Biological Conservation 201 (2016) 327–335

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/bioc

Future frequencies of extreme weather events in the National Wildlife Refuges of the conterminous U.S.

Sebastián Martinuzzi [a],*, Andrew J. Allstadt [a], Brooke L. Bateman [a], Patricia J. Heglund [b], Anna M. Pidgeon [a], Wayne E. Thogmartin [c], Stephen J. Vavrus [d], Volker C. Radeloff [a]

[a] SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA
[b] U.S. Fish and Wildlife Service, NWRS, Region 3, 2630 Fanta Reed Road, La Crosse, WI 54603, USA
[c] U.S. Geological Survey, Upper Midwest Environmental Sciences Center, 2630 Fanta Reed Road, La Crosse, WI 54603, USA
[d] Nelson Institute Center for Climatic Research, University of Wisconsin-Madison, 1225 W. Dayton St, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 3 July 2016
Accepted 6 July 2016
Available online 1 August 2016

Keywords:
Protected areas
Climate change
Conservation planning
Droughts
Extreme heat
False springs

ABSTRACT

Climate change is a major challenge for managers of protected areas world-wide, and managers need information about future climate conditions within protected areas. Prior studies of climate change effects in protected areas have largely focused on average climatic conditions. However, extreme weather may have stronger effects on wildlife populations and habitats than changes in averages. Our goal was to quantify future changes in the frequency of extreme heat, drought, and false springs, during the avian breeding season, in 415 National Wildlife Refuges in the conterminous United States. We analyzed spatially detailed data on extreme weather frequencies during the historical period (1950–2005) and under different scenarios of future climate change by mid- and late-21st century. We found that all wildlife refuges will likely experience substantial changes in the frequencies of extreme weather, but the types of projected changes differed among refuges. Extreme heat is projected to increase dramatically in all wildlife refuges, whereas changes in droughts and false springs are projected to increase or decrease on a regional basis. Half of all wildlife refuges are projected to see increases in frequency (>20% higher than the current rate) in at least two types of weather extremes by mid-century. Wildlife refuges in the Southwest and Pacific Southwest are projected to exhibit the fastest rates of change, and may deserve extra attention. Climate change adaptation strategies in protected areas, such as the U.S. wildlife refuges, may need to seriously consider future changes in extreme weather, including the considerable spatial variation of these changes.

1. Introduction

Protected areas are a cornerstone for biodiversity conservation, and climate change represents one of the major challenges for managers of protected areas globally (Hole et al., 2009; Lawler, 2009). As climate changes, conditions within protected areas are also expected to change, potentially triggering shifts in species and changing ecosystem properties (Langdon and Lawler, 2015; Wiens et al., 2011). Conserving biodiversity into the future therefore, requires understanding future climatic conditions in protected areas (Hannah, 2008).

Most studies assessing effects of climate change on biodiversity and protected areas have focused on climate averages, e.g. changes in mean temperature or precipitation, rather than potential changes in the frequency of extreme weather such as prolonged droughts, extreme heat, or unseasonable cold periods (Garcia et al., 2014; Loarie et al., 2009; Scriven et al., 2015; Wiens et al., 2011). However, studying the changes in extremes explicitly allows for better interpretation of the consequences for protected area managers, because extreme weather events can pose stronger threats to species and ecosystems, and make habitat management more challenging, than shifts in average conditions (Reyer et al., 2013). Increased frequency or intensity of extreme heat and droughts can facilitate plant invasions (Jiménez et al., 2011), increase tree mortality (Allen et al., 2010), reduce avian breeding success and survival (Jenouvrier, 2013), and trigger species movement and range shifts, potentially changing community composition, resource availability, and ecosystem properties (Parmesan et al., 2000). For example, the Dickcissel (*Spiza americana*), a grassland bird species of the U.S. Midwest, exhibits strong abundance shifts at its range edges during drought events compared to years of average precipitation (Bateman et al., 2015). In Mediterranean forests, droughts can trigger widespread tree defoliation that disrupts insect and fungal communities and alters food webs (Carnicer et al., 2011). At times when managers are trying to initiate a restoration, flood a wetland management unit, or perform some other management action, droughts may prevent implementing the desired management action at the most beneficial time (Dale et al., 2001; Thurow and Taylor, 1999). In general, extreme heat and drought are projected to become more frequent in some

---

* Corresponding author.
E-mail address: martinuzzi@wisc.edu (S. Martinuzzi).

http://dx.doi.org/10.1016/j.biocon.2016.07.007

regions in the next decades (IPCC, 2012; Walsh et al., 2014) but future patterns of these extremes in protected areas are largely unknown (Monahan and Fisichelli, 2014).

