

Research article

Identifying important military installations for continental-scale conservation of marsh bird breeding habitat

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ABSTRACT

Degradation of wetland ecosystems has negatively impacted many species, perhaps none more so than marsh birds that breed in vegetative emergent wetlands throughout North America. The U.S. Department of Defense manages approximately 29 million acres of land within the continental U.S., and many military installations contain wetland complexes that may be important for wetland birds. Thus, failure to adequately manage habitat for marsh birds could result in species extirpations and additional listings under the Endangered Species Act, and may result in regulatory burdens that reduce military readiness. We conducted spatial analyses to identify important breeding habitat on > 500 military installations for 12 species of marsh birds, with the goal of identifying installations that are, and are not, likely to harbor breeding habitat for each species. We also sought to assess the local value of military installations for species of greatest concern by comparing habitat suitability within installations to that in areas directly adjacent to those sites. We built range-wide, spatially-explicit models of species distribution to project suitability of breeding habitat for marsh birds within and adjacent to military installations. Our results demonstrate that installations with the best marsh bird habitat are geographically aggregated (both among and within species), primarily at sites along the eastern seaboard and within the southern U.S. In addition, only a few sites appear to contain high-quality habitat for most species. Five or fewer sites contained most of the high-quality habitat for 9 of 12 species, whereas most of the high-quality habitat for remaining species was found at ≤ 10 sites. This work fills an information gap regarding the distribution of breeding habitat for marsh birds on military lands across the U.S., and should facilitate both strategic conservation of habitat over broad scales and the integration of marsh birds into management efforts at the site level. Our analyses also identify installations that are *not* likely to harbor breeding habitat for priority species, and thus should help minimize conflicts between needs of the military and marsh-bird conservation.

1. Introduction

Wetlands are among the most imperiled ecosystems in North America, and anthropogenic degradation of wetlands has negatively impacted many avian species. Over half of the original wetlands in the continental United States (U.S.) have been destroyed since the 1700s (Dahl, 1990, 2006, 2011), and many wetland-dependent birds have suffered population declines (Eddleman et al., 1988; Conway et al., 1994; Naugle et al., 2001; Conway and Sulzman, 2007; Ward et al., 2010; Quesnelle et al., 2013). As such, many wetland birds are conservation priorities at state, regional, and national levels (U.S. Fish and Wildlife Service, 2005, 2008). Indeed, >50% of avian species of concern within the U.S. are associated with wetlands or aquatic ecosystems

(Erwin et al., 2000, U.S. Fish and Wildlife Service, 2008). Wetland birds that require emergent marsh vegetation (marsh birds) are of particular concern because vegetated freshwater wetlands have declined more than other wetland types in North America (Dahl, 2006, 2011).

Secretive marsh birds are a group of cryptic, wetland-dependent waterbirds that breed in vegetative emergent wetlands throughout North America (e.g., bitterns, rails, and gallinules), many of which are species of concern (Eddleman et al., 1988; Conway, 1995, U.S. Fish and Wildlife Service, 2008; Tozer, 2016; Rush et al., 2018). For example, multiple secretive marsh birds are considered focal or priority species for conservation by the U.S. Fish and Wildlife Service, as well as by broad-scale and multi-agency conservation initiatives such as Partners-in-Flight (U.S. Fish and Wildlife Service, 2005, 2008). Secretive

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marsh birds of greatest conservation concern in North America include American bitterns (*Botaurus lentiginosus*), least bitterns (*Ixobrychus exilis*), king rails (*Rallus elegans*), clapper rails (*Rallus crepitans*), Ridgway's rails (*Rallus longirostris*), and black rails (*Laterallus jamaicensis*) (U.S. Fish and Wildlife Service, 2005, 2008). Many states also consider these species threatened or of special concern (e.g., Conway, 1995; Eddleman and Conway, 1998), and several species are federally threatened or endangered in Mexico, Canada, or the U.S. (Committee on the Status of Endangered Wildlife in Canada, 2002; Diario Oficial de la Federacion, 2002). Identification and wise management of wetlands that provide habitat for these species is therefore vital to ensuring their persistence, and is legally mandated on federal lands within the U.S. for species protected under the Endangered Species Act (e.g., Ridgway's rail).

The U.S. Department of Defense (DoD) manages only approximately 1.3% of the land in the United States (nearly 12 million hectares), yet many installations are in coastal areas, near major estuaries, or adjacent to large river systems, and thus contain wetland complexes that include marshland. Failure to adequately manage important wetland habitats for secretive marsh birds may therefore result in regulatory burdens (e.g., through the Endangered Species Act) that limit training exercises and other activities at individual military installations, and thus has the potential to curtail the DoD's mission and reduce military readiness. To ensure that both environmental and military objectives are met on installations, the DoD emphasizes natural resource management that integrates regional ecosystem management, military readiness, range sustainment, and cooperative and international conservation through their Legacy Program and Integrated Natural Resource Management Plans (INRMPs). The installation-level INRMPs provide the planning tool to formally integrate objectives related to secretive marsh bird conservation into the management of existing DoD installations.

