Kirtland's Warbler Winter Habitat Changes Across the Bahamian Archipelago in Response to Future Climate-condition Scenarios

Daniel M. Wolcott[1,2,*], Deahn M. Donner[3], Donald J. Brown[4], and Christine A. Ribic[5]

Abstract - Changing climate may impact species through several processes, including phenologic shifts in seasonal timing of food supplies. These temporal changes can create trophic mismatches for species during major life-cycle events such as migration. For long-distance Neotropical–Nearctic migratory songbirds, body condition prior to migration is related to quality and quantity of food supply, which is a function of precipitation and temperature conditions on the wintering grounds. We assessed how future climate-change scenarios might affect wintering habitat of *Setophaga kirtlandii* (Kirtland's Warbler) on the Bahamian Archipelago. We used ensembles of general-circulation models to project precipitation and temperature patterns across the archipelago over the winter period, from baseline average until the end of the century. We also used topography layers to define Kirtland's Warbler winter habitat (open lands) and then made landcover-loss projections for open lands using 1- and 2-m sea-level–rise scenarios. Our results indicate that the Bahamian islands used by Kirtland's Warbler will become warmer and wetter during the winter months, except during March when central islands are predicted to go through a drying trend. Moreover, our models predict that the greatest habitat loss of coastal open land due to sea-level rise will occur on the northern, lower-elevation islands. If we consider both potential changes in habitat quality and quantity from changing climate, the north-central islands, which currently contain the majority of the wintering population, are likely the critical islands on which to focus climate-adaptation strategies. To help land managers spatially plan for habitat alteration, continued processing of high-resolution imagery is necessary for finer assessments of potential habitat loss, changes in habitat quality, and redistribution of habitats across this island system in response to changing environmental conditions and sea-level rise.

Introduction

Increasing variation in global temperature and precipitation cycles has led to widespread impacts within terrestrial and marine communities, which has been documented across many natural systems (IPCC 2014). Increasing surface-

[1]Wisconsin Cooperative Wildlife Research Unit, Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, WI 53706, USA. [2]Current address - University of Central Missouri, Department of Biology and Agriculture, Warrensburg, MO 64093, USA [3]Northern Research Station, US Forest Service, Rhinelander, WI 54501, USA.[4]School of Natural Resources, West Virginia University, Morgantown, WV 26506, USA, and Northern Research Station, US Forest Service, PO Box 404, Parsons, WV 26287, USA. [5]US Geological Survey, Wisconsin Cooperative Wildlife Research Unit, Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, WI 53706, USA . [*]Corresponding author - wolcott@ucmo.edu.

temperature trends and increasing frequency of extreme events from precipitation changes (e.g., drought or flooding) have explained broad-scale distributional shifts of plants and animals (Parmesan and Yohe 2003, Scavia et al. 2002). Increasing temperatures are also predicted to result in sea-level rise from terrestrial ice melt and thermal expansion of seawater that may impact terrestrial resources through direct habitat loss in coastal areas (Nicholls and Cazenave 2010).

Observed phenologic shifts in seasonal timing of food as a consequence of these environmental changes can create trophic mismatches for species during major life-cycle events such as migration (Both et al. 2009, Mayor et al. 2017, Saino et al. 2011). For long-distance migratory species, productivity and survivorship on the breeding grounds is dependent on body condition prior to spring migration on the wintering grounds (Cooper et al. 2015; Studds and Marra 2005, 2007). If nutritional resources are limited and body condition is poor prior to spring migration, productivity and survivorship can be reduced on the breeding grounds through carry-over effects (Bearhop et al. 2004; Ockendon et al. 2014; Rockwell et al. 2012, 2016). Resource availability is a function of the quality and quantity of food supply, which is moderated by precipitation and temperature conditions, as well as habitat availability (Brown and Sherry 2006, Wunderle et al. 2014).

Setophaga kirtlandii (Baird) (Kirtland's Warbler) is an endangered Neotropical–Nearctic migrant that winters almost exclusively within the Bahamian Archipelago and feeds on fruits of a variety of shrubs as well as arthropods that are present in open and disturbed landcover types prevalent in the archipelago (Sykes and Clench 1998, Wunderle et al. 2010). While overwintering on the archipelago, the quantity and quality of food resources can be limited through multiple pathways, thus reducing body condition and potentially reducing productivity and survivorship of this endangered species. One possible pathway for affecting food-resource quantity is through reduction in habitat availability due to sea-level rise. The Bahamian Archipelago is a low-lying island chain that is particularly vulnerable to landcover loss due to sea-level rise (Dasgupta et al. 2009). These Caribbean islands are projected to sustain sea-level changes greater than eustatic global sea-level rise (Bamber et al. 2009). Increased loss of habitat can negatively influence food availability. Loss of habitat can increase bird density above carrying capacity and alter habitat composition, further reducing body condition through increased competition (Cooper et al. 2015).

Changes in environmental conditions can also influence the quality of the food supply (Wang and Camp 2000), and precipitation has been shown to have a positive influence on the abundance of fruits preferred by the Kirtland's Warbler (Wunderle et al. 2014). Further, late winter (March) precipitation on the wintering grounds prior to migration has been linked to both Kirtland's Warbler survival during migration and reproductive success on the breeding grounds (Rockwell et al. 2012, 2016; Wunderle et al. 2014). Within a range of March precipitation values from 10 mm to 50 mm, there has been a documented increase in Kirtland's Warbler fecundity of 0.23 fledglings per 10 mm of precipitation (Rockwell et al. 2012). Temperature may also play a role in influencing the available food

supply (Wang and Camp 2000); however, less is known regarding the relationship between temperature and Kirtland's Warbler reproductive success. Arthropod fitness (measured as intrinsic rate of population growth) is strongly related to temperature, with the most deleterious effects of temperature occurring in tropical arthropods (Deutsch 2008). Within the latitudinal range of the Bahamas, the thermal optimum for arthropods is around an annual temperature of 28 ºC (Deutsch 2008). Temperature increases above the thermal optimum have a negative influence on arthropod abundance, further compounding body-condition deficiencies of Kirtland's Warbler prior to migration.