In addition to extreme heat and drought, false springs can have large ecological effects. False springs, which occur when leaf-out of plants is followed by a hard freeze, typically cause severe vegetation damage (Augspurger, 2013). False springs can occur when there is a combination of premature warm temperatures followed by late freezes. Widespread vegetation damage from false springs has been observed in both natural and agricultural systems, with negative consequences for plant productivity, survival, and growth (Augspurger, 2011; Inouye, 2008). In turn, the effects from false springs can percolate through an ecosystem, as reduced plant productivity negatively affects dependent animal populations, interactions among species, and the provision of ecosystem services (Hufkens et al., 2012; Nixon and McClain, 1969). In 2010, for example, false springs reduced annual gross productivity in forest ecosystems of the northeastern United States (U.S.) by 7–14% (Hufkens et al., 2012). Projections of future climate change in places such as the U.S. indicate that false springs may become more frequent in certain regions (Allstadt et al., 2015), yet their effects on protected areas are unknown.

Assessing how droughts, extreme heat, and false springs may change across protected area networks as a result of future climate changes can provide important information about potential challenges that species and managers may face. In particular, evaluating future changes in extreme weather during the spring season can be of major importance, because plant and animal populations can be especially sensitive to extremes during those months (Bolger et al., 2005; Both and Visser, 2001; Drever et al., 2012), when many wildlife species are breeding, and plants are growing and blooming (Jenouvrier, 2013; Filewod and Thomas, 2014). Furthermore, when assessing the exposure of protected areas to different types of extreme weather, it is important to evaluate their exposure to each extreme individually, as well as to all types of extremes combined, because the interactions among multiple environmental stressors can exacerbate ecosystem responses (Albright et al., 2010; Breitburg et al., 1998). While the ultimate response of the biota will depend on other factors as well, including individual species' tolerances and interactions within and among trophic levels (Parmesan et al., 2000; Walther, 2010), knowing their exposure to future changes is a critical first step.

Patterns of climate change vary, however, especially at regional and continental scales, and that variability matters when prioritizing management actions across protected area networks (Monahan and Fisichelli, 2014). For protected area managers and governmental agencies, knowing which protected areas will be affected by multiple stressors is of major importance because those protected areas can be considered under potentially increasing threat due to climate changes, and thus may require particular attention. Furthermore, individual protected areas are typically embedded within larger administrative regions. Assessments of future climate change in protected areas are therefore more useful if they can inform both managers of individual protected areas as well as higher-level administrators, yet such assessments are rare. Finally, because of the uncertainty in predictions of future climate conditions, it is important to evaluate multiple models and scenarios of climate change (Lawler, 2009).

The goal of our study was to quantify future changes in the frequency of extreme weather events during the spring breeding season in protected areas, focusing on the National Wildlife Refuge System (NWRS) in the conterminous United States. The NWRS is one of the world's largest protected area networks designated to protect wildlife and plants, and information about future climate conditions is needed for the NWRS' climate change adaptation plans (Czech et al., 2014; Griffith et al., 2009). Our specific objectives were to: i) quantify future changes in the frequency of extreme heat, droughts, and false springs for each administrative region under different climate change scenarios, and ii) map future changes in extreme heat, droughts, and false springs at the level of individual wildlife refuges across the nation. We also identified which refuges are projected to see increases in multiple types of extremes, our main indicator of increasing threat due to future climate changes.

2. Materials and methods

2.1. Data

2.1.1. Wildlife refuges

In the conterminous U.S. alone, there are over 460 wildlife refuges aggregated in seven Fish and Wildlife Service (FWS) administrative regions. We focused on the conterminous U.S., and excluded NWRS lands not directly managed by the FWS (namely, cooperatively managed lands) or not specifically designated as refuges, as in previous studies (Hamilton et al., 2013). In addition, because the weather data used in this study are best suited for analyzing changes on continental lands, we did not consider wildlife refuges and wildlife refuge's portions in the oceans and the Great Lakes, but included river refuges. As a result, the final number of wildlife refuges that we assessed was 415, with 42 to 99 wildlife refuges in each of the seven FWS administrative regions (Fig. 1a). Wildlife refuges are relatively small in size (the median size was 2754 ha), typically embedded in a matrix of developed lands, and situated at low elevations and on productive soils (Griffith et al., 2009). Wetlands are common in the NWRS.

