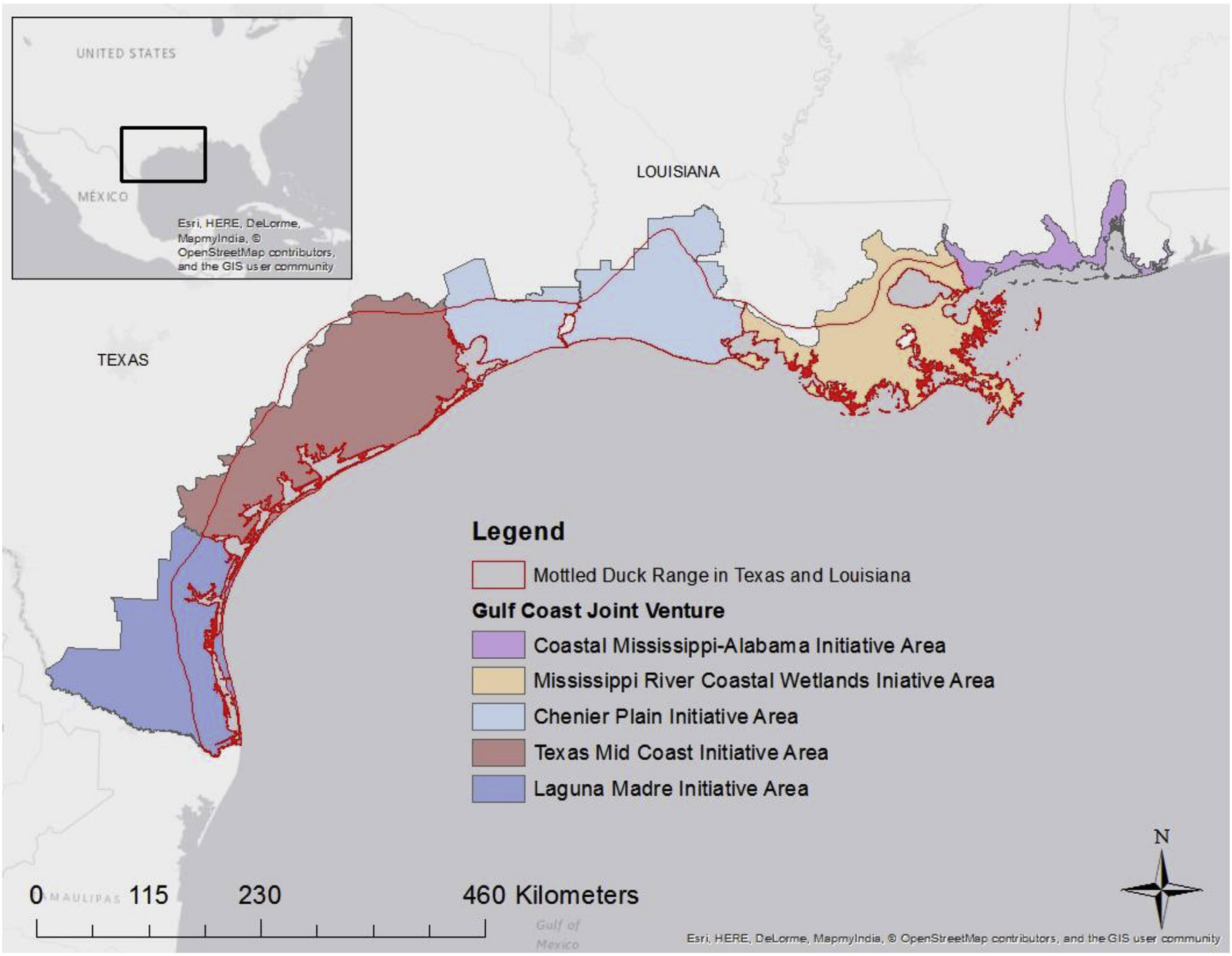

Fig. 1. Mottled Duck range in Texas and Louisiana and GCJV Initiative Areas. Final area of analysis and spatial delivery is consistent with Mottled Duck range (outlined in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

habitat (Durham and Afton, 2006; Moorman et al., 1991). Previous studies suggest that landscapes selected by female dabbling ducks during the brood-rearing period are dominated by semi-permanent and seasonally flooded estuarine and palustrine vegetated wetlands (Belanger and Couture, 1988; Ringleman and Longcore, 1982; Rotella and Ratti, 1992a; b). Emergent vegetation provides ducklings escape cover from predators and thermal cover from inclement weather (Bielefeld et al., 2010; Durham and Afton, 2003; Sargeant and Raveling, 1992; Moorman and Gray, 1994; Raven et al., 2007). Variables for identifying brood-rearing habitat included wetland type, water permanence (i.e., hydroperiod), and distance to nesting habitat (Table 2). Because no spatial data layers were available to provide information on wetland salinity or depth, we considered wetland type as a reasonable proxy for these variables. We considered wetland hydroperiod, defined as the number of years during which a wetland was inundated across a wet-dry environmental gradient, to be an appropriate measure of a wetland's reliability.

To calculate wetland hydroperiod, we first obtained average

Table 1
Biological variables and thresholds used to identify mottled duck nesting habitat in the western Gulf Coast of Texas and Louisiana (* in coastal zone only,** in inland zone only).