This information, combined with previous research that used high-resolution satellite imagery to identify Kirtland's Warbler wintering habitat on Eleuthera Island (Helmer et al. 2010), creates an opportunity to explore how predicted precipitation and temperature changes and predicted sea-level rise might interact to impact habitat quality and quantity on wintering grounds and, thus, population viability of the Kirtland's Warbler (MDNR et al. 2014). A better understanding of the spatial extent of potential habitat changes along the Bahamian Archipelago under future climate-change scenarios would enhance the ability to refine population-viability assessments that incorporate winter conditions (e.g., Brown et al. 2017) and help land managers plan and mitigate predicted future changes.

Our objectives were to project changes in Kirtland's Warbler wintering-habitat quality and quantity due to predicted changes in precipitation and temperature under future climate-change scenarios in the winter (October–April) for the nearer (2050) and longer term (2100), as well as habitat loss due to sea-level rise within the Bahamian Archipelago. Specifically, we focused on islands where Kirtland's Warblers have been documented and their preferred wintering habitat is presently found. We also discuss potential implications to Kirtland's Warbler wintering populations as they relate to known limitations to habitat quality and quantity within the focal islands of the Bahamian Archipelago.

Field-Site Description

Historically, Kirtland's Warblers have been found throughout the Bahamian Archipelago; however, the north and central islands are the most highly occupied and were the islands of focus for this study. The northern focal islands were Grand Bahama, Abaco, and Bimini, and the north-central focal islands were Eleuthera, New Providence, and Andros, which together accounted for 79% of reported Kirtland's Warbler observations prior to 1998 (Haney et al. 1998, Sykes and Clench 1998). The central focal islands were Cat, Long, and San Salvador. Recent surveys have documented relatively large numbers of Kirtland's Warblers on these islands (D. Ewert, The Nature Conservancy, Lansing, MI), with additional support for disproportionate use on Eleuthera, Cat, Long, and San Salvador from geolocator data (Cooper et al. 2017). Most of the northern islands in the archipelago are mesic, pine-dominated islands, while the central and southern islands in the archipelago are drier and covered by coppice (dense scrub habitat). Floristically, the islands

share many plant species, though the abundance and distribution of plant communities vary between islands (Sykes and Clench 1998).

Methods

Projected precipitation and temperature changes

We focused the precipitation and temperature-change analyses on the early winter period (November–January), middle–late winter (February–April), and the month of March. The abundance of fruits and arthropods preferred by Kirtland's Warbler is highest in the early winter period and lower in the middle-late winter period (Wunderle et al. 2014). We focused on the month of March because March precipitation has been identified as the strongest climatic predictor of Kirtland's Warbler annual survivorship and fledgling production on the breeding grounds (Rockwell et al. 2012, 2016).

We used the program SimCLIM 2013 (CLIMsystems Ltd., Hamilton, New Zealand) to project percent changes in average winter precipitation and temperature in 2050 and 2100 relative to baseline precipitation and temperature conditions (1986–2005) for the focal islands within the Bahamian Archipelago. We used SimCLIM because it contains an easy-to-use interface for selecting models, time periods, and scenarios for projecting future climate conditions. In addition, when projecting climate changes at small spatial scales (e.g., Bahamian islands), it is necessary to use fine-resolution downscaled data because the spatial resolution of global climate models is too coarse for accurate local-scale predictions (Busuioc et al. 1999, Laflamme et al. 2016). Although many options exist for obtaining downscaled future-climate projections in the US (e.g., PRISM Climate Group, Corvallis, OR), publicly available fine-resolution downscaled projections were lacking for the Bahamian Archipelago. The spatial data we used were derived from the most current general circulation models (GCM) developed for the 5th Coupled-model Inter-comparison Project (CMIP5; Taylor et al. 2012), which corresponds to Assessment Report 5 of the IPCC (IPCC 2013). We employed pattern scaling (CLIMsystems Ltd. 2013, Tebaldi and Arblaster 2014) to statistically downscale these GCM data from 0.5° x 0.5° (~50 km x 50 km) resolution to 0.008° x 0.008° (~1 km x 1 km) resolution for the Bahamian Archipelago. We obtained the baseline precipitation and temperature data from the 20-y observation period between 1986 and 2005 (IPCC 2013).

The IPCC recommends using GCM model ensembles to project climate changes because ensembles capture variability among models (an estimate of uncertainty in projections), and ensemble averages buffer against unusually low or high estimates from a single model relative to other models (IPCC 2010). Thus, we used an ensemble of 40 GCMs for this study. We chose mid-equilibrium climate-sensitivity levels for the models (equilibrium-climate sensitivity represents the expected atmospheric warming in response to a doubling of CO_2 [IPCC 2013]). To account for multiple potential future emissions scenarios, we used the representative concentration pathways (RCP) 4.5 and 8.5. The RCP4.5 scenario represents a potential future

pathway where CO_2 emissions stabilize and then decrease over the next century, and the RCP8.5 scenario represents a potential future pathway where CO_2 emissions continue to increase over the next century (Moss et al. 2010).

For each cell, SimCLIM calculates the median value from the ensemble models (CLIMsystems Ltd. 2013). We also calculated the lower 10th percentile and upper 90th percentile values for GCM model estimates and the interquartile range. The interquartile range is a non-parametric measure of uncertainty. The 10th and 90th percentiles are commonly used as a measure of uncertainty among models for ensemble projections (e.g., Booth et al. 2013, Burton et al. 2010).

Projected Kirtland's Warbler habitat loss

Kirtland's Warblers primarily forage in early-successional habitat that supports preferred fruiting shrubs and arthropods. Pine woodlands used by Kirtland's Warbler typically have a well-developed shrub layer with scattered openings (Sykes and Clench 1998); however, much of the Caribbean pine-forest understory is very short with a reduced shrub layer due to frequent fires. Landcover types that encompass this early-successional habitat are fairly broad and may include any area that was disturbed (e.g. fire, grazing, or anthropogenic clearing) 3–28 years prior to use (Wunderle et al. 2010). High-resolution landcover data that can be used to specifically define Kirtland's Warbler wintering habitat are only available for Eleuthera (Helmer et al. 2010). Therefore, for the focal islands that did not have high-resolution landcover data available, we defined Kirtland's Warbler habitat as a broad "open land" category consisting of any land that was not defined as forest, urban, or water within the available GIS layers.