2.1.2. Extreme weather data

We derived focal weather variables (extreme heat, droughts, and false springs) based on daily records from the Coupled Model Intercomparison Project 5 (CMIP5) multi-model ensemble General Circulation Models (GCM) dataset. Specifically, we used data spanning from 1950 to 2100 that have been statistically downscaled to approximately 12-km resolution from the coarse-scale GCM using the Bias-Corrected Constructed Analog (BCCA) technique (Maurer et al., 2007; Reclamation, 2014). The main reason for going back to 1950 was to obtain a large sample size, which is important for analysis of extreme events. We analyzed data for 19 GCMs (Table A.1), and present here the multi-model median values, and in some cases the 25th and 75th percentile values to represent variation among GCMs. We considered two emissions scenarios that were available for each of the 19 GCMs, including the Representative Concentration Pathway 4.5, or RCP4.5 (medium-low emissions) and the RCP8.5 (high emissions). Our study variables were summarized into simulated historical (1950–2005), mid-century (2041–2070), and end of the century (2071–2100) time periods, and were based on spring season only (March, April, May), which is when birds make their settling decisions in the northern states, and in the southern U.S., includes the early breeding season. Spring precipitation, or the lack thereof, strongly affects resource availability and water levels during the avian breeding season.

2.1.2.1. Droughts. We quantified changes in spring drought by comparing the frequency of droughts with a 20-year recurrence interval observed during the simulated historical period, with the frequency of droughts of similar magnitude in the future. For example, for a certain pixel, a 20-year drought during the historical period might occur every 10 years by mid-century, which means that the frequency has doubled. We chose twenty-year events as our key metric, because they clearly represent an extreme event, and are frequent enough that managers can expect at least one of these to occur during their career.

We calculated 20-year droughts based on the Standardized Precipitation Index (SPI) (McKee et al., 1993). The SPI is a widely used drought metric (World Meteorological Association, 2009) defining drought as a probabilistic lack of precipitation in terms of a standard normal distribution (Guttman, 1999; McKee et al., 1993). That is, a 20-year drought is defined as a SPI ≤ -1.64. We calculated SPI independently for each model, and for each grid cell. In each cell, we calculated the total