Biological Variables	Variable Threshold	Justification
Land cover type of nesting patch	Fallow/Idle Cropland, Pasture/Hay, Herbaceous Grassland, Herbaceous Wetland*[a] = suitable All other categories = unsuitable	Stutzenbaker, 1988; Wilson, 2007; Stakeholder input
Size of nesting patch	≥16.2 ha = suitable < 16.2 ha = unsuitable	Wilson, 2007
Edge-to-interior ratio of nesting patch**	< 0.025 m/m^2 = suitable ≥0.025 m/m^2 = unsuitable	Stakeholder input
Distance from nesting to brood-rearing habitat	≤1.6 km = suitable > 1.6 km = unsuitable	Stutzenbaker, 1988; Wilson, 2007; B. M. Ballard, unpublished data

[a] Landcover classes are based on CropScape-Cropland Data Layer classification (Boryan et al., 2011).

Table 2
Biological variables and thresholds used to identify mottled duck brood-rearing habitat in the western Gulf Coast of Texas and Louisiana.

Biological Variables	Variable Threshold	Justification
Wetland type	Appendix I & K (Krainyk and Ballard, 2014) = suitable All other categories = unsuitable	Stutzenbaker, 1988; Wilson, 2007; Stakeholder input
Hydroperiod	≥3 years out of 9 = suitable < 3 years out of 9 = unsuitable	Wilson, 2007; Stakeholder input
Distance from brood-rearing to nesting habitat	≤1.6 km = suitable > 1.6 km = unsuitable	Ballard et al., unpublished data, Stutzenbaker, 1988; Wilson, 2007

monthly precipitation data at 4 × 4 km resolution from PRISM Climate Group, Oregon State University (http://www.prism.oregonstate.edu/recent/), and calculated total precipitation from 1 September to 31 May each year (1985–86 to 2010–11), peak breeding and brood-rearing season (Grand, 1992; Paulus, 1988), for each GCJV initiative area by summing values across pixels. We then determined the average precipitation across all pixels per year per initiative area. Among the years examined (26 years), we chose the three driest, three wettest, and three medial cumulative rainfall years to represent the range of potential wetland conditions during the breeding season in our study area (i.e., 9 years). All wetlands of appropriate type were considered potential brood-rearing wetlands, irrelevant of their hydroperiod. We assumed (with stakeholders input) that wetlands of appropriate type and inundated during medial and wet years (i.e., ≥3 of 9 years of our sample years) would provide reliable brood-rearing habitat, and therefore value, positively related to number of years inundated. These wetlands were included as potential brood-rearing habitat in the currently suitable brood-rearing habitat model. Wetlands of appropriate type and inundated ≤3 of 9 years were considered to be appropriate for wetland enhancement, as they were only available in the wettest of years. Thus, our goal was to increase their reliability as brood-rearing habitat by increasing their hydroperiod through wetland enhancement.

We calculated hydroperiod based on Landsat Thematic Mapper (TM) satellite imagery using Normalized Difference Water Index (NDWI) proposed by McFeeters (1996) to delineate non-urban water associated with wetlands. Some permanently and semi-permanently flooded wetlands in the coastal zone possessed dense vegetation that rendered the TM-based hydroperiod analysis ineffective at detecting surface water beneath the vegetation. Thus, we supplemented our hydroperiod analysis by identifying all wetlands in the coastal zone possessing National Wetland Inventory (NWI) permanent or semi-permanent flooding modifiers (Cowardin et al., 1979) and manually assigning them a hydroperiod value of 8 (e.g. represents a wetland being inundated 8 out of 9 years). We used a combination of NWI, National Hydrography Data, 2010 U.S. Census data, spatial delineations of saline habitats (Enwright et al., 2014; Sasser et al., 2008), and expert opinion to identify and exclude wetland types not considered to be valuable brood-rearing habitat or ones that were within the boundaries of urban centers; all remaining areas with a hydroperiod value of ≥3 were retained as potential brood-rearing habitat. This process included several models to identify suitable brood-rearing habitat in the inland and coastal zone that met all of the requirements and thresholds for suitability (Table 2; see Appendices G–K in Krainyk and Ballard, 2014 for more detail) and then converted the spatial layer into raster format for subsequent prioritization.

There was general agreement among stakeholders that distances between nesting and brood-rearing habitats of ≤1.6 km are optimal, as they reduce overland travel by ducklings, thereby lowering the probability of mortality due to depredation and exposure (Rotella and Ratti, 1992b; Stutzenbaker, 1988; Wilson, 2007). Thus, we considered wetlands to be suitable as brood-rearing habitat only if they occurred within 1.6 km of identified nesting habitat, and we considered grasslands to be suitable nesting habitat only if they occurred within 1.6 km of identified brood-rearing habitat. Consequently, we prioritized nesting or brood-rearing habitat based on the availability of its counterpart within 1.6 km on the surrounding landscape. We prioritized nesting habitat for conservation based on three landscape characteristics: 1) density of nesting habitat within a 1.6-km radius landscape around the center pixel (higher priority assigned to nesting habitat pixels with greater density of nesting habitat within 1.6 km); 2) density of brood-rearing habitat within a surrounding 1.6-km radius landscape around the center pixel (higher priority assigned to nesting habitat pixels with greater density of wetlands within 1.6 km); and, 3) distance to brood-rearing habitat (higher priority assigned to nesting habitat pixels positioned closer to brood-rearing habitat).