While planning tools exist to incorporate secretive marsh birds into management of activities on DoD lands, the conservation value of each installation for these birds is unknown. Indeed, not all wetlands are occupied by, or even suitable for, secretive marsh birds. The cryptic nature of secretive marsh birds paired with limited on-the-ground field sampling for these birds on DoD sites has resulted in an incomplete understanding of which installations provide habitat for each species, and thus it is not clear which species should be included in the INRMPs at any given site. Moreover, the relative value of DoD lands for conserving secretive marsh birds at a local level is unclear (e.g., compared to other areas in the same region). Thus, land managers and policy makers would benefit from a data-driven, science-based, and broad-scale assessment of which DoD installations are likely to harbor breeding habitat for secretive marsh bird species, as well as an assessment of the value of DoD lands for local conservation relative to adjacent non-DoD lands. This would ensure that conservation and management efforts across broad scales are focused on the most important military lands by including the appropriate species in the INRMPs at appropriate sites, while also ensuring military readiness is not hindered by regulatory burdens at individual bases that are unlikely to provide quality habitat for secretive marsh birds. This assessment would also provide information for conservation planning by indicating the relative value of habitat on DoD sites as compared to adjacent areas.

Despite the need to identify important areas for conserving secretive marsh birds, we currently lack data-driven, spatially-explicit models of habitat suitability for these birds across their breeding ranges (as opposed to broad-scale, expert opinion models). This information gap means that managers are ill equipped to properly identify, protect, and manage the most important remaining wetlands for this group of birds on DoD lands, and that better information on the location of important marsh bird habitat is needed. Here we take a multi-species approach to the identification of important breeding habitats on DoD lands for 12 species of secretive marsh birds, with the complementary goal of identifying installations that are not likely to have breeding habitat for each species. We took advantage of recently developed predictive species distribution models that used broad-scale data on marsh bird occurrence

collected over a 14-year period by multiple federal, state, and non-governmental agencies from throughout North America (Stevens and Conway, 2018), and developed spatially-explicit versions of these models to predict breeding habitat suitability on >500 DoD installations across the continental U.S. Specifically, our objectives for this project were to: 1) develop spatially-explicit breeding habitat suitability models for 12 priority species of secretive marsh birds on all DoD installations throughout the continental U.S., 2) use those models to identify important DoD installations and rank all installations based on their relative value as breeding habitat to each species, and 3) compare breeding habitat suitability between DoD installations and lands that are directly adjacent to those installations for secretive marsh birds of greatest concern.

2. Materials and methods

2.1. Study area

The study area included DoD installations throughout the continental U.S. that were contained within the geographic range of 12 secretive marsh bird species, many of which are considered Birds of National Conservation Concern or focal species for conservation action (U.S. Fish and Wildlife Service, 2005, 2008): pied-billed grebe (*Podilymbus podiceps*), American bittern, least bittern, American coot (*Fulica americana*), common gallinule (*Gallinula galeata*), purple gallinule (*Porphyrio martinicus*), king rail, clapper rail, Ridgway's rail, Virginia rail (*Rallus limicola*), sora (*Porzana carolina*), and black rail. We used published ranges from the Gap Analysis Program (GAP) to define the geographic range extent for each of the 12 species (Gergely and McKerrow, 2013), and included all DoD installation lands that fell within the area identified by the GAP range of each species. Thus, inferences about breeding habitat suitability for a particular species of secretive marsh bird at each DoD installation were dependent on that installation being present within the published GAP range for that species.

2.2. Habitat suitability modeling

We used raster regression to develop spatially-explicit habitat suitability models to predict areas of high-quality breeding habitat for secretive marsh birds. Stevens and Conway (2018) used a hierarchical Bayesian implementation of a multi-season occupancy model (MacKenzie et al., 2002, 2006; Royle and Dorazio, 2008) to develop predictive species distribution models for marsh birds within their breeding ranges, where models were calibrated with detection-non-detection data collected over a 14-year period (from 1999 to 2012) from across each species' range within the continental U.S. Here, we build spatially-explicit versions of the optimally-predictive model for each of 12 marsh bird species (the models were selected using the logarithmic scoring rule calculated on out-of-sample testing data; Stevens and Conway, 2019a), and use these models to project breeding habitat suitability for marsh birds on DoD installations and adjacent lands. Using habitat associations developed in Stevens and Conway (2018, 2019a, 2019b), we predicted breeding-season occupancy across the U.S. with a spatially-explicit version of the optimal model for each species by inverting the logistic-regression equation, which included species-specific wetland and disturbance covariates:

$$\psi = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \dots + \beta_k X_k)}}$$

for k predictor variables (Table A1; Appendix A). Sets of predictor variables and the spatial extent over which each variable was measured were species-specific and maximized spatial predictive ability. Moreover, goodness-of-fit of the optimally-predictive model for each species was assessed by Stevens and Conway (2018), where the model for only

one species, the sora, provided evidence for possible lack of fit. Covariate rasters used for spatial prediction were created at their optimal extent for each variable and species by using moving-window analyses, and included wetland attributes described by the National Wetland Inventory dataset (NWI; delineation as of November 2014 with classification described by Cowardin et al., 1979), agricultural land cover and human development from the National GAP Land Cover Dataset Version 2 (GAP; Gergely and McKerrow, 2013; downloaded November 2014), and variables describing modification of watershed hydrology derived from the National Anthropogenic Barrier Dataset (NABD; Ostroff et al., 2013) and the National Hydrography Dataset Plus Version 2 (NHDPlusV2; McKay et al., 2012; http://www.horizon-systems.com/nhdplus/NHDPlusV2_home.php) (Table A1; Appendix A).