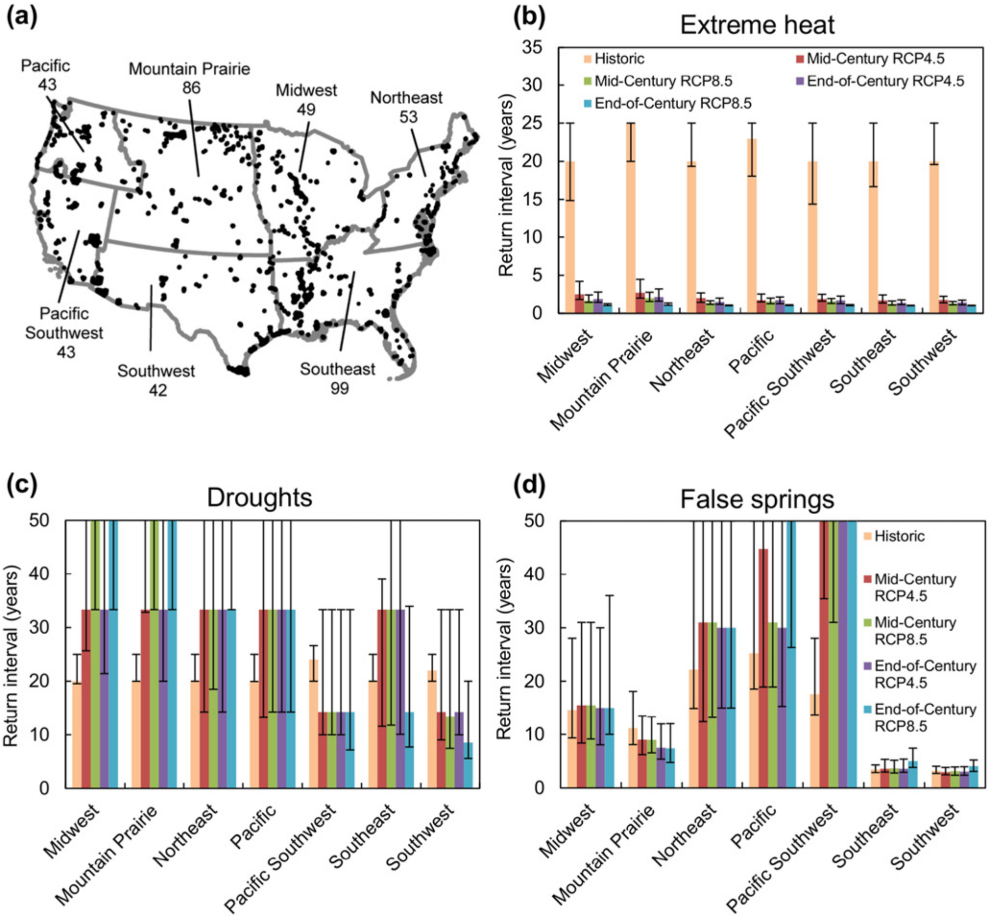

Fig. 1. Distribution of wildlife refuges in the conterminous United States (a), and projected changes in extreme weather events in wildlife refuges at the level of administrative regions (b–d). In (a), the grey lines represent the boundaries of the seven U.S. Fish and Wildlife Service administrative regions. The number of wildlife refuges in each administrative region is included under the region's name. The size of the wildlife refuges is exaggerated for visualization purposes. (b–d) Shows the frequency of extreme heat, droughts, and false springs in wildlife refuges aggregated within administrative regions, under historical conditions and under different scenarios of future climate change. Frequencies are expressed as return intervals in years (the shorter the return interval, the more frequent the event is projected to be). The values for each administrative region include the multi-model median of 19 GCMs (i.e. the columns), as well as the 25th and 75th percentiles (i.e. lower and upper limits of the segments). Scenarios include historical (1950–2005), mid-century (2041–2070), and end-of-century (2071–2100), and under two emission scenarios from the Intergovernmental Panel on Climate Change, including RCP4.5 (medium-low emissions) and RCP8.5 (high-emissions). The graphs display return intervals up to 50-years for visualization purposes, but some values are larger than that.

precipitation in the spring months (March, April, May) for each year during the historical time period (1950–2005). We fit a Pearson-III distribution to annual totals and converted percentiles from this distribution to the standard normal of the SPI (Guttman, 1999). Based on these distribution parameters, we calculated droughts in the future time periods in terms of historical conditions. That is, SPI ≤ −1.64 represents by definition a 20-year drought during the historical period, but may occur more or less often in the future given changes in modeled weather patterns. We repeated this procedure for each grid cell, model and scenario, and report changes in probability of the 20-year droughts for each grid cell, model, and scenario.

2.1.2.2. Extreme heat. Similar to droughts, we focused on 20-year extreme heat events observed during the historical period and quantified their probability under future climate scenarios. We examined standardized spring temperature anomalies analogous to SPI, hereafter referred to as the spring Standardized Temperature Index (STI). We chose to use STI based on the mean daily maximum temperature during the spring months at each location. Unlike precipitation, temperatures do not typically have complex distributions, allowing us to fit a simple normal distribution to these spring temperatures during the simulated historical period. Then, as for SPI, we converted annual values for all years based on the historical distribution. We calculated STI values during the spring months for each of the 19 GCMs, and determined the probabilities of 20-year extreme seasonal heat as defined by the simulated historical period (STI ≥ 1.64) for all of the time periods.

2.1.2.3. False springs. Assessing changes in false springs required a different approach than those for extreme heat or droughts. A false spring is a hard freeze (a daily minimum temperature below −2.2 °C) after spring plant growth has begun (Marino et al., 2011; Schwartz, 1993). Flowers are generally more sensitive to freeze damage than leaves (Sakai and Larcher, 1987), and flowers and resulting seeds are often important food sources for animals (Nixon and McClain, 1969), beyond the reproduction of the plants themselves. Therefore, we calculated flower emergence date, estimated by using the extended Spring Indices (Schwartz et al., 2013), and any hard freeze afterwards constituted a potentially damaging false spring event. We extracted the occurrence of these false springs for each GCM from a dataset we had previously generated (Allstadt et al., 2015; data available at http://silvis.forest.wisc.edu/climate-averages-and-extremes) and calculated the probability of false springs for each pixel during each time period: historic (1950–2005), mid-century (2041–2070), and end-of-century (2071–2100) under the two emission scenarios, RCP4.5 and RCP8.5.

2.2. Analysis

First we extracted, for each wildlife refuge, the mean annual probability values for extreme heat, drought, and false springs under the historical period and for the four different scenarios of future climate change considered in this study (mid-century RCP4.5, mid-century RCP8.5, end-of-century RCP4.5, and end-of-century RCP8.5).

For objective one, we aggregated the wildlife refuges into their administrative regions ($n = 7$), and calculated the median probabilities for each type of extreme weather event across wildlife refuges within each region. We used the median value within each region, rather than the mean, due to skewness of the data, and converted the annual probability values into return intervals (in years) by dividing one by the annual probability. Return interval, i.e., average time between occurrences of an event (20-year, 5-year, etc.), represents a more intuitive unit of frequency, making it particularly well suited for communicating our results with protected area managers. We reported the median return intervals for extreme heat, drought, and false springs in each administrative region under the historical period and under the different future climate scenarios. The return intervals here were the multi-model median values across the 19 GCMs. In order to assess the variability among GCMs we also calculated the 25th and 75th percentile values.