We employed ArcMap 10.3 (ESRI 2014) to define open land and then project open-landcover loss due to sea-level rise in the Bahamas. There are currently no publicly available high-resolution LIDAR data sets for the Bahamas from which to develop a digital elevation model (DEM). Instead, we used a digital surface model (DSM) developed by the Shuttle Radar Topography Mission (SRTM), which estimated surface elevation at 30-m pixel resolution in the Bahamas (Farr et al. 2007). A DSM is based on the surface height of the landscape, rather than the earth surface, as determined by bare earth (measured by a DEM). Gesch et al. (2012) used known elevation points to assess vertical accuracy of SRTM and other DSM layers compared to National Land Cover Data landcover classes in the conterminous US. They reported that the mean elevation error in open land (which included shrub/scrub land) was +0.16 m, whereas the mean elevation error in forest and developed land was +2.40 m and +0.81 m, respectively.

The mean elevation error in forested and developed land could confound projected sea-level rise considered in this analysis; thus, it was necessary to remove pixels that included forested and developed land from the analysis. To identify forested land, we used a tree-canopy–cover raster layer developed by Hansen et al. (2013), which represents forest cover in the year 2000, at a cell resolution of 30 m. We used the MODIS global urban-extent data set (Schneider et al. 2009) to identify urban landcover. The MODIS cell resolution is 500 m, and urban area is defined as >50% of the area in each cell consisting of human-constructed features. We

overlaid the tree canopy and urban landcover raster layers with the 30-m resolution DSM, clipped areas of overlap between the layers, and subsequently removed them from any further analyses. We classified the remaining land as open-land habitat.

To estimate the impact of the sea-level rise on the open land, we used the projections by the IPCC (1-m rise; Church et al. 2013) and National Oceanic and Atmospheric Administration (2-m rise; Parris et al. 2012). We reclassified the clipped DSM twice, at elevations ≤1 m and at ≤2 m. We converted these reclassified raster layers to vector layers as non-simplified polygons for each pixel, and extended the polygon area when multiple neighboring pixels existed; only polygons touching the ocean layer were included in the landcover-loss analysis. To account for inundation of inland water bodies that would occur as a result of sea-level rise, if an inland water body became connected with the ocean after a projected sea-level rise event, we considered the water body to be part of the ocean, and we included in the landcover loss analysis any reclassified polygon that touched this water body. We identified inland water bodies using the SRTM water-body data set at a cell resolution of 30 m (USGS 2015). We assessed the relationship between the proportion of open lands that might be lost to sea-level rise and the average elevation of open lands with Spearman's rho (Conover 1999).

We focused on Eleuthera to determine how much of the open-land loss might be specifically Kirtland's Warbler winter habitat. We reclassified the high-resolution layer from Helmer et al. (2010) as acceptable Kirtland's Warbler wintering habitat: cattle pasture with up to 60% woody cover (coded as 4 and 5 in Helmer et al. 2010), naturally disturbed stands of palms (coded as 53–54), any land area characterized as goat-grazed (coded as 30–35 and 37), tidally flooded mangrove (coded as 58), and coastal vegetation (coded as 59). We could have included other disturbance types; however, many of these landcover types were primarily located within the Hansen et al. (2013) forest layer and would not have been considered open landcover. We converted the reclassified Kirtland's Warbler wintering habitat to polygons and assessed the topography of these areas by calculating zonal statistics (i.e., descriptive statistics on spatial layers) for the elevation data within the open landcover DSM that overlapped the wintering habitat. We then compared this information with zonal statistics from the available open land on Eleuthera and also assessed how much Kirtland's Warbler wintering habitat would be lost on Eleuthera due to sea-level rise.

Results

Baseline precipitation and temperature

For baseline precipitation data (1986–2005), totals across the Bahamian Archipelago varied from 96 mm to 222 mm (mean = 156 mm) during early winter, 78 mm to 241 mm (mean = 127 mm) during middle–late winter, and 17 mm to 88 mm (mean = 36 mm) during March. In general, total annual precipitation decreased from northern islands to southern islands (Fig. 1a). The focal islands received similar amounts of precipitation during the early winter (Appendix 1). In middle–

late winter as a whole and also during just March alone, the northern focal islands received slightly more than the average precipitation for all islands, while the north-central and central focal islands became drier (Appendix 1).

For baseline mean annual temperature data (1986–2005) across the Bahamian Archipelago, values varied from 23.8 °C to 26.5 °C (mean = 25.1 °C). Average temperature varied from 20.6 °C to 24.9 °C (mean = 22.9 °C) during early winter, 21.1 °C to 24.9 °C (mean = 23.1 °C) during middle–late winter, and 21.1 °C to 25.0 °C (mean = 23.1 °C) during March. In general, average annual temperature increased from the northern islands to the southern islands (Fig. 1b). The central focal islands were consistently warmer than the northern focal islands throughout the winter season (Appendix 2).