We obtained spatial data for each habitat and disturbance covariate to predict breeding-season occupancy probability for marsh birds at each 30-m raster pixel within a landscape. The NWI geospatial data represents vector polygons that delineate all existing wetlands, where codes are also used to describe attributes of each wetland polygon that include hydrology, geomorphology, substrate, and dominant forms of vegetation (Cowardin et al., 1979). We used 13 NWI variables to predict marsh bird occupancy as a function of wetland system-subsystems, wetland classes, water regimes, and special modifiers (Table A1; see Glisson et al., 2017 for additional description of NWI attribute categories). We also used a set of 6 land cover types related to agriculture and urbanization that were obtained from the GAP program (raster data with 30-m pixel resolution) to predict marsh bird occupancy (Table A1).

We rasterized all NWI polygon data at a resolution of 30-m pixels to have compatible spatial representation of NWI and GAP data, and also to facilitate their use as predictor variables in raster-regression models of marsh bird habitat suitability. Habitat suitability models included NWI and GAP variables measured over a range of spatial extents (Appendix A), where the extent of each covariate in each model was selected in order to maximize the spatial predictive capability of the model (i.e., the optimally-predictive scale; Stevens and Conway, 2018, 2019a, 2019b). Thus, we characterized each NWI and GAP variable over their optimal extent for each species: 100-m, 224-m, or 500-m (224-m produces a buffered area 5-times larger than 100-m, and 500-m produces a buffered

area 5-times larger than 224 m Fig. 1). To create covariate rasters for each NWI and GAP variable at the appropriate extent, we used circular moving-window analyses with radii of 100 m, 224 m, and 500 m to assign a value for each variable at each 30-m pixel within the landscape. The NWI and GAP covariate data are binary at the pixel scale (i.e., cover type present or not), thus moving window analyses quantified the proportional coverage of each variable over the appropriate spatial extent. Specifically, for each moving window analysis and each covariate, each 30-m raster pixel was assigned a value representing the proportion of raster cells within the window surrounding that pixel (100-m, 224-m, or 500-m) that was covered by that variable. Thus, while the original coverage data were binary, the covariates used in modeling were proportions that were continuous on the 0–1 scale. As such, each NWI and GAP covariate raster was characterized at a resolution of 30 m and represented proportional coverage values at one of the three spatial extents, where specific covariates and their measurement extents varied by species (Tables A1–A13).

We also included covariates that quantified human disturbance and modification of hydrology at much broader spatial extents within the watersheds surrounding each raster pixel (Fig. 1). Watershed-level covariates included proportional cover of agriculture and human development from GAP data described above, and hydrologic modification variables derived from NABD and NHDPlusV2 (Table A1). Hydrologic modification variables were continuous metrics and described disturbances related to storage capacity of dams and the restriction and interruption of natural flow regimes by water control structures within the watershed.

Watershed-level predictor variables were measured at two extents: catchments and networks. The extent of catchments were defined by the NHDPlusV2 dataset, where a catchment contains the direct drainage area for a given surface water reach. Thus, disturbance covariates measured over the extent of the catchment captured local watershed disturbances. However, local sites also receive water from upstream sources and are thus influenced by conditions further upstream within a watershed. To incorporate upstream dynamics in addition to local watershed characteristics, we calculated disturbance variables within a broader network of upstream wetlands (hereafter network). We defined