For objective two, i.e., the mapping of future changes for each refuge, we categorized each refuge into one of three classes based on projected change in frequency of extremes: decrease, increase, or no change in frequency. We converted the annual probability values to return intervals in years, and used the multi-model median value. Wildlife refuges projected to see a >20% increase in the return interval of extreme weather relative to the historical period were categorized as having "fewer events," while those projected to see a >20% decrease in the return interval were categorized as having "more events." Finally, wildlife refuges projected to see return-interval increases or decreases <20% were categorized as "no change." As part of this analysis we also modified one of the classes for false springs. Extreme heat and droughts were defined based on historical, 20-year events. However, false springs occurred in some location at very low frequencies, or were even completely absent, in both the historical period and future scenarios. Thus, we combined wildlife refuges with a very low frequency of false spring under both historical and future conditions (i.e. >30-year return interval) with the class "no change." This means that for false springs, the class "no change" includes wildlife refuges with little change (<20%) in the frequency of false springs, as well as those with very rare or no false springs.

To map future patterns of extreme weather across wildlife refuges, we created individual maps for changes in extreme heat, droughts, and false springs across wildlife refuges for the different scenarios. We evaluated differences in spatial patterns of change between scenarios, and compared the patterns of change from the refuge-level maps with the regional averages reported in objective 1. For each extreme weather variable, we reported the number of wildlife refuges in each change class ("fewer," "more," and "no change").

To identify wildlife refuges that may be under increasing threat of multiple types of extreme weather due to future climate change, we combined the change maps for extreme heat, droughts, and false springs into a single map, and reported the number of wildlife refuges projected to see increased frequency of one, two, or three of our weather variables. We reported the results for each scenario separately. Our assumption was that more variables with increased frequency represent a higher level of stress on the natural resources (plant and animal) in that wildlife refuge.

2.2.1. Sensitivity analysis

We focused in our study on the number of wildlife refuges projected to see increases in frequency of extreme weather using a rate of change >20% above the current rate. To assess the effect of that threshold in our study, we reported how many refuges are projected to see increases in frequency of multiple weather variables using rates of change >30%, >40%, and >50% above the current rate.

3. Results

3.1. Changes in extreme weather by FWS administrative region

We first compared the frequencies of extreme weather in wildlife refuges aggregated by FWS administrative regions (i.e., regional medians, Fig. 1b–d). Extreme heat was projected to increase dramatically in all administrative regions, from a median 20-year return interval in the historical period, to about 1–3 years under all time periods and emission scenarios (Fig. 1b). There was little variation among GCMs, as reflected by the 25th and 75th percentile values.

On the other hand, droughts were projected to increase in frequency in the southwestern administrative regions (Pacific Southwest, Southwest), but decrease in frequency in northern regions (Midwest, Mountain Prairie, Northeast; Fig. 1c). In the Pacific Southwest and Southwest administrative regions, for example, the median return interval of droughts within refuges was projected to decline from about 20 years to 14 years by mid-century, but increase from 20 years to 33 years or more in the Midwest and Mountain Prairie administrative regions. There were little or no differences between mid-century and end-of-century periods, but differences from historical conditions were greater under the RCP8.5 emission scenario than RCP4.5 in a few cases (Fig. 1c). Contrary to extreme heat, there was a greater variation among GCMs as reflected by the 25th and 75th percentiles.

Finally, while the frequency of extreme heat and droughts in the historical period were by definition relatively constant (i.e., ~20 years), the frequency of false springs in the historical period did vary by administrative region. During the historical period, false springs were more frequent in the Southeast and Southwest (~3-year return interval), followed by Mountain Prairie and Midwest (11–15 years return interval), and least frequent in the Northeast, Pacific, and Pacific Southwest (18–25 years; Fig. 1d). Under the future climate scenarios only the Mountain Prairie administrative region showed some increase in the frequency of false springs, from 11-year return interval in the historical period to 7–9 years under the future scenarios, whereas in the other regions the frequency of false springs is projected to decrease or remain the same.

3.2. Changes in extreme weather at the level of individual wildlife refuges

We found strong spatial patterns in the changes in extreme weather when examining all refuges individually. We first developed separate categorical maps depicting projected changes in extreme heat, droughts, and false springs in each wildlife refuge, using three categories of change: "fewer," "more," and "no change" (Fig. 2). Because changes from historical in both mid- and end-of-century were usually of the same sign, we focused our results on mid-century. Our projections at the level of individual wildlife refuges showed far more wildlife refuges projected to see increases in extreme heat (all refuges, or 100%), than in droughts or false springs (~26%). Variations between the RCP4.5 and RCP8.4 scenarios were typically small by mid-century, and more visible by end-of-century (Fig. 2).