Projected precipitation changes

Projections in RCP4.5 predicted that near-term precipitation (2050) will increase from baseline values (Appendix 1); however, there were seasonal changes in which islands became wetter. In early winter, the central focal islands were predicted to be wetter than the north and north-central islands, while in middle–late winter, the north-central islands were predicted to be wetter compared to the other focal islands (Appendix 1). Focusing specifically on March, the northern and north-central islands were predicted to become wetter, while the central focal islands became drier (Appendix 1). The predicted precipitation patterns for the focal islands in the longer-term (2100) based on RCP4.5 were similar to the mid-term (2050) patterns, but with larger values (Appendix 1). For RCP8.5, the direction and spatial pattern of the projected changes for winter precipitation
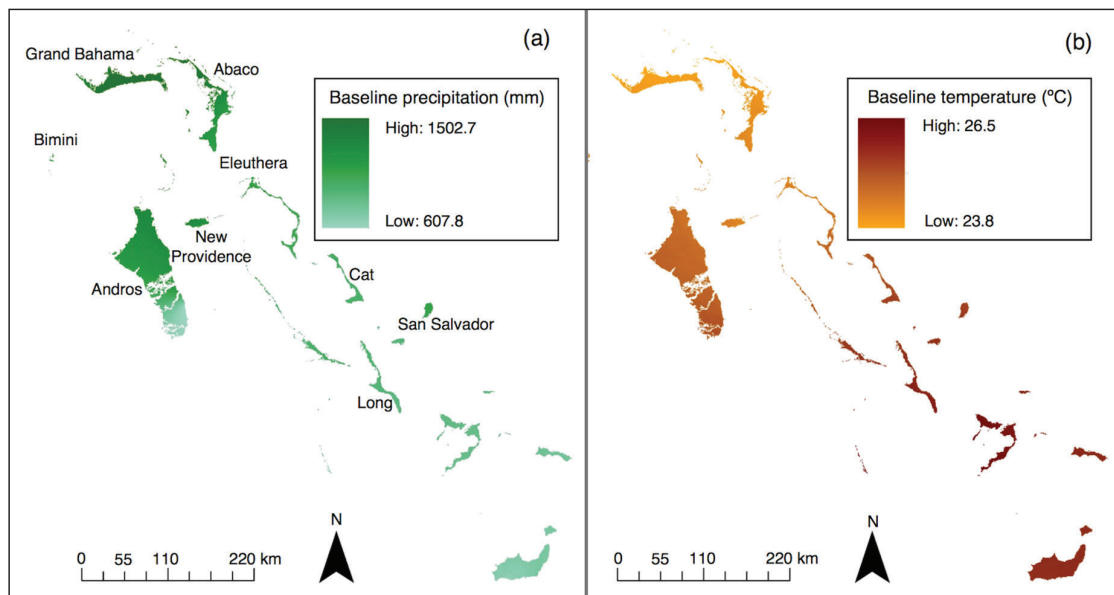

Figure 1. (a) Baseline annual precipitation and (b) mean daily temperature for the Bahamian Archipelago, derived from the 20-y observation period between 1986 and 2005. The labeled islands in (a) are the focal islands used by Kirtland's Warbler (*Setophaga kirtlandii*) in the winter.

on the focal islands did not differ from RCP4.5, but the magnitude of projected changes increased (Appendix 1).

Projected temperature changes

In near-term (2050) temperature projections from RCP4.5 analyses, early-winter temperature change was the same across the focal islands, with increasing temperatures on all islands (Appendix 2). The projected temperature in 2050 for RCP8.5 was similar to the RCP4.5 projections, except that the changes were slightly larger (Appendix 2). Based on RCP4.5, changes for temperature by 2100 varied from 1.3% to 1.4% in early winter and 1.2% to 1.3% in middle–late winter as a whole as well as just in March. The 10th-percentile projections for changes in March temperature varied from 0.9% to 1.1%, and the 90th-percentile projections varied from 1.7% to 2.0%. Early-winter temperature change was the same across the focal islands, with all islands increasing in temperature (Appendix 2). The projected temperature change in 2100 for RCP8.5 was similar to the RCP4.5 projections, except the changes were almost twice as large (Appendix 2).

Projected open-habitat loss

Total land area (excluding inland water bodies) for the archipelago consisted of 12,522.4 km^2. After removing forested and developed lands, the remaining open land consisted of 8357 km^2 (66.7% of total land area). A projected 1-m rise in sea level removed 614.0 km^2 (7.3% of open-land area), thus reducing available open land across the Bahamian Archipelago to 7742.9 km^2. A projected 2-m rise in sea level removed 1127.8 km^2 (13.5%) of open land, further reducing open land on the Bahamian Archipelago to 7229.1 km^2.

There was considerable variation in loss of open land on the focal islands; San Salvador (central island) had the lowest loss (<1%) and Abaco (northern island) had

Table 1. Land-area information for 9 focal islands and archipelago-wide projections of landcover loss due to 1- and 2-m sea-level rise (SLR) events on the Bahamian Archipelago. Focal islands are ordered by elevation of open lands. Total area represents the total island area excluding inland water bodies. Open habitat represents available open land after forest and urban land cover and inland water bodies were removed. Values in parentheses (%) for open habitat, 1-m SLR land-loss, and 2-m SLR land-loss are percentages of denoted land area (with respect to Total area for Open habitat and Open habitat for both SLR scenarios).

Island	Total area (km^2)	Open habitat (km^2) (%)	Mean open habitat elevation (m) (SD)	1-m SLR land loss (km^2) (%)	2-m SLR land loss (km^2) (%)
Abaco	1432.4	809.90 (56.5)	2.67 (2.73)	269.5 (33.3)	385.4 (47.6)
Grand Bahama	1179.7	819.68 (69.5)	3.03 (2.60)	175.3 (21.4)	335.1 (40.9)
Long	478.2	191.70 (40.1)	3.53 (3.88)	30.2 (15.7)	66.6 (34.8)
Cat	369.0	79.46 (21.5)	4.28 (3.90)	6.5 (8.2)	8.3 (10.4)
Andros	5663.7	4164.80 (73.5)	4.60 (2.66)	32.0 (0.78)	104.5 (2.5)
San Salvador	155.1	60.26 (38.8)	6.63 (2.73)	0.1 (0.2)	0.3 (0.6)
Eleuthera	467.7	133.43 (28.5)	7.05 (5.30)	2.3 (1.7)	6.8 (5.1)
New Providence	230.4	125.32 (54.4)	7.32 (3.67)	0.6 (0.4)	0.9 (0.7)
Bimini	34.4	23.93 (69.6)	7.58 (3.56)	0.8 (3.1)	1.1 (4.4)

the largest loss (>30%) (Table 1). This variation was due to the elevational differences among the islands (Table 1). Islands with open land at lower elevations will lose proportionately more open-land due to sea-level rise (Spearman's rho = -0.75 [1-m sea-level rise]; -0.78 [2-m sea-level rise]).