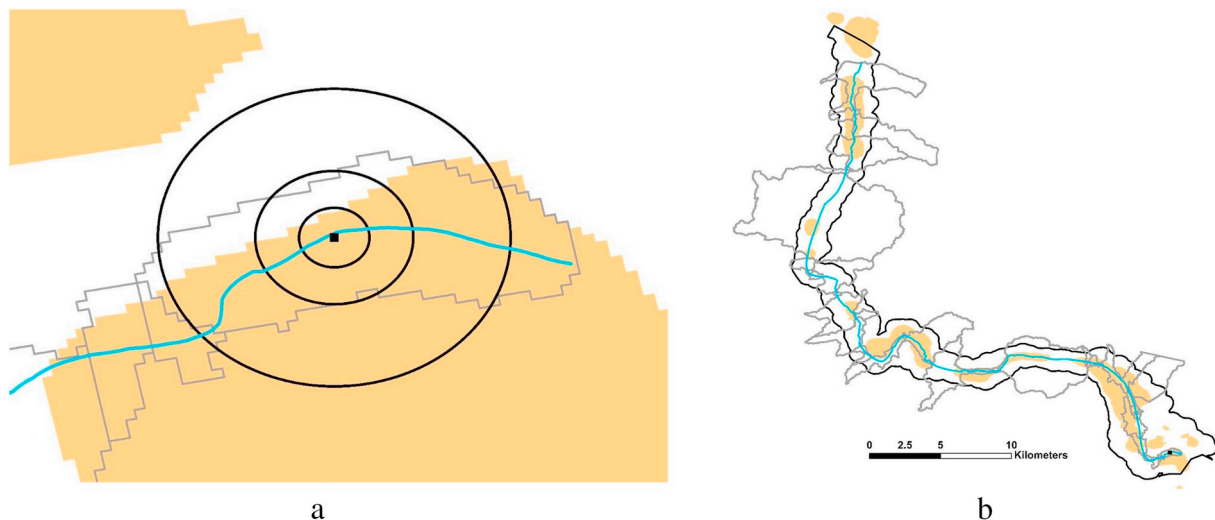


Fig. 1. Schematic example of spatial measurement extents for covariates used to predict marsh bird occupancy probability within and adjacent to military installations across the continental United States. Diagrams show how a habitat or disturbance covariate (e.g., hypothetical cover of agriculture indicated by tan color) was quantified at each scale for a given raster pixel (black square) within an example river (blue line) corridor. a) Moving window buffers (black circles) around each pixel were used to calculate the proportional coverage at the appropriate scale (100-m, 224-m, or 500-m radii) for every pixel within a landscape of interest, and proportional coverage of each variable within the catchment (grey outline) was also calculated. b) Proportional coverage (agriculture and human disturbance variables) or continuous measures (hydrologic disturbance variables) for each variable was calculated within the network of wetlands (black outline), where the upstream network assigned to each pixel generally crossed through multiple upstream catchments (grey outlines). Thus, catchment-scale measurements described attributes of the direct drainage area for a specific surface water reach, whereas network-scale measurements also described attributes of the network of wetlands upstream of a given location. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

wetland networks spatially by first identifying all wetland polygons (from NWI) that received water directly from sources contained within the catchment of interest, as well as upstream catchments, by selecting the wetland polygons that intersected the National Hydrography Dataset (NHD) flow line (vector data). We then iteratively selected adjacent (i.e., touching) wetland polygons until no additional wetlands were found, or until a marine or another riverine wetland was reached moving away from the flow line. We rasterized all of these network wetland polygons to a spatial resolution of 30-m, buffered these areas by 500 m, and defined the network as all of the 30-m pixels located within this 500-m buffer.

The relevant disturbance variables were measured for the catchment and network extents, and a given 30-m pixel was assigned a value for each of these extents based on its location within a catchment and network (Fig. 1). That is, each 30-m pixel was assigned a value for each broad-scale disturbance variable calculated over the extent of the catchment in which the pixel was located. For example, if maximum storage capacity of dams (Table A1) was being calculated at the catchment extent, then this metric would be calculated using all of the dams physically located within the catchment of interest (i.e., cumulative storage capacity of all dams). Similarly, each 30-m pixel was assigned a value for each broad-scale disturbance variable calculated over the extent of its network, where the network for a given pixel included all of the network wetlands in the same catchment, as well as within the catchments located upstream. Notably, variables calculated over the catchment and network extent result in the same value for all pixels within a catchment or network, respectively, which differs from the moving window analyses used to assign covariate values at the 100-m, 224-m, and 500-m extents. Lastly, the raw GAP land cover variables were binary at the pixel scale (described above), but were again calculated as proportional coverage metrics (continuous on 0–1 scale) when measured over the catchment and network extents. Specifically, each 30-m pixel was assigned a value for these variables based on the proportional coverage of each variable within the catchment or network to which that pixel resided.

We combined the predictive distribution model for each species with geospatial data for habitat and disturbance covariates to develop spatially-explicit models of marsh bird habitat suitability. Specifically, we developed raster regression models that used 30-m pixel raster data for each covariate as inputs to predict occupancy probability for each species at a 30-m resolution on all DoD lands within the continental U.S. as well as on lands adjacent to DoD installations. We used the analyses described above to create the appropriate raster datasets for each relevant NWI, GAP, and hydrologic modification covariate over the extent of the continental U.S. This allowed us to pair predictive distribution models with their appropriate covariate rasters to project marsh bird habitat suitability, and ensured identical measurement scales for the original data used to fit models (Stevens and Conway, 2018) and the covariate data used to project model predictions in space on DoD and adjacent lands. That is, all of the same variables from the optimally-predictive models, each measured in the same way for each species as Stevens and Conway (2018), were used to project habitat suitability in space to ensure that the regression coefficients estimated by Stevens and Conway (2018) were directly useable for predicting breeding-season occupancy probability of secretive marsh birds on DoD lands in this study. We used ArcMap 10.4.1 (ESRI, Redlands, CA) to conduct all spatial analyses, and used the raster calculator in the spatial analyst extension of ArcMap to create raster regression models. We built species-specific habitat suitability models within the boundaries of all existing DoD lands located within the breeding range of each species (defined by GAP models as described above). To evaluate relative local importance of DoD lands for marsh birds, we also compared suitability of habitat on DoD installations to that of adjacent lands by projecting the raster regression models within 10-km and 20-km buffers around each installation for 3 species of greatest concern: king rails, Ridgway's rails, and black rails. We focused on these species for comparisons of DoD and

adjacent lands because their populations have declined (Sauer et al., 2017, Stevens and Conway, 2019b), and they are species of high conservation concern. For example, Ridgway's rails are federally endangered under the U.S. Endangered Species Act, whereas king rails and the eastern subspecies of black rails have been petitioned for listing.