The patterns of change in the frequencies of extreme weather events at the level of individual wildlife refuges were consistent with the results at the level of administrative region. However, the refuge-level analysis revealed fine-scale variations within regions that were not evident at the administrative level, highlighting the value of the refuge-level analysis. For example, although the Pacific Southwest and Southwest were the only regions projected to see increases in droughts, some individual refuges in the Southeast region (e.g. Florida) were projected to see increases in droughts too (Fig. 2b). Similarly, the Midwest administrative region was projected to see little or no change in the frequency of false springs, yet wildlife refuges in the southern

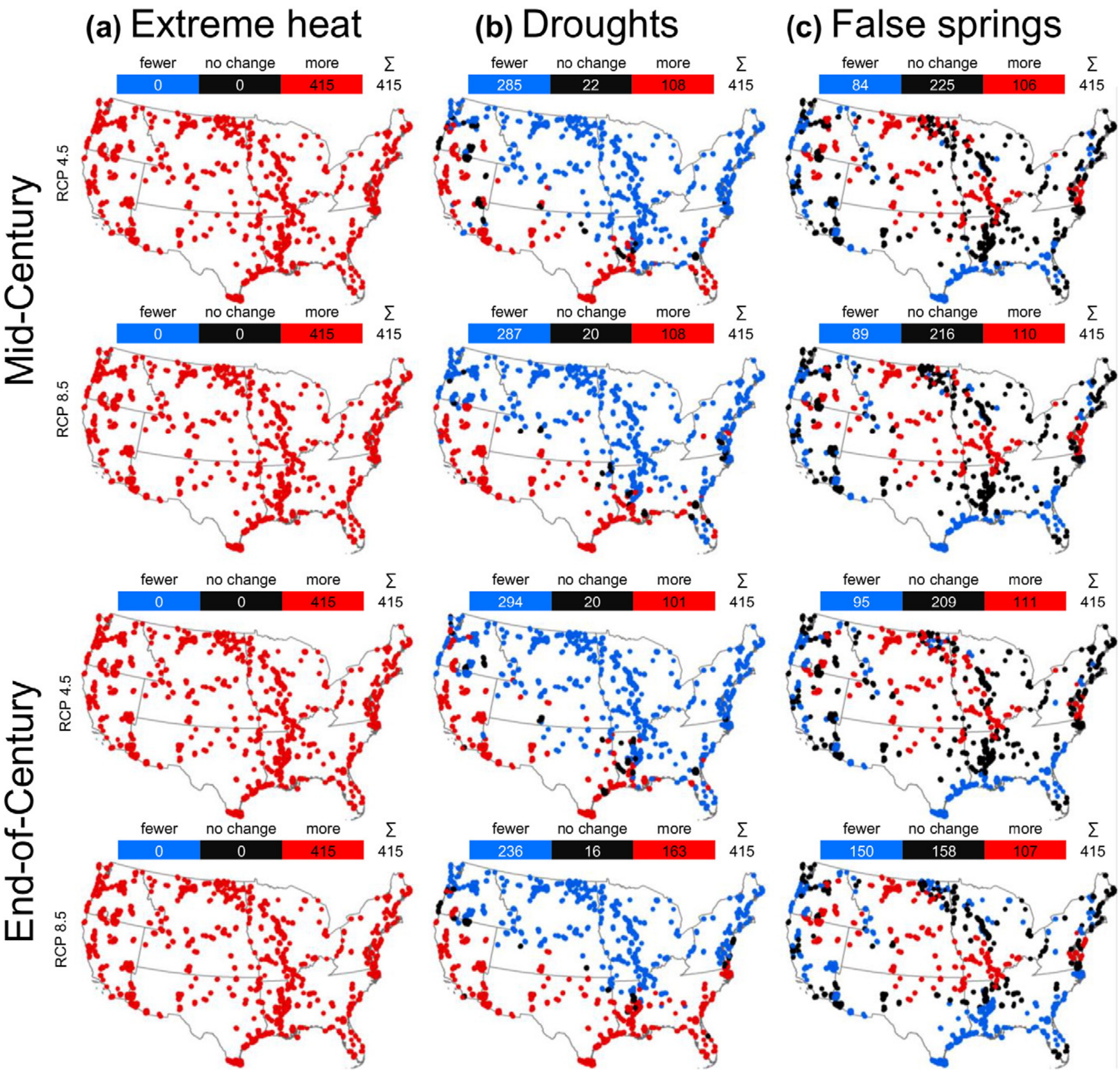

Fig. 2. Projected changes in extreme heat (a), droughts (b), and false springs (c) in wildlife refuges under different scenarios of future climate change. The maps depict the changes in frequency from the historical period (1950–2005) to mid-century (2041–2070) and end-of-century (2071–2100), and under two emission scenarios from the Intergovernmental Panel on Climate Change, including RCP4.5 (medium-low emissions) and RCP8.5 (high-emissions). The distinction between the classes "fewer," "no change," and "more," is based on rates of change of 20%. The black lines represent the boundaries of the seven U.S. Fish and Wildlife Service administrative regions. The number of wildlife refuges in each class of the map is included in the map legend. The size of the wildlife refuges is exaggerated for visualization purposes.

portion of the Midwest region were projected to see increased frequency of false springs (Fig. 2c).