For Eleuthera, 133.4 km^2 (28.5% of Eleuthera land area) was categorized as open land (Table 1). Projected 1- and 2-m sea-level rise resulted in a loss of 1.7% and 5.1% of open land, respectively (Table 1). Of that open land, 44.0 km^2 (12.9%) was considered wintering habitat for the Kirtland's Warbler and of this wintering habitat, 0.4 km^2 (0.8%) and 1.1 km^2 (2.6%) were projected to be lost to 1- and 2-m sea-level rise, respectively.

Discussion

Our results indicate a potential for the Bahamian islands, which are used as wintering grounds by the Kirtland's Warbler, to become warmer and wetter than the baseline average, especially during the early–mid winter months. Martin and Weech (2001) demonstrated an interdecadel annual drying trend beginning in January for the Bahamian Archipelago. Our results, however, predict this drying trend to begin in March, which agrees with other work using GCM ensembles to predict future climatic conditions in the Caribbean (Hall et al. 2013, Nurse and Sem 2001). Our results also indicate that variation in the magnitude and direction of precipitation will change seasonally and spatially across the Bahamian focal islands. This variation in winter precipitation will likely influence habitat quality for the Kirtland's Warbler by affecting the spatial and seasonal distribution of food resources (i.e., ripened fruits and arthropods) that ultimately influence the distribution of Kirtland's Warblers across the islands (Wunderle et al. 2014).

Reduction in habitat quality (i.e., via food availability) for the Kirtland's Warbler is of concern because of documented carry-over effects between the wintering and breeding grounds (Rockwell et al. 2012). Although increased precipitation on the northern islands may improve habitat quality, the potential for increased drying on the central islands during late winter could reduce fruit and arthropod availability prior to migration for migratory bird species (Johnson and Sherry 2001, Studds and Marra 2011). For the Kirtland's Warbler, decreased precipitation in March has been linked to reduced productivity and annual survival through delayed arrival and nest initiation and lower body condition (Rockwell et al. 2012, 2016; Wunderle et al. 2014). Although it appears that the projected values for average percent-change in precipitation only demonstrate a limited threat to the Kirtland's Warbler, large interannual fluctuations are predicted which could incur long-term consequences for population stability. The general negative trend in percent change for the central islands and Eleuthera suggests that the interannual variability will be skewed towards more years with less-than-average precipitation on these islands. Kirtland's Warblers will redistribute seasonally and annually in response to changing food availability (Wunderle et al. 2014); thus, we expect to see continued redistribution of the Kirtland's Warbler wintering population among the focal islands in response to changing environmental conditions.

Arthropod fitness is directly related to annual temperature, with increases above a thermal optimum resulting in a reduced population-growth rate. Tropical arthropods are much closer than temperate arthropods to their thermal optimum; thus, it has been suggested that trends in increasing temperatures will have the most deleterious influences within the tropics (Deutsch 2008). Although annual temperatures on the Bahamian Archipelago are close to documented thermal optima for several species of arthropods, temperature increases projected by this study do not exceed documented thermal optima. Projected temperature values did not exhibit the high interannual variability observed in the precipitation projections. Although temperature alone may not strongly influence food availability within the Bahamian Archipelago, these findings are important because the effects of precipitation and temperature are often related through drought conditions. The synergy between these 2 environmental factors may cause effects on the central and southern islands, with the most southern islands exhibiting the warmest and driest environments.

The potential for direct loss of wintering habitat from sea-level rise that we found in our study may also contribute to any potential redistribution of the population along the archipelago. Our study indicated that loss of habitat due to predicted sea-level rise was greatest for coastal open land on the lower-elevation northern islands. So, while greater precipitation may improve habitat quality on the northern islands, there is the potential for less open-land habitat on those islands. Of note is the commonly reported use of pine woodlands (Haney et al. 1998), which is a cover type not included in our definition of suitable wintering habitat based on the SRTM data we used, but these habitats are used when there is a well-developed shrub layer with scattered openings (Sykes and Clench 1998). Including a small portion of this cover type as suitable within the pine woodland-dominated islands in the north may provide additional offsets for reduced habitat quality; however, current evidence demonstrates limited use by Kirtland's Warbler due to current fire regimes that limit shrub availability in this habitat (D. Ewert, The Nature Conservancy, Lansing, MI, pers. comm.). Currently, the lack of high-resolution landcover datasets makes it difficult to project impacts on the wintering habitat of the Kirtland's Warbler population across much of the Bahamian Archipelago.

If we consider both potential changes in habitat quality and quantity from changing climate, the north-central islands, which currently contain the majority of the wintering population, are likely the most critical islands on which to focus climate-adaptation strategies. These islands had relatively lower levels of habitat loss due to sea-level rise, and increasing precipitation from baseline conditions should increase habitat quality, thus allowing these islands to maintain the habitat quantity and quality needed for wintering Kirtland's Warbler as climate changes. We predict that abundance of Kirtland's Warblers will decrease on the central islands, where Kirtland's Warblers are now most abundant, as habitat quality and quantity decline. The northern islands, which historically had low populations of Kirtland's Warbler, may maintain these low populations as a trade-off between reduced habitat and increased habitat quality.

In conclusion, the multiple impacts of landcover loss across the generally low-elevation Bahamian Archipelago has been a repeated topic of concern (Bamber

et al. 2009, Dasgupta et al. 2008, Hu et al. 2009), as have the impacts of drying conditions within the Neotropics (Rockwell et al. 2012, 2016; Studds and Marra 2011, Wunderle et al. 2014). Much less attention has been focused on the combination of potential habitat loss and environmental changes that may reduce the quality of existing habitat. We attempted to examine this possibility within the context of Kirtland's Warbler ecology and conservation, but the coarse resolution of landcover data was a limitation in our evaluation of impacts at the archipelago scale. Continued processing of high-resolution imagery is necessary for finer assessments of potential habitat loss, changes in habitat quality, and the potential redistribution of habitats across this island system in response to changing environmental conditions and sea-level rise. This information will be important in helping land managers assess and spatially plan for likely habitat alterations in tandem with additional risks within the wintering grounds (e.g., predation by feral cats, invasive species), as well as within a full life-cycle and range-wide population-viability context.