We ranked each DoD installation for each species according to the amount of high-quality breeding habitat contained within the installation boundaries, and also compared breeding habitat within DoD installations to that on adjacent properties for king rails, Ridgway's rails, and black rails. First, we calculated the value associated with the top 30% of the range of predicted occupancy probabilities across all DoD installations for each species (i.e., maximum pixel value - $0.3 \times (\text{maximum pixel value} - \text{minimum pixel values for predicted probabilities occurring on DoD lands})$). This allowed identification of pixels with the largest predicted occupancy probabilities for each species, and this value was used as a threshold to define locations with high-quality breeding habitat for each species at all sites. Specifically, we calculated the area of habitat with predicted occupancy probabilities greater than the top 30% threshold for each species at each location (defined as high-quality habitat), and then scaled these values by the total area of high-quality breeding habitat across all installations for that species to account for the large variation in sizes of the >500 DoD installations. We then ranked DoD installations for each species based on the scaled area of high-quality habitat (i.e., area of high-quality habitat on installation of interest divided by the total area of high-quality habitat summed over all installations), which ranked sites for each species based on the total proportion of high-quality habitat that was contained at each installation. Lastly, to identify installations that provided the best habitat for all species combined we summed the number of times each installation was ranked among the top five sites for any of the target species. To visually portray marsh bird habitat suitability at the best sites identified in this manner, we used a stacked distribution modeling approach that summed species-specific occupancy probabilities at each pixel (Calabrese et al., 2014).

To evaluate sensitivity of species-specific installation rankings to the threshold value used to define high-quality breeding habitat, we also replicated the above calculations and site rankings with higher (top 20% of range) and lower (top 40% of range) threshold values to be less (20%) or more (40%) inclusive in our definition of high-quality habitat. However, two species (least bitterns and soras) had left-skewed distributions of predicted occupancy among pixels on DoD sites, where pixel values aggregated at larger values (i.e., mean and median pixel values very close to the maximum value of all pixels). Use of the three thresholds as defined above to characterize high-quality habitat for these 2 species thus resulted in characterizing most pixels as high quality, and consequently site rankings based primarily on the area (i.e., the number of pixels) of an installation. To avoid characterizing marginal habitat as high-quality habitat for these 2 species, we ranked DoD sites as described above, but used 3%, 5%, and 7% of the range of predicted values to define high-quality breeding habitat (instead of 20%, 30%, and 40%) for least bitterns and soras. The thresholds for defining high-quality habitat were thus more strict for least bitterns and soras, yet our sensitivity analyses demonstrated that site rankings for these species were relatively insensitive to the range of thresholds considered (see Results and Discussion, and Appendix B). Thus, the important conclusions for these species relative to our study objectives were not substantively affected (Appendix B). Lastly, we compared the amount of breeding habitat within DoD lands to that of adjacent properties (within 10-km and 20-km buffers) for the 3 species of greatest concern by comparing the fraction of pixels classified as high-quality habitat (using the 30% threshold) within and adjacent to all DoD installations.

3. Results and discussion

Ranking of DoD installations demonstrated geographic aggregation of high-quality breeding habitat, both among and within species of

marsh birds. Most high-quality habitat was located on installations along the eastern seaboard and within the southern U.S. Additional important sites also occurred in the southwestern U.S. and some high-quality habitat was also located on installations in the midwestern U.S. (Table A2; Fig. 2). DoD installations in the southeast and along the eastern seaboard included the best habitat for 7 species (least bittern, American coot, common gallinule, purple gallinule, king rail, clapper rail, and black rail), whereas the best habitat for 2 species (Ridgway's rail, and Virginia rail) was in the western U.S. and 3 species (American bittern, pied-billed grebe, and sora) had breeding habitat spread among installations across the U.S. (Table A2; Appendix B). DoD installations in GA, FL, NC, or a combination of these states had the best breeding habitat for the most species (least bitterns, American coot, common gallinule, clapper rail, and black rail; Appendix C). Installations in NC, MN, and NJ had the best breeding habitat for king rails, and installations in LA, MS, TX, and FL had the best breeding habitat for purple gallinule (Appendix C). In contrast, the top 5 installations for Virginia rails were located in CA and NV (Appendix C). Nearly all (>99%) of the quality habitat for Ridgway's rail on military installations was located on one installation in AZ (Appendix C). The best breeding habitat for pied-billed grebes and American bitterns was widely distributed, like the species themselves, and occurred at installations located in GA, IN, MN, NC, NJ, NV, TX, and VA (Table A2; Appendix C). Importantly, the ranking of DoD installations for each species was relatively insensitive to the threshold value used to define high-quality habitat. While the specific order of the top installations did change in some instances, most sites included in the top 5 for each species remained in the top 5 (Appendix B) as the threshold value changed, demonstrating a robust identification of important installations by species.