3.3. Combined weather variables and identification of potentially threatened wildlife refuges

Ultimately, managers of protected areas will have to address all types of extreme weather events, including extreme heat, droughts, and false springs, making it useful to examine these categories of weather change jointly (Fig. 3). Because 100% of the wildlife refuges were projected to experience more frequent extreme heat events in the future, the patterns of change were determined by the projected patterns of droughts and false springs (Fig. 3a).

Our multivariable map highlights the ubiquity of potential future threats. By mid-century, only 3–4% of the wildlife refuges were projected to see increases in all three extreme weather types, our "maximum" level of threat. However, >40% of the wildlife refuges (44–45%) were projected to see increases in two types of extremes, including extreme heat and droughts, or extreme heat and false springs (Fig. 3). The other half of the wildlife refuges were projected to see decreases or no changes in droughts or false springs in conjunction with increasing frequency of extreme heat, and were located mainly in the Midwest, Northeast, and parts of the Pacific and Southeast administrative regions (Fig. 3a).

Wildlife refuges projected to see increases in the frequency of two or three types of extremes, in total 48% of wildlife refuges by mid-century, occurred in all seven administrative regions, yet at different rates and

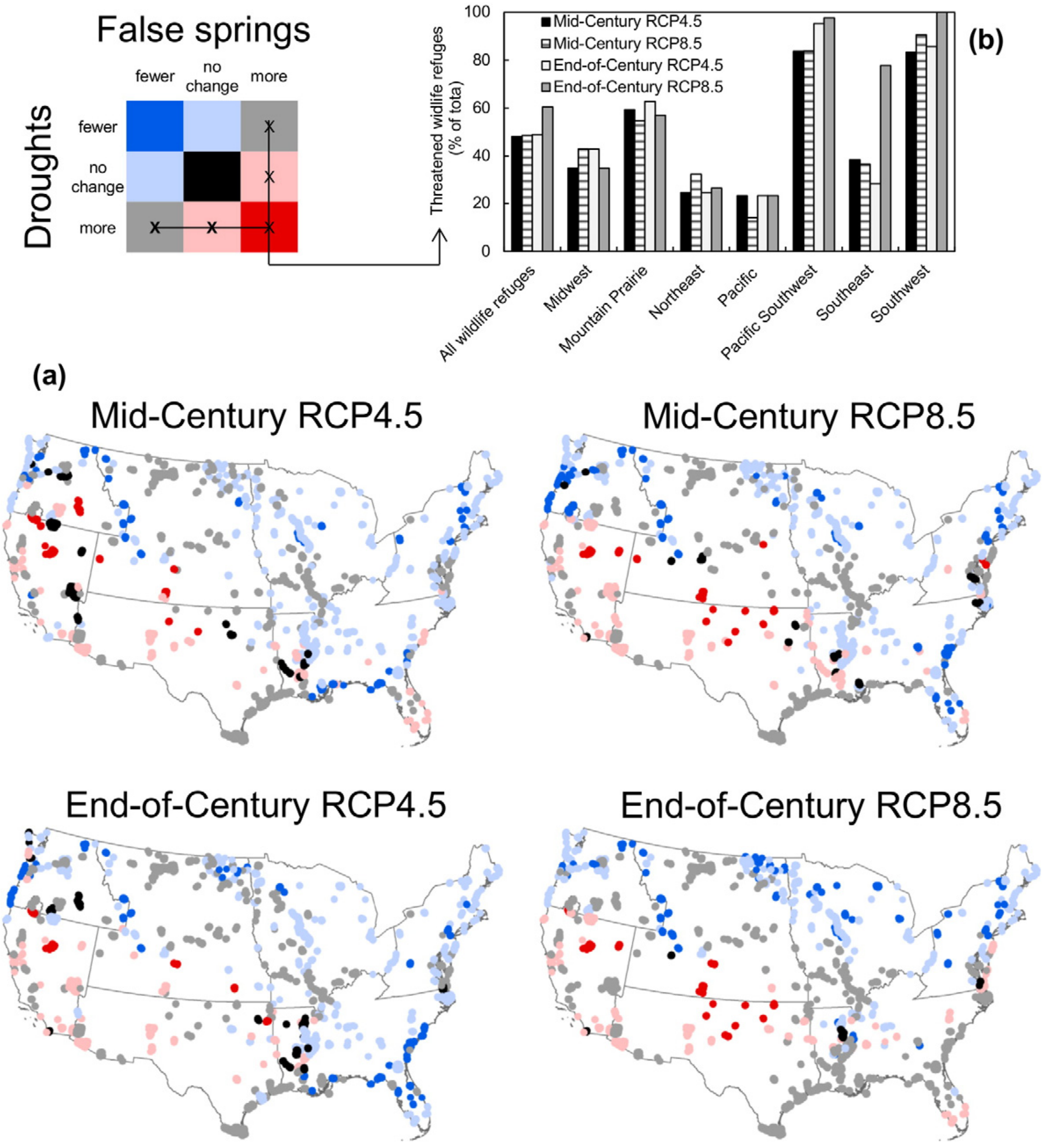

Fig. 3. Combined changes in droughts and false springs in wildlife refuges under different scenarios of future climate change. Extreme heat is projected to increase in all wildlife refuges and therefore not shown. The maps in (a) depict the changes in frequency from the historical period (1950–2005) to mid-century (2041–2070) and end-of-century (2071–2100), and under two emission scenarios from the Intergovernmental Panel on Climate Change, including RCP4.5 (medium-low emissions) and RCP8.5 (high-emissions). The black lines in the maps represent the limits of the seven administrative regions, and the size of the wildlife refuges is exaggerated for visualization purposes. Wildlife refuges projected to see increases in frequency of two or three types of extremes (among extreme heat, droughts, and false springs) are considered threatened. Section (b) shows the number of these wildlife refuges for each U.S. Fish and Wildlife Service administrative region. An increase in frequency is defined as >20% above the current rate.