We prioritized brood-rearing habitat for conservation based on four landscape or patch characteristics: 1) density of brood-rearing habitat within a surrounding 1.6-km radius landscape around the center pixel (higher priority was assigned to brood-rearing habitat pixels with greater density of brood-rearing habitat within 1.6 km); 2) density of nesting habitat within a surrounding 1.6-km radius landscape around the center pixel (higher priority was assigned to brood-rearing habitat pixels with greater density of nesting habitat within 1.6-km); 3) distance to nesting habitat (higher priority was assigned to brood-rearing habitat pixels positioned closer to nesting habitat); and, 4) hydroperiod of a given brood-rearing wetland.

In our prioritization scheme, each pixel in our raster datasets depicting nesting and brood-rearing habitat was assigned a value of 0 or 1, depending on whether it was suitable (value = 1) or unsuitable (value = 0). For each pixel of habitat (i.e., those that had a value of 1) in these datasets, we used a moving window analysis to calculate the average of all pixel values within a 1.6-km radius landscape. We performed these calculations separately for the nesting and brood-rearing datasets, thus producing two new datasets that represented, respectively, the density of nesting and brood-rearing habitat in the landscape surrounding each pixel of habitat. We then multiplied these raster datasets by 10 to create two weighted datasets for subsequent use in prioritization. We used this weighted dataset as a proxy for distance, rather than measuring linear distances between habitat pixels, because exploratory analyses revealed a high degree of (inverse) correlation between measures of density and distance. We developed our prioritized nesting habitat dataset by adding the un-weighted dataset of nesting habitat density (pixel values ranged 0–1) to the weighted dataset of brood-rearing habitat density (pixel values ranged 0–10). Similarly, we developed our prioritized brood-rearing habitat dataset by adding the un-weighted dataset of brood-rearing habitat density (which also accounted for wetland hydroperiod) to the weighted dataset of nesting habitat density. This produced two unique datasets, each with pixel values having the potential to range from 0 to 11, with higher values representing higher priority. We chose this prioritization scheme to emphasize the importance of having both nesting and brood-rearing habitat within the same landscape, as well as reflect the interaction between patch and landscape characteristics in determining relative suitability of an area as mottled duck breeding habitat. Thus, areas identified as high priority nesting or brood-rearing habitat were expected to provide conditions conducive to greater mottled duck nest success or duckling survival, respectively. Finally, we clipped the continuous raster datasets to the original boundaries of the nesting and brood-rearing patches in the landscape to derive a spatial map reflecting prioritization of suitable nesting and brood-rearing habitats

(Appendix).

2.3. Wetland enhancement model

Wetland basins that are unsuitable for brood-rearing activities (i.e. basins with a hydroperiod of < 3 of 9 years inundated) may become suitable with proper hydrological management. We identified wetland basins having a suitable wetland type (Table 2) and within 1.6 km of existing nesting habitat, but were inundated <3 of the 9 years based on our TM-based hydroperiod analysis. We assumed these wetlands were inundated in the wettest years only, but could become of greater value through management that increased their hydroperiod to ≥3 out of 9 years. We used results from our brood-rearing habitat model to identify wetlands that failed to meet suitability based solely on having a hydroperiod <3.

We used our raster datasets depicting available nesting and brood-rearing habitat, derived in the first model, to prioritize the wetland basins for enhancement. We used a moving window analysis to assign each pixel in the landscape a value based on the sum of nesting or brood-rearing habitat pixels within a 1.6-km radius. Next we used the polygons of wetland basins previously identified as having hydroperiods < 3 to extract a value (average of the pixels within the basin) from the raster dataset produced by the moving window analysis, indicating the availability of nesting and brood-rearing habitat within a 1.6-km radius. Basins that had a high (relative to other areas on a continuous scale) average value for the amount of nesting habitat within 1.6 km received a higher rank. Basins that had a low average value for the amount of brood-rearing habitat within a 1.6-km radius received a higher rank. These prioritizations were based on the assumption that improving wetland basins for brood-rearing activities would be more beneficial in a landscape matrix that had abundant nesting habitat but was currently lacking brood-rearing habitat. Both of these layers were standardized on a scale from 0 to 1 and summed using the 'raster calculator' function in ArcGIS (ESRI, 2011). The resulting layer represented a spatial depiction of wetland basins prioritized for freshwater enhancement based on the surrounding matrix of nesting and brood-rearing habitat.

2.4. Grassland establishment model

We defined grassland establishment in our model as the restoration of native grasses. Available spatial datasets did not discern landscape characteristics within the coastal zone where grassland establishment would be practical and most valuable (e.g., fine-scale elevation changes). Additionally, availability of nesting habitat within the coastal zone is generally not considered a limiting factor for mottled ducks, as large expanses of vegetation suitable for nesting (e.g., *Spartina patens*) are common throughout this zone. Instead, habitat features such as marsh elevation and vegetation composition and structure are considered of greater concern for influencing mottled duck nesting within the coastal zone (Wilson, 2007). We recognized that dredge material could be used beneficially at some sites to create nesting habitat of the proper elevation and vegetation composition, but the proportion of the total landscape affected by this process is not significant to the objectives of this project. Consequently, we restricted our identification of areas for grassland establishment to the inland zone of the WGC.