In addition to being geographically aggregated at broad scales, only a few installations stood out as having the majority of high-quality breeding habitat for each species. Five or fewer installations had nearly all high-quality habitats on DoD lands for 9 of 12 species (Appendix C; Table A2). Even for the 3 species where the best habitat was dispersed over more sites (least bittern, clapper rail, and sora), the majority of breeding habitat was located at ≤ 10 installations (Appendix C). Moreover, the area of habitat classified as high-quality within the top five sites was sufficient to maintain breeding marsh birds for all species (range = 95–26,645 ha; Table A2). The fraction of the land classified as high-quality breeding habitat was also greater on DoD installations than on adjacent lands for 2 of the 3 highest-priority marsh bird species. The fraction of high-quality habitat was 1.5 times and 1.8–2.2 times greater on installations than on adjacent lands for Ridgway's rail (within installations: 0.003; 10-km buffer: 0.002; 20-km buffer: 0.002) and black rail (within installations: 0.020; 10-km buffer: 0.009; 20-km buffer:

0.011), respectively. However, the fraction of area classified as high-quality habitat for king rails was 3–3.5 times greater on adjacent lands than on installations (within installations: 0.004; 10-km buffer: 0.012; 20-km buffer: 0.014), and the overall proportion of pixels classified as high-quality habitat across all sites was small for all three species (0.002–0.020), indicating that high-quality habitat was rare both within and adjacent to most military sites.

Whether considering marsh birds as a group or the 3 highest-priority species individually (Ridgway's rail, king rail, black rail), a relatively small number of installations provided the best-quality habitat for these birds. For example, 3 installations provided the best habitat for all species combined (Fig. 3; Table A3); Fort Stewart (GA), the Marine Corps Base Camp Lejeune West (SC), and the Dare County Range (NC) were all ranked among the top 5 sites for the most marsh birds (5 species each). Marsh bird habitat quality changed along an east-west gradient at Fort Stewart (higher in the east; Fig. 3A), was concentrated in the western portion of Camp Lejeune (Fig. 3B), and was concentrated along the southeastern and western edges of Dare County Range (Fig. 3C). Marine Corps Base Camp Lejeune West and Dare County Range also ranked as the top installations for king rails and black rails, and together contained >75% of the best habitat for these species (Table A2; Appendix B). The best habitat for king rails and black rails at these sites was also located in similar locations as the best habitat for all species combined (e.g., concentrated in the western portion of Camp Lejeune West; Figs. B12–B13), indicating cumulative benefits of conserving habitats specifically for these priority species. In contrast, the vast majority of the top installation for Ridgway's rail (Yuma Proving Ground) provided poor habitat, where high-quality habitat was concentrated over a relatively small area along the Colorado River (Fig. B14).

Although a small number of sites contained the most habitat for each species, the species-specific results depended on the spatial distribution of their important habitat features. Thus, specific areas identified as important for each species were a direct result of local conditions relative to species- and scale-specific habitat relationships (Appendix A). Yet, the existence of sites and areas within sites that were important for suites of marsh birds indicates some commonalities in the spatial distribution of important habitat features within and among DoD installations. For example, the effects of agriculture and human development on marsh birds, including priority species like king rails and black rails, were often negative (Stevens and Conway, 2018, 2019b; Appendix A). There was generally a positive effect of naturally vegetated wetlands (e.g., scrub-shrub wetlands) and often negative consequences of hydrologic modification on habitat quality (Appendix A). As a consequence of these similarities, both individual installations (e.g., Marine Corps Base Camp Lejeune West) and areas within those

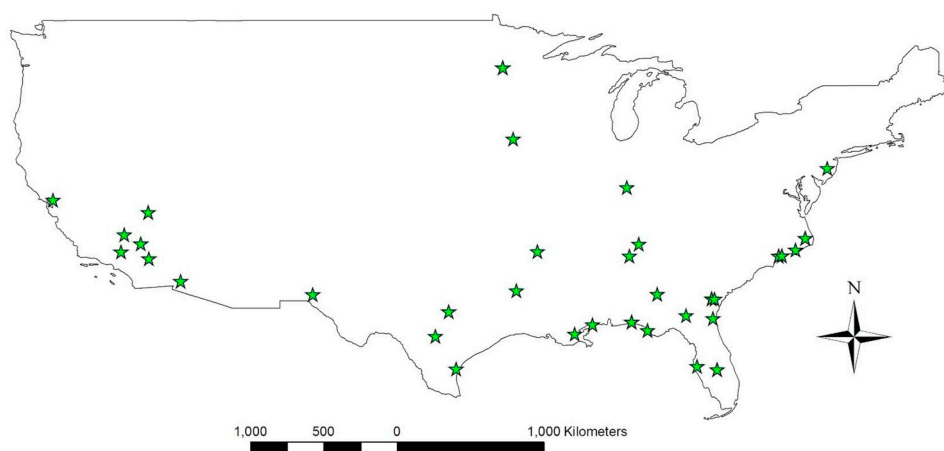


Fig. 2. Locations of DoD installations containing high-quality breeding habitat (ranked in the top 5 among all installations) for at least one of the 12 secretive marsh birds considered in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