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Appendix 1. Summary statistics for baseline winter precipitation (mm) and projected changes (%) from baseline in 2050 and 2100 for 9 focal islands in the Bahamian Archipelago. Focal islands are in geographic order from north to south. Baseline average precipitation was derived from the 20-y observation period between 1986 and 2005. We conducted our analyses for early winter (November–January), middle–late winter (February–April) as a whole, and March on its own. Projected changes include the median value from 40 general circulation models (GCM) and representative concentration pathways (RCP) 4.5 and 8.5 SD = standard deviation.

	North			North-Central			Central		
Season	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
Baseline									
Early winter									
Mean	186.1	169.8	146.9	155.8	146.8	135.2	157.9	217.2	174.7
SD	8.2	20.9	3.2	8.0	7.4	16.0	1.9	2.4	5.1
Middle-late winter									
Mean	224.9	173.0	150.9	108.2	116.9	109.7	99.8	114.6	99.6
SD	9.4	25.6	5.4	13.0	9.6	14.4	1.3	0.6	4.7
March									
Mean	79.9	54.4	50.4	32.7	30.6	28.8	24.9	30.0	26.3
SD	4.5	11.8	2.0	6.3	4.8	3.7	0.7	0.5	1.2
2050									
Early winter (RCP4.5)									
Median	5.58	5.40	6.94	5.35	5.64	6.17	5.67	7.86	7.72
Interquartile range	-1.78, 13.43	-1.04, 13.86	-1.33, 15.47	-1.56, 15.49	-0.79, 14.73	-1.10, 14.57	-2.07, 15.60	-2.65, 18.69	-1.82, 18.24
(10th, 90th percentiles)	(-9.0, 19.5)	(-6.8, 20.1)	(-6.5, 21.6)	(-5.9, 23.1)	(-5.2, 23.0)	(-5.2, 23.6)	(-7.1, 22.8)	(-9.3, 24.1)	(-9.3, 26.1)
Early winter (RCP8.5)									
Median	7.65	7.40	9.51	7.34	7.73	8.46	7.78	10.78	10.59
Interquartile range	-2.44, 18.41	-1.42, 19.0	-1.82, 21.21	-2.13, 21.24	-1.08, 20.19	-1.51, 19.97	-2.84, 21.38	-3.63, 25.63	-2.50, 25.0
(10th, 90th percentiles)	(-12.4, 26.7)	(-9.3, 22.8)	(-8.9, 29.6)	(-8.1, 31.7)	(-7.2, 31.5)	(-7.1, 32.4)	(-9.7, 31.2)	(-12.7, 33.1)	(-12.8, 35.7)
Middle-late winter (RCP4.5)									
Median	0.42	0.45	1.69	1.04	1.58	2.54	1.04	0.84	1.22
Interquartile range	-8.65, 9.83	-9.55, 9.05	-10.53, 10.58	-9.61, 8.57	-11.54, 10.38	-12.85, 10.79	-11.59, 8.92	-12.66, 9.61	-12.33, 11.09
(10th, 90th percentiles)	(-17.5, 19.6)	(-17.1, 17.0)	(-20.6, 21.3)	(-16.2, 17.5)	(-17.3, 17.1)	(-19.3, 17.6)	(-17.7, 18.0)	(-18.0, 19.1)	(-19.9, 20.3)

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	North				North-Central		Central		
Season	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
Middle-late winter (RCP8.5)									
Median	0.60	0.62	2.31	1.43	2.16	3.48	1.43	1.15	1.68
Interquartile range	-11.86, 13.48	-13.10, 12.41	-14.43, 14.50	-13.18, 11.75	-15.82, 14.23	-17.62, 14.80	-15.88, 12.23	-17.36, 13.18	-16.90, 15.20
(10th, 90th percentiles)	(-24.0, 26.9)	(-23.5, 23.3)	(-28.3, 29.3)	(-22.2, 23.9)	(-23.7, 23.4)	-26.5, 24.2)	(-24.3, 24.6)	(-24.7, 26.2)	(-27.3, 27.8)
March (RCP4.5)									
Median	0.56	0.17	2.31	-0.25	0.75	1.57	-1.39	-2.33	-2.80
Interquartile range	-7.17, 8.71	-8.66, 7.74	-7.58, 10.49	-10.15, 7.44	-11.82, 7.66	-11.91, 8.92	-10.61, 5.07	-10.38, 5.94	-9.02, 4.18
(10th, 90th percentiles)	(-16.1, 20.9)	(-18.8, 17.5)	(-17.8, 22.4)	(-15.2, 19.3)	(-14.8, 17.7)	(-15.3, 18.4)	(-16.0, 17.1)	(-17.9, 14.5)	(-18.5, 13.6)
March (RCP8.5)									
Median	0.77	0.24	3.16	-0.34	1.03	2.16	-1.90	-3.20	-3.84
Interquartile range	-9.83, 11.94	-11.87, 10.61	-10.40, 14.38	-13.91, 10.21	-16.21, 10.51	-16.33, 12.23	-14.54, 6.95	-14.22, 8.15	-12.37, 5.73
(10th, 90th percentiles)	(-22.1, 28.7)	(-25.8, 24.0)	(-24.3, 30.8)	(-20.8, 26.4)	(-20.3, 24.3)	(-21.0, 25.3)	(-22.0, 23.4)	(-24.6, 19.9)	(-25.4, 18.6)
2100									
Early winter (RCP4.5)									
Median	7.83	7.58	9.73	7.51	7.91	8.66	7.96	11.03	10.84
Interquartile range	-2.50, 18.84	-1.46, 19.44	-1.86, 21.71	-2.18, 21.74	-1.1019, 20.66	-1.55, 20.44	-2.91, 21.89	-3.72, 26.23	-2.56, 25.59
(10th, 90th percentiles)	(-12.7, 27.4)	(-9.5, 28.2)	(-9.2, 30.3)	(-8.3, 32.5)	(-7.4, 32.2)	(-7.2, 33.1)	(-10.0, 32.0)	(-13.0, 33.8)	(-13.1, 36.6)
Early winter (RCP8.5)									
Median	18.41	17.81	22.88	17.65	18.60	20.36	18.71	25.93	25.48
Interquartile range	-5.88, 44.29	-3.43, 45.70	-4.38, 51.02	-5.13, 51.09	-2.59, 48.57	-3.63, 48.04	-6.83, 51.45	-8.74, 61.66	-6.01, 60.15
(10th, 90th percentiles)	(-29.8, 64.3)	(-22.4, 66.3)	(-21.5, 71.2)	(-19.5, 76.3)	(-17.3, 75.8)	(-17.0, 77.9)	(-23.4, 75.1)	(-30.7, 79.6)	(-30.8, 85.9)
Middle-late winter (RCP4.5)									
Median	0.59	0.63	2.37	1.46	2.21	3.57	1.46	1.17	1.72
Interquartile range	-12.14, 13.80	-13.41, 12.70	-14.77, 14.84	-13.49, 12.03	-16.20, 14.56	-18.03, 15.14	-16.26, 12.52	-17.77, 13.49	-17.30, 15.56
(10th, 90th percentiles)	(-24.6, 27.5)	(-24.1, 23.8)	(-29.0, 29.9)	(-22.7, 24.5)	(-24.3, 24.0)	(-27.1, 24.8)	(-24.8, 25.2)	(-25.3, 26.8)	(-28.0, 28.5)
Middle-late winter (RCP8.5)									
Median	1.38	1.49	5.56	3.43	5.20	8.38	3.44	2.76	4.04
Interquartile range	-28.54, 32.44	-31.51, 29.86	-34.73, 34.88	-31.71, 28.27	-38.07, 34.23	-42.39, 35.60	-38.21, 29.43	-41.77, 31.71	-40.67, 36.57
(10th, 90th percentiles)	(-57.8, 64.7)	(-56.6, 56.0)	(-68.1, 70.4)	(-53.5, 57.6)	(-57.1, 56.4)	(-63.8, 58.2)	(-58.4, 59.3)	(-59.5, 63.0)	(-65.8, 66.9)