We limited our grassland establishment analysis to cultivated crops or other land cover types that we believed were feasible for conversion to grasslands. Therefore, we excluded all areas classified as developed, forested, current grasslands, and open water and woody wetlands from our grassland establishment model. However, we considered areas that were classified as forested in the 2011 Cropland Data Layer but were previously fallow/idle cropland, herbaceous grassland, or pasture/hay in either 1992, 2001, or 2006 National Land Cover Datasets, as potential sites for grassland establishment. We believed these areas represented former agricultural lands that had recently been abandoned and colonized by shrubs, young trees, or other early successional vegetation that may be easier to convert to grassland than mature forests. Additionally, we excluded all areas that were considered brood-rearing habitat, as we did not want to promote grassland establishment on already functional mottled duck brood-rearing habitat.

Although we considered rice rotation lands to provide brood-rearing habitat, they occur primarily within the range of the historical Gulf Coast Prairies, and when not in active rice production they can become quickly colonized by communities of grasses, sedges, and other terrestrial plants where mottled duck nesting has been documented (Durham and Afton, 2003). Due to recent market-driven declines in rice acreage within the mottled duck range (Alston et al., 2000), some rice rotation lands are transitioning to other land cover types and offer opportunities for grassland establishment. Consequently, we considered lands in rice rotations to also be candidates for grassland establishment, especially when such establishment would occur in proximity to continuing rice growing operations or other wetlands that would provide access to brood-rearing habitats. The resulting dataset of areas for grassland establishment to benefit nesting mottled ducks was further restricted to only those areas within 1.6 km of current brood-rearing habitat or wetlands that met all brood-rearing suitability requirements except having nesting habitat within the proximity threshold.

Our prioritization scheme was designed to encourage grassland establishment in areas that would increase the size or reduce the edge-to-interior ratio of current nesting habitat patches. Also, areas that were in closer proximity to current brood-rearing habitat, as defined by our model, were considered higher priority for grassland establishment, as these should produce landscapes containing optimal types and configurations of habitats for breeding mottled ducks.

The first step in our prioritization scheme was to calculate a Grassland Value (GV) for each pixel identified as potentially suitable for grassland establishment, as previously defined. We used the GV to measure the amount of nesting habitat within a 1.6-km buffer of the perimeter of each wetland of suitable type and hydroperiod. For each such wetland, we calculated a single GV by summing the number of nesting habitat pixels within the 1.6-km buffer and dividing it by the total number of pixels within that buffer. If a pixel for potential grassland establishment occurred within the buffer of ≥2 wetlands, the higher GV value was used. The resulting GV reflected the proportion of area within the landscape surrounding the wetland that was currently nesting habitat, and we assigned the inverse of the GV to each pixel within the 1.6-km buffer. The inverse value was assigned because it represented our belief that grassland establishment priority should be higher at sites (i.e., pixels) within 1.6 km of current or potential brood-rearing habitat that have little or no existing nesting habitat. The inverse GV metric accounted for 70% of the prioritization score for grassland establishment, which reflected our belief that the relative lack of grassland in proximity to suitable wetlands for brood-rearing should be the primary determinant of grassland establishment.

We also calculated the shortest distance from each potential grassland establishment pixel to the nearest brood-rearing and nesting habitats. The shortest distance to brood-rearing habitat reflected our belief that grasslands would be more valuable if located nearer to wetlands, therefore minimizing risks of overland travel by broods. The shortest distance to nesting habitat reflected our belief that adding to existing nesting patches should be a higher priority than creating a grassland tract distant from other grasslands, as this would promote larger nesting patches and therefore lower nest predation through reduced predator search efficiency (Rotella and Ratti, 1992b; Stutzenbaker, 1988; Wilson, 2007). These two distance variables were recorded in meters and each accounted for 10% of the prioritization score. Finally, each potential grassland establishment pixel was assigned a value to reflect the number of brood-rearing wetlands within 1.6 km. This value was calculated using the 1.6-km wetland buffer overlaps. We created 1.6-km buffers around each brood-rearing wetland and then assigned pixels a value equal to the number of overlapping buffers from adjacent wetlands. This value was also worth 10% of the final prioritization for grassland establishment. The final parameter gave marginally higher priority to establishment of grasslands within a matrix of multiple wetlands and assumed that: 1) availability of multiple wetlands made it more likely that at least one would be in suitable condition during any given year; 2) brood-rearing or foraging females on nest breaks may prefer visual isolation from conspecifics (Anderson and Titman, 1992), rendering the grassland patch suitable for more nests; and 3) pairs searching for nest sites may be more likely to select a grassland patch proximal to multiple wetlands because of assumptions 1 and 2. We summed each of the raster datasets to produce a layer of areas that are potentially suitable for grassland establishment. This final priority rank was on a scale from 0 to 1, with 1 being highest priority for grassland establishment.