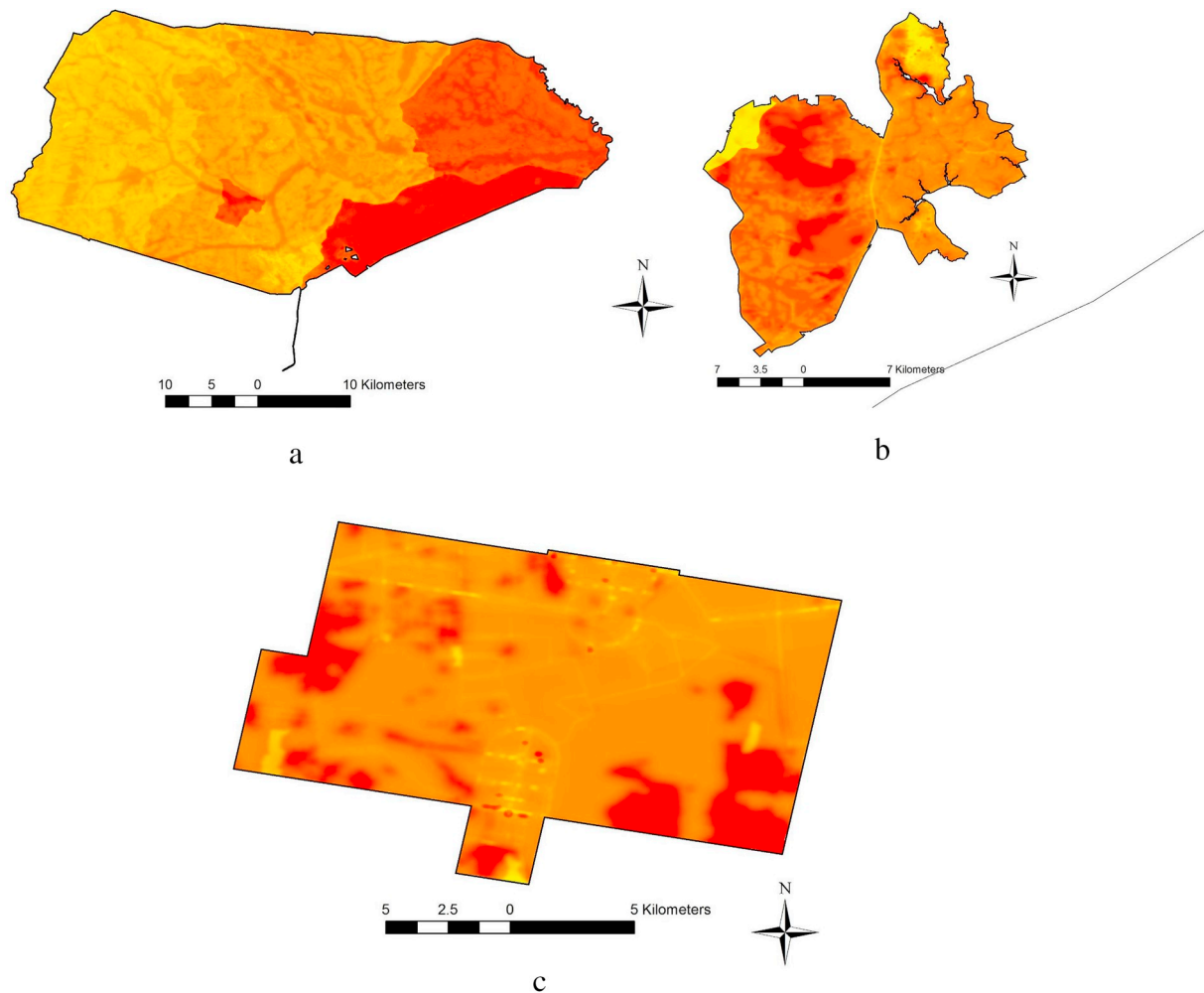


Fig. 3. Maps of the spatial distribution of high-quality habitat for secretive marsh birds at the most important DoD installations: a) Fort Stewart (GA), b) Marine Corps Base Camp Lejeune West Site (SC), and c) the Dare County Range (NC). Colors depict relative habitat suitability for all marsh bird species (darker is better) using stacked distribution models, where per-pixel predicted occupancy probabilities were summed across species. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

installations (e.g., western portion of that site) with a larger area of intact natural wetlands with less hydrologic disturbance that are farther from agriculture and human development provided high-quality habitat for multiple species of marsh birds.