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Season	North			North-Central			Central		
	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
March (RCP4.5)									
Median	0.79	0.24	3.24	-0.35	1.05	2.21	-1.94	-3.27	-3.93
Interquartile range	-10.06, 12.22	-12.15, 10.86	-10.64, 14.71	-14.24, 10.45	-16.59, 10.75	-16.72, 12.51	-14.89, 7.11	-14.56, 8.34	-12.66, 5.86
(10th, 90th percentiles)	(-22.6, 29.4)	(-26.4, 24.5)	(-24.9, 31.5)	(-21.3, 27.0)	(-20.8, 24.9)	(-21.4, 25.8)	(-22.5, 24.0)	(-25.2, 20.4)	(-26.0, 19.1)
March (RCP8.5)									
Median	1.86	0.57	7.61	-0.82	2.47	5.19	-4.57	-7.69	-9.24
Interquartile range	-23.64, 28.72	-28.56, 25.52	-25.01, 34.59	-33.46, 24.55	-39.0, 25.28	-39.29, 29.42	-34.99, 16.72	-34.22, 19.60	-29.76, 13.78
(10th, 90th percentiles)	(-53.2, 69.1)	(-62.2, 57.7)	(-58.6, 74.0)	(-50.1, 63.6)	(-48.8, 58.4)	(-50.4, 60.8)	(-52.8, 56.4)	(-59.2, 47.8)	(-61.0, 44.9)

Appendix 2. Summary statistics for baseline winter temperature (°C) and projected changes (%) in 2050 and 2100 for 9 focal islands in the Bahamian Archipelago. Focal islands are in geographic order from north to south. Baseline temperature was derived from the 20-y observation period between 1986 and 2005. We conducted our analyses for early winter (November–January), middle–late winter (February–April) as a whole, and March on its own Projected changes include the median value from 40 general circulation models (GCM) and representative concentration pathways (RCP) 4.5 and 8.5. SD = standard deviation.

Season	North			North-Central			Central		
	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
Baseline									
Early winter									
Mean	21.4	21.7	22.1	22.7	22.3	22.6	23.5	23.7	24.2
SD	0.1	0.3	0.3	0.2	0.1	0.1	0.2	0.0	0.1
Middle-late winter									
Mean	21.8	22.1	22.5	22.7	22.6	23.0	23.6	23.7	24.1
SD	0.1	0.2	0.2	0.2	0.0	0.2	0.1	0.1	0.1
March									
Mean	21.9	22.1	22.2	22.6	22.4	22.9	23.4	23.6	24.3
SD	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.2
2050									
Early winter (RCP4.5)									
Median	0.95	0.94	0.96	0.93	0.93	0.94	0.93	0.93	0.94
Interquartile range	0.76, 1.13	0.80, 1.09	0.76, 1.12	0.82, 1.06	0.81, 1.08	0.81, 1.08	0.83, 1.07	0.84, 1.07	0.85, 1.07
(10th, 90th percentiles)	(0.6, 1.3)	(0.7, 1.2)	(0.6, 1.3)	(0.7, 1.2)	(0.7, 1.2)	(0.7, 1.2)	(0.8, 1.2)	(0.8, 1.2)	(0.8, 1.2)
Early winter (RCP8.5)									
Median	1.30	1.29	1.32	1.27	1.28	1.28	1.28	1.27	1.29
Interquartile range	1.05, 1.55	1.09, 1.50	1.05, 1.53	1.12, 1.46	1.11, 1.48	1.11, 1.48	1.14, 1.46	1.15, 1.47	1.16, 1.46
(10th, 90th percentiles)	(0.9, 1.8)	(0.9, 1.7)	(0.9, 1.8)	(1.0, 1.7)	(1.0, 1.7)	(1.0, 1.7)	(1.0, 1.6)	(1.0, 1.7)	(1.1, 1.7)
Middle-late winter (RCP4.5)									
Median	0.91	0.89	0.93	0.88	0.88	0.89	0.89	0.90	0.90
Interquartile range	0.78, 1.07	0.78, 1.03	0.79, 1.08	0.81, 0.98	0.81, 1.01	0.81, 1.02	0.81, 0.97	0.81, 0.98	0.83, 0.99
(10th, 90th percentiles)	(0.7, 1.3)	(0.7, 1.2)	(0.6, 1.3)	(0.7, 1.2)	(0.7, 1.2)	(0.7, 1.2)	(0.7, 1.2)	(0.7, 1.2)	(0.7, 1.2)