2.5. Evaluating model performance

We used two approaches to test model performance. We 1) used ground-truthing to evaluate the ability of our MODU-DST to identify current nesting and brood-rearing habitat; and 2) evaluated the effectiveness of our prioritization scheme for identifying high quality habitat matrices. Our hypothesis was that breeding mottled ducks will select nesting and brood-rearing habitats defined by our MODU-DST as high priority for conservation, and will avoid those defined as low priority for conservation.

2.5.1. Assessment of patch suitability

Our MODU-DST models were based on the best available spatial data; however, these datasets have unknown amounts of inherent error. Common spatial dataset errors are 1) misclassification of thematic satellite imagery, 2) change in condition of patch and landscape characteristics from release date of dataset to its inclusion in these models, and 3) coarse spatial resolution of some datasets. Thus, we collected ground truth data from a helicopter to evaluate the ability of the MODU-DST to correctly identify nesting and brood-rearing habitat. Our approach assessed patch attributes and did not include distance from nesting or brood-rearing habitat as part of our suitability criteria. We limited our ground-truthing surveys to the Texas Mid-Coast and Chenier Plain Initiative Areas of the GCJV (Fig. 1). Both Initiative Areas accounted for 77% of all nesting habitat and 70% of all brood-rearing habitat identified by our model. Given time and financial restrictions of surveying the entire study area, we felt surveying these two initiative areas was most efficient. We generated 420 sample points for assessment, of which 60 points were allocated to each of three categories of model-identified nesting and brood-rearing habitat (i.e., we divided the full range of priority scores equally into thirds), and 60 points were allocated to areas identified by the model as not suitable for mottled duck nesting or brood-rearing activities. We allocated sampling points based on a stratified random design, such that points were allocated proportional to the amount of nesting and brood-rearing habitat in each Initiative Area and within the inland and coastal zones (Appendix). To determine the actual suitability of selected patches (i.e., points), we visited each sample point in a R44 helicopter during June 2015, hovered above the patch, and recorded the vegetation type and land cover characteristics observed (Appendix) from the helicopter. The type of patch at each point (e.g., low, medium, or high priority nesting or brood-rearing habitat) was unknown to the observer at the time of data collection, and the observer simply recorded the habitat type of each patch they observed (Appendix). The use of a helicopter both negated the need to gain permission to access the large number of sample points, and enabled us to more easily survey areas that were difficult to access from the ground.

We calculated percent agreement between our ground-truth data and output from our model identifying currently available habitat for three categories: 1) areas not suitable for nesting or brood-rearing activities (i.e., non-habitat); 2) current mottled duck nesting habitat; and, 3) current mottled duck brood-rearing habitat. This analysis provided a quantified measure of accuracy for the MODU-DST and helped elucidate model weaknesses and limitations.

2.5.2. Assessment of priority ranks for nesting and brood-rearing habitat

We used georeferenced data on the location of mottled ducks observed during the WGC mottled duck breeding population survey in 2009–2014, to identify sites used by mottled ducks during the breeding season (USFWS Division of Migratory Birds Branch of Population and Habitat Assessment, unpublished data). Using ArcGIS 10.3, we plotted the georeferenced locations of observed mottled ducks for each year separately. We generated a 1.6-km radius buffer around each sighted mottled duck location, as well as an equal number of randomly generated points within the mottled duck range in Texas and Louisiana (2009: $n = 1496$; 2010: $n = 2070$; 2011: $n = 2274$; 2012: $n = 1170$; 2013: $n = 1284$; 2014: $n = 2222$). Within these buffers, we calculated mean priority rankings (0–11) of nesting and brood-rearing habitat pixels from our model output of currently available habitat. We used Kolmogorov-Smirnov test of distributions to determine if mean priority rankings of the 1.6-km radius buffers differed between random points and sighted mottled duck locations. The Kolmogorov-Smirnov test of distributions tests if the distribution function of observed data is different from a hypothesized distribution function (Lopes, 2011; Wilcox, 2005). The hypothesized distribution function in this project is the distribution of mean priority rankings for nesting and brood-rearing habitat in landscapes where no mottled ducks were observed. Additionally, we used Chi-square tests to assess whether mottled ducks observed during the breeding population survey selected landscapes in a manner consistent with our model-based priority rankings. This was included because reporting histograms of the hypothesized distribution and mottled duck distribution functions does not indicate whether certain priority rank categories were avoided or selected (Cherry, 1998).

3. Results

The primary outputs from our models were 16 spatially explicit datasets (i.e., maps) that identified landscape prioritizations for habitat conservation across the WGC mottled duck range (Appendix). Our model indicated there to be 19,149 km^2 of nesting habitat and 9285 km^2 of brood-rearing habitat currently available for mottled ducks in the WGC. Our model prioritizing areas for grassland establishment identified 10,558 km^2 with potential for such activities, which if established, would increase the area of available nesting habitat by 55%. Likewise, our model identified 9216 km^2 of wetland basins that would be a priority for wetland enhancement, which could double the amount of brood-rearing habitat. Throughout the study area, 1640 km^2 of wetlands were considered unsuitable for brood-rearing activities because they were > 1.6 km from nesting habitat. Additionally, there were 1188 km^2 of grasslands that were not suitable as nesting habitat because they were > 1.6 km from brood-rearing habitat. Descriptive statistics of model results are reported by GCJV initiative area (Table 3) as these represent biological planning units adopted by a multi-organizational bird conservation partnership and several active habitat implementation teams within the region. Additionally, each initiative area has a different mix of habitats, land uses, management opportunities, and habitat objectives (Esslinger and Wilson, 2001, 2002; Wilson and Esslinger, 2002; Wilson et al., 2002).