This work represents the first effort to project habitat suitability for secretive marsh birds on military installations across the continental U. S. Concerns over population declines for secretive marsh birds has been expressed for >30 years (Eddleman et al., 1988), and many secretive marsh birds are species of national concern (Tacha and Braun, 1994; Conway and Eddleman, 2000; Conway and Timmermans, 2005; U.S. Fish and Wildlife Service, 2005, 2008; Tozer, 2016). Some of these species are also experiencing continental-scale contraction of their breeding ranges (Stevens and Conway, 2019b), or are listed or under consideration for listing under the Endangered Species Act. Consequently, many of these species have long been the focus of conservation and management, and the information presented herein is a step towards proactive management of breeding habitat for these birds on lands administered by DoD. These results will help guide habitat conservation efforts on federal lands, and also represent one of the most thorough broad-scale depictions of habitat suitability conducted for this group of birds.

Our models predicted the spatial distribution of breeding habitat suitability for secretive marsh birds within and among DoD installations, which provides information needed to improve both conservation and

military functioning at DoD sites. Our analyses imply that continental-scale efforts to conserve breeding populations of most secretive marsh birds on DoD lands should target a relatively small number of installations (e.g., Fort Stewart, Camp Lejeune, Dare County Range, Elgin Air Force Base, Avon Park Air Force Range, Yuma Proving Ground, etc.; Appendices A-C), and that these sites also provide high-quality habitat for the most sensitive species. Our results also suggest that only a few installations provide high-quality habitat for a given species, and that these sites likely harbor sufficient amounts of habitat to support breeding secretive marsh birds. Collectively, these results imply that the few installations containing high-quality habitat will play a key role in DoD conservation efforts for each species. This work thus fills an information gap necessary for pragmatic consideration of secretive marsh bird conservation at the installation level. More specifically, installation-level INRMPs provide the planning tool to integrate each species into conservation and management efforts at relevant sites. The INRMPs could include, for example, guidelines to conserve important habitat in specific areas (e.g., western portion of Camp Lejeune) or recommendations for avoiding disturbance of key areas during the breeding season. This would allow for training exercises and other military activities in less important locations at an installation or during periods of the year less vital to marsh birds, and thus help minimize conflict between military functioning and the needs of secretive marsh birds.

In addition to identifying specific DoD installations that are likely to

provide high-quality habitat for each species, we identify many more installations that are *not* likely to harbor high-quality habitat. Specifically, this work implies that most installations provide little high-quality habitat for secretive marsh birds, including a majority of installations in the northwest and midwestern regions of the U.S. This distinction is also key to minimizing conflicts between marsh bird conservation and military readiness over broad scales, as it implies that incorporation of secretive marsh birds into site-level INRMPS may be less important at the majority of sites, and more important at a much smaller number of installations. The majority of installations may therefore deem it unnecessary to include marsh birds in their INRMPS, thus alleviating conflict that might have existed between site-level activities and marsh bird conservation.

Lastly, this work provides baseline predictions of the locations of high-quality habitat for secretive marsh birds that currently exists on DoD lands, as well as a frame of reference for habitat suitability on DoD lands relative to surrounding areas. This amounts to a broad-scale baseline of marsh bird habitat that can be used for developing future monitoring programs, measuring effects of management and conservation efforts over time, and predicting the likely effect of future management decisions on individual species at each site. This information should support existing conservation programs such as Partners-in-Flight and other species-at-risk programs, and should enable a multi-species approach to protecting habitat for secretive marsh birds across all DoD installations. These models also provide a frame of reference for the suitability of habitat on DoD lands relative to surrounding properties, and thus their local value in providing habitat for the highest-priority species. For example, our results suggest that breeding habitat suitability on DoD sites is greater than on surrounding properties for black rails and Ridgway's rails and, hence, DoD is likely maintaining important local breeding habitat for these rare birds.

4. Conclusions

We fill an information gap regarding the spatial distribution of high-quality breeding habitat for secretive marsh birds on DoD installations across the continental U.S. Our models can be used to facilitate integration of secretive marsh birds into site-level management at the relatively small number of installations that contain high-quality breeding habitat (e.g., Fort Stewart, Marine Corps Base Camp Lejeune West, and Dare County Range), but also facilitate military readiness and flexibility by identifying many more installations that are less valuable as marsh bird breeding habitat. Consequently, this work helps to identify specific DoD installations that are *not* likely to harbor high-quality breeding habitat for priority species (Tables C1–C12) and will help minimize conflicts between military needs and the conservation needs of marsh birds. Our habitat models and the resultant lists (Table A2; Appendix C) and maps (Figs. 2 and 3; Appendix B) of installations with the highest-quality breeding habitat can thus aid in development of INRMPS that explicitly incorporate marsh birds into management planning at specific military installations that provide high-quality breeding habitat. This information can also help with strategic and scenario planning for military activities on DoD sites that are needed to ensure military readiness. These results therefore make it easier to ensure that management and conservation responsibilities for marsh birds are met, while also helping DoD more effectively plan and ensure their mission is not compromised. Lastly, our analyses and models focused on predicting high-quality breeding habitat on military installations, but sites lacking breeding habitat may still be relevant for conserving migratory and winter habitat for wetland birds. Additional work is therefore needed to identify habitat for marsh birds for the remainder of their annual cycle.

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Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2019.109664>.

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