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Season	North			North-Central			Central		
	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
Middle-late winter (RCP8.5)									
Median	1.25	1.22	1.27	1.20	1.21	1.22	1.22	1.23	1.24
Interquartile range	1.08, 1.47	1.07, 1.41	1.08, 1.48	1.10, 1.35	1.11, 1.39	1.12, 1.39	1.11, 1.33	1.11, 1.34	1.13, 1.35
(10th, 90th percentiles)	(0.9, 1.7)	(0.9, 1.7)	(0.9, 1.7)	(0.9, 1.7)	(0.9, 1.7)	(0.9, 1.7)	(1.0, 1.7)	(1.0, 1.7)	(1.0, 1.7)
March (RCP4.5)									
Median	0.89	0.86	0.91	0.85	0.86	0.86	0.87	0.87	0.88
Interquartile range	0.75, 1.07	0.77, 1.01	0.77, 1.08	0.80, 0.96	0.78, 0.98	0.80, 0.99	0.80, 0.93	0.81, 0.93	0.82, 0.94
(10th, 90th percentiles)	(0.7, 1.4)	(0.7, 1.3)	(0.7, 1.4)	(0.7, 1.3)	(0.7, 1.3)	(0.7, 1.3)	(0.7, 1.3)	(0.7, 1.3)	(0.7, 1.3)
March (RCP8.5)									
Median	1.22	1.18	1.25	1.17	1.18	1.18	1.19	1.19	1.21
Interquartile range	1.03, 1.47	1.06, 1.39	1.05, 1.48	1.09, 1.31	1.07, 1.35	1.09, 1.36	1.10, 1.27	1.11, 1.28	1.12, 1.30
(10th, 90th percentiles)	(0.9, 1.9)	(1.0, 1.8)	(0.9, 2.0)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.7)
2100									
Early winter (RCP4.5)									
Median	1.33	1.32	1.35	1.30	1.31	1.31	1.31	1.30	1.32
Interquartile range	1.07, 1.58	1.12, 1.54	1.07, 1.57	1.15, 1.49	1.13, 1.51	1.13, 1.52	1.17, 1.50	1.18, 1.50	1.19, 1.50
(10th, 90th percentiles)	(0.9, 1.8)	(1.0, 1.7)	(0.9, 1.8)	(1.0, 1.7)	(1.0, 1.7)	(1.0, 1.7)	(1.1, 1.7)	(1.1, 1.7)	(1.1, 1.7)
Early winter (RCP8.5)									
Median	3.14	3.09	3.18	3.05	3.08	3.09	3.07	3.07	3.11
Interquartile range	2.52, 3.72	2.62, 3.61	2.52, 3.68	2.69, 3.51	2.66, 3.55	2.67, 3.56	2.74, 3.52	2.76, 3.53	2.79, 3.52
(10th, 90th percentiles)	(2.0, 4.3)	(2.2, 4.1)	(2.1, 4.3)	(2.4, 4.0)	(2.4, 4.0)	(2.4, 4.0)	(2.5, 4.0)	(2.5, 4.0)	(2.6, 4.0)
Middle-late winter (RCP4.5)									
Median	1.28	1.25	1.30	1.23	1.24	1.25	1.25	1.26	1.27
Interquartile range	1.10, 1.50	1.09, 1.44	1.10, 1.51	1.13, 1.38	1.13, 1.42	1.14, 1.43	1.14, 1.36	1.14, 1.38	1.16, 1.39
(10th, 90th percentiles)	(0.9, 1.8)	(1.0, 1.7)	(0.9, 1.8)	(1.0, 1.7)	(1.0, 1.7)	(0.9, 1.7)	(1.0, 1.7)	(1.0, 1.7)	(1.0, 1.7)
Middle-late winter (RCP8.5)									
Median	3.01	2.93	3.06	2.89	2.91	2.93	2.93	2.96	2.98
Interquartile range	2.59, 3.54	2.57, 3.38	2.59, 3.56	2.66, 3.24	2.66, 3.35	2.68, 3.35	2.68, 3.20	2.67, 3.24	2.72, 3.26
(10th, 90th percentiles)	(2.2, 4.2)	(2.3, 4.1)	(2.1, 4.2)	(2.3, 4.0)	(2.3, 4.1)	(2.2, 4.1)	(2.3, 4.0)	(2.3, 4.1)	(2.4, 4.1)

D.M. Wolcott, D.M. Donner, D.J. Brown, and C.A. Ribic

Season	North			North-Central			Central		
	Grand Bahama	Abaco	Bimini	Eleuthera	New Providence	Andros	Cat	San Salvador	Long
March (RCP4.5)									
Median	1.25	1.21	1.28	1.20	1.20	1.21	1.22	1.22	1.24
Interquartile range	1.05, 1.51	1.08, 1.42	1.07, 1.51	1.12, 1.34	1.10, 1.38	1.12, 1.39	1.13, 1.30	1.13, 1.31	1.15, 1.33
(10th, 90th percentiles)	(0.9, 1.9)	(1.0, 1.8)	(0.9, 2.0)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)	(1.0, 1.8)
March (RCP8.5)									
Median	2.93	2.84	3.00	2.82	2.83	2.85	2.87	2.87	2.91
Interquartile range	2.47, 3.54	2.54, 3.33	2.53, 3.55	2.63, 3.15	2.58, 3.24	2.63, 3.26	2.65, 3.06	2.66, 3.07	2.71, 3.12
(10th, 90th percentiles)	(2.2, 4.5)	(2.3, 4.3)	(2.2, 4.7)	(2.3, 4.3)	(2.4, 4.3)	(2.3, 4.3)	(2.3, 4.2)	(2.3, 4.3)	(2.4, 4.2)