3.1. Laguna Madre initiative area

The Laguna Madre Initiative Area encompasses 8706 km^2 of the WGC mottled duck range as defined by Wilson (2007), the least of all the initiative areas. Within this initiative area, our model identified 1679 km^2 and 431 km^2 of currently available mottled duck nesting and brood-rearing habitat, respectively. We estimated that > 76 km^2 of

Table 3
Area (ha) of mottled duck nesting and brood-rearing habitat identified as currently suitable or for grassland establishment and wetland enhancement by spatially explicit models within each priority level for four Initiative Areas of the Gulf Coast Joint Venture. High, Medium, Low priority categories are based on equal intervals of a continuous prioritization scheme.

		Laguna Madre IA		Texas Mid Coast IA		Chenier Plain IA		Mississippi River Coastal Wetlands IA	
		Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Nesting Habitat	High Priority	53	0.03	2610	0.30	16,363	2.78	4966	1.82
	Medium Priority	3661	2.18	46,194	5.22	122,933	20.89	44,249	16.18
	Low Priority	164,213	97.79	835,362	94.48	449,147	76.33	224,196	82.00
	Total	**167,927**	**100.00**	**884,166**	**100.00**	**588,443**	**100.00**	**273,411**	**100.00**
Brood-rearing Habitat	High Priority	4862	11.28	16,656	9.88	31,445	6.49	9116	3.93
	Medium Priority	12,336	28.62	76,792	45.55	125,477	25.88	45,404	19.59
	Low Priority	25,909	60.10	75,157	44.58	327,855	67.63	177,274	76.48
	Total	**43,107**	**100.00**	**168,605**	**100.00**	**484,777**	**100.00**	**231,794**	**100.00**
Grassland Establishment	High Priority	113,239	62.59	230,860	46.26	199,208	60.90	39,489	81.03
	Medium Priority	61,991	34.26	236,121	47.32	120,490	36.84	9189	18.86
	Low Priority	5693	3.15	32,053	6.42	7396	2.26	57	0.12
	Total	**180,923**	**100.00**	**499,034**	**100.00**	**327,094**	**100.00**	**48,735**	**100.00**
Wetland Enhancement	High Priority	8059	26.36	73,983	31.33	210,769	41.39	74,803	51.37
	Medium Priority	21,982	71.91	108,744	46.05	142,605	28.01	67,297	46.21
	Low Priority	527	1.72	53,392	22.61	155,811	30.60	3518	2.42
	Total	**30,568**	**100.00**	**236,119**	**100.00**	**509,185**	**100.00**	**145,618**	**100.00**

wetlands and > 130 km^2 of grasslands were eliminated from consideration as brood-rearing and nesting habitat, respectively, because they failed to satisfy the minimum distance threshold. Of the combined area of nesting and brood-rearing habitat, 90.1% was classified as "low" priority, 7.6% was classified as "medium" priority, and 2.3% was classified as "high" priority for protection/maintenance.

Our model identified 1809 km^2 as having potential for grassland establishment, with areas of highest priority rank concentrated in the northern and southwestern portions of the initiative area. A total of 305 km^2 were identified for wetland enhancement, and basins with the highest priority rank were concentrated near the coast (Table 3).

3.2. Texas Mid-Coast initiative area

The Texas Mid-Coast Initiative Area encompasses 29,203 km^2 of the mottled duck range, the most of all initiative areas. Our model identified 8841 km^2 and 1686 km^2 of currently available nesting and brood-rearing habitat, respectively. We estimated that > 49 km^2 of wetlands and > 857 km^2 of grasslands were eliminated from further consideration as brood-rearing and nesting habitat because they failed to satisfy the minimum distance threshold. Of the combined area of nesting and brood-rearing habitat, 86.5% was classified as "low" priority, 11.7% was classified as "medium" priority, and 1.8% was classified as "high" priority for protection/maintenance.

Our model identified 4990 km^2 as having potential for grassland establishment, with areas of highest priority rank concentrated in the southern and central portions of the initiative area. A total of 2361 km^2 were identified for wetland enhancement, and basins with the highest priority rank were concentrated near the coast and in the northwestern corner (i.e., rice prairies) of the initiative area (Table 3).

3.3. Chenier Plain initiative area

The Chenier Plain Initiative Area encompasses 20,076 km^2 of the mottled duck range. Our model identified 5884 km^2 and 4847 km^2 of currently available nesting and brood-rearing habitat, respectively. We estimated that > 561 km^2 of wetlands and > 33 km^2 of grasslands were eliminated from further consideration as brood-rearing and nesting habitat because they failed to satisfy the minimum distance threshold. Of the combined area of nesting and brood-rearing habitat, 72.4% was classified as "low" priority, 23.1% was classified as "medium" priority, and 4.5% was classified as "high" priority for protection/maintenance.

Our model identified 3270 km^2 as having potential for grassland establishment, with areas of high priority rank concentrated in the northeastern and east central portions of the initiative area. A total of 5091 km^2 were identified for wetland enhancement, and basins with highest priority rank were concentrated along the coast of the initiative area (Table 3).

3.4. Mississippi River Coastal Wetlands initiative area

The Mississippi River Coastal Wetlands Initiative Area encompasses 17,347 km^2 of the mottled duck range. Our model identified 2734 km^2 and 2317 km^2 of currently available nesting and brood-rearing habitat, respectively. We estimated that > 953 km^2 of wetlands and > 167 km^2 of grasslands were eliminated from further consideration as brood-rearing and nesting habitat because they failed to satisfy the minimum distance threshold. Of the combined area of nesting and brood-rearing habitat, 79.5% was classified as "low" priority, 17.7% was classified as "medium" priority, and 2.8% was classified as "high" priority for protection/maintenance.

Our model identified 487 km^2 as having potential for grassland establishment, with areas of high priority rank concentrated in the northeastern portion of the initiative area. A total of 1456 km^2 were identified for wetland enhancement, and basins with highest priority rank were concentrated in the eastern portion of the initiative area (Table 3).

3.5. Model performance

3.5.1. Assessment of patch suitability

Due to weather delays and constraints on helicopter time, we were unable to survey all sampling points. Our final sample included 60 of 60 non-habitat points, 168 of 180 brood-rearing habitat points, and 162 of 180 nesting habitat points. We reported the results from our ground-truthing survey as the percent agreement between model classification and observed ground conditions. Overall agreement between model predictions and ground conditions during the time of the survey was 85%. Of the 60 points classified by our MODU-DST model as not suitable mottled duck habitat, 56 (91% agreement) were observed during surveys to match this designation. The remaining 4 points were observed to be capable of providing brood-rearing or nesting habitat at the time of the survey.

Of the 168 points classified by our MODU-DST model as brood-rearing habitat, 132 (79% agreement) were observed during surveys to match this designation. The remaining 36 points were primarily in active row crop or other agricultural land uses and unsuitable as brood-rearing habitat.

Of the 162 points classified by our MODU-DST model as nesting habitat, 143 (89% agreement) were observed during surveys to match this designation. The remaining 19 points were primarily in active row crop, bare ground, or developed residential areas; all unsuitable as nesting habitat.

3.5.2. Assessment of priority ranks for nesting and brood-rearing habitat

The distribution of mean priority rankings for nesting habitat on the landscapes (i.e., 1.6- km buffers) surrounding sites where mottled ducks were observed during the breeding population survey was significantly different ($Z \geq 5.91$, $P < 0.001$) than those surrounding random sites. In all years, mottled ducks avoided landscapes with mean priority ranking of nesting habitat < 2, and tended to select landscapes with mean priority ranking ≥2. However, mottled ducks used landscapes with mean priority ranking of 6 (2011–2014), 9 and 10 (2012), and 8 and 9 (2014) in proportion to their availability during certain years.

Similarly, the surrounding landscapes around sites where mottled ducks were observed had a significantly different distribution of mean priority rankings for brood-rearing habitat ($Z \geq 4.27$, $P < 0.001$) than landscapes surrounding random sites. Specifically, mottled ducks avoided landscapes with a mean priority ranking of brood-rearing habitat of < 2, and selected landscapes with a mean priority ranking of > 7 (scale 0–10).

4. Discussion

The GCJV Mottled Duck Conservation Plan (Wilson, 2007) recommends priority actions for conservation of grasslands and wetlands to address key limiting factors for the WGC mottled duck population. However, until now there has been a lack of science-based knowledge about where, on a spatial scale, to apply these actions to provide the greatest biological return on resource investment. According to our MODU-DST model, availability of brood-rearing and nesting habitat, as well as opportunities for brood-rearing and nesting habitat enhancement or establishment, differ spatially across the GCJV region. For example, the Laguna Madre and Texas Mid-Coast Initiative Areas appear to be limited by availability of brood-rearing habitat, as a large amount of grassland was not considered suitable for nesting because these patches were > 1.6 km from brood-rearing wetlands. These conclusions are consistent with other studies that suggest mottled ducks in Texas are limited by availability of ephemeral wetlands during drought years and that populations tend to fluctuate with variation in precipitation (Grand, 1992; Haukos, 2012). In the Chenier Plain and Mississippi River Coastal Wetlands Initiative Areas, the trend is opposite, whereby nesting habitat is the more limiting component.

The combination of input parameters we used to build the MODU-DST appears to provide relatively high accuracy for identifying mottled duck nesting and brood-rearing habitats in the WGC. Most discrepancies between MODU-DST output and ground conditions observed during our survey stemmed from changes in land use over time. Texas is experiencing a human population growth rate that is twice that of the rest of the U.S. (12.7% versus 6.4%, respectively), which has caused expansive urban development and contributed to the loss of working agricultural and ranch lands (Texas Land Trends, 2014). Louisiana has experienced large losses (4876 km^2) of coastal wetlands, mostly due to hurricanes, rising sea levels (Couvillion et al., 2011), erosion, and saltwater intrusion (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority, 1998). Declines in rice agriculture in Texas (Alston et al., 2000) may also have negative implications for mottled ducks, as well as millions of migrating and wintering waterfowl that rely on these fields for important foraging habitat (Petrie et al., 2014). Because this change is occurring rapidly, some areas that were classified as pasture, rice, or fallow/idle (suitable land cover type for nesting mottled ducks) in 2011 or 2012 landcover datasets had been converted to urban uses by the time of our survey. Thus, timely updates of the MODU-DST using the most recent spatial datasets will increase the model's accuracy for delineating nesting and brood-rearing habitats.

An indication that our MODU-DST performed well was the strong pattern of selection for landscapes with higher priority rankings for nesting and brood-rearing habitat exhibited by mottled ducks during the annual breeding population survey. However, selection for nesting habitat with the highest mean priority rankings was not observed in all years, which may have been the result of observed mottled ducks occurring only on wetlands during the breeding population survey (i.e., females sitting on a nest within a large patch of grassland were not visible from an aerial survey). Consequently, large contiguous blocks of grassland may, in fact, be used by nesting females, but the grassland block could have been large enough that few wetland basins were within 1.6 km of nest locations occupied by females, thus impeding our ability to observe paired males, underestimating the density. In general, we would not expect as strong a correlation between ducks observed exclusively on wetlands and their (or their mate's) use of nearby grassland habitat. Other researchers (Stutzenbaker, 1988; Wilson, 2007) have suggested that protecting high quality habitat, which should increase nest success and brood survival, may be as important as increasing the quantity of habitat. It is our recommendation that protection/maintenance of currently available nesting and brood-rearing habitat should focus on matrices of habitat patches with high priority rankings.

We recognize some important limitations in the model, such as our use of spatial datasets that are not inclusive of all required information and have some amount of inherent error. For example, the coarse resolution of spatial data precluded modeling of vegetation structure or percent woody cover to refine our identification of nesting habitat. Additionally, some spatial data, such as the National Wetland Inventory, have not been updated in recent years and may not represent contemporary wetland conditions. Importantly, our MODU-DST is intended to be used as a form of decision support, where site visits and consideration of other extraneous factors are still required before management or conservation actions are prescribed. Despite these limitations, our assessment of the MODU-DST performance provides a metric of its accuracy, as well as avenues for future improvement. Generally, few decision support tools have been evaluated empirically (Sodja, 2007) or methodologically (Rykiel, 1996; Schmolke et al., 2010). However, we believe this is a critical step, as decision support tools are implemented to direct efficient and informed decisions towards the production (e.g., waterfowl recruitment) or maintenance (e.g., maintaining population goals) of natural resources.

The limitations described herein and the interactive and adaptive nature of our MODU-DST makes it an ideal example of how the Strategic Habitat Conservation framework (U.S. Fish and Wildlife Service, 2008) can be applied to monitor outcomes of specific management actions, test assumptions and hypotheses upon which models are built, and refine models as new information becomes available. To minimize the effect of these limitations within the MODU-DST, we recommend that it be periodically updated using contemporary spatial data. Refinement of the model every three to five years would allow the use of recently released spatial data and help account for habitat that has been improved or lost to anthropogenic and natural processes, such as urban development. Future refinements should include sea-level rise predictions to help understand associated changes to habitats, especially in the coastal zone. Finally, we recommend that feedback from current MODU-DST users be included in the refinement process. Recommendations for protection and enhancement should be taken with an understanding of underlying assumptions and in a retroductive approach (Guthery, 2008) to formulate hypotheses about the effects that landscape variables used to build the model will have on mottled duck production.

Based on the results of this MODU-DST, our recommendations for mottled duck habitat protection/maintenance, enhancement and establishment within the WGC are as follows:

Protection/Maintenance:

- Use fee-title acquisitions, conservation easements, or other mechanisms to protect nesting and brood-rearing habitats that have the highest priority rankings within the area of interest, particularly those patches within matrices of high priority habitat.
- Use incentive-based programs and educational initiatives to encourage activities (e.g., prescribed fire, managed grazing) that will maintain currently available mottled duck habitat in optimal conditions for nesting and brood-rearing.

Enhancement/Establishment:

- Enhance landscapes with lower priority nesting and brood-rearing habitats to increase their expected value to mottled ducks.
- Identify habitat patches recognized in the enhancement model that already meet some of the biological parameters and thresholds to deem them suitable, but that would realize significant gains in habitat quality with modest or minimal inputs.
- Increase the suitability of existing habitat patches by targeting individual characteristics of a given patch (e.g., increase patch size, increase wetland hydroperiod).
- Control hydrology to increase inundation frequency and use drawdowns and flooding at appropriate times of the year to promote optimal vegetation communities to enhance brood-rearing habitat.

5. Conclusion

Our MODU-DST accounts for numerous environmental variables, such as precipitation, land cover, and wetland availability, and relates them both spatially and temporally to identify and prioritize mottled duck habitats based on relative quality. This tool will aid managers of grasslands, agricultural lands, and wetlands in the WGC in making well-informed decisions for allocating funds to mottled duck conservation and management initiatives. More importantly, it will allow for adaptive management, whereby the model can be revised as new research and information becomes available. In a broader sense, this DST provides science-based, spatial guidance for conserving and managing habitats to benefit breeding mottled ducks. In addition to aiding managers in decision making at different spatial scales, the tool may help standardize mottled duck habitat conservation across the WGC.

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Appendix A. Supplementary data

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