due to different types of extremes depending on the region (Fig. 3a–b). Among regions, the Southwest and Pacific Southwest administrative regions had the largest number of wildlife refuges projected to see increases in the frequency of two or three types of extremes (up to 83–90% of all wildlife refuges), while the Pacific and Northeast administrative regions had the lowest numbers (14–32%; Fig. 3b). The main threats also varied by administrative region. In the Southwest and Pacific Southwest regions the main threat is increasing frequency of extreme heat and droughts, while in regions such as Mountain Prairie and Northeast it is increasing frequency of extreme heat and false springs (see Table A.2). The results by mid-century and end-of-century were very similar, although the projections under the end-of-century RCP8.5 scenario resulted in a slightly larger number of wildlife refuges projected to see increased frequency of two or three types of extremes, and those differences were most evident in the Southeast (Fig. 3b).

3.3.1. Sensitivity analysis

Our estimates of the number of wildlife refuges projected to see increased frequency of extreme weather events were based on rates of change >20%. Increasing the threshold value defining a change in frequency from >20% to >30% or >40% reduced the number of wildlife refuges projected to see increases in two or three types of extremes, as we expected (Fig. 4). However, these reductions did not change the main findings of our study. Even at a > 40% threshold, we found a substantial number of refuges projected to see increases in two or three types of extremes (19–33% depending on the scenario;

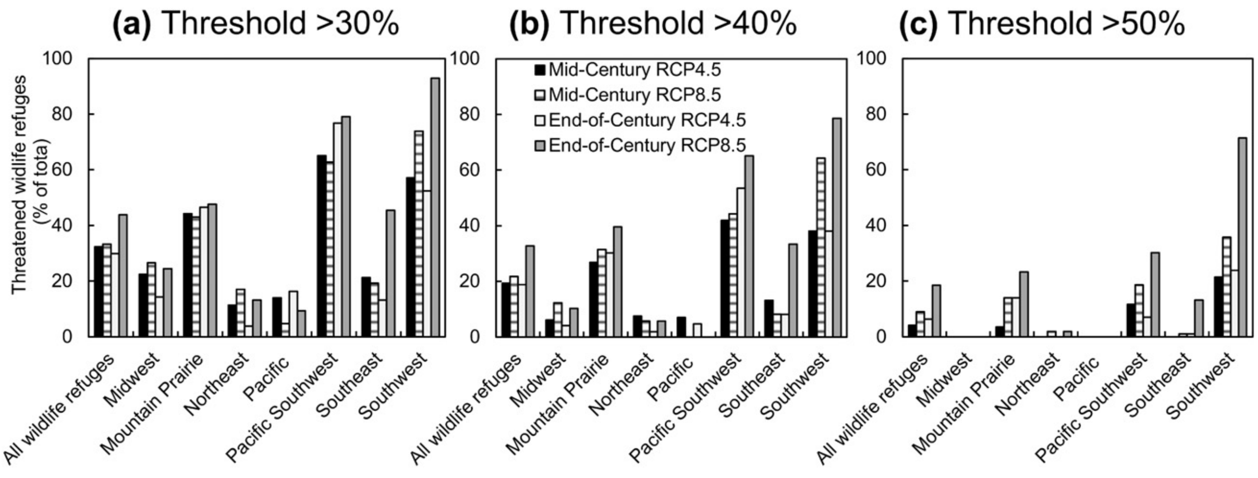

Fig. 4. Results from our sensitivity analysis, i.e., the number of wildlife refuges projected to see increases in frequency of multiple types of extremes, based on different threshold values (>30%, >40%, >50%) defining an "increase" in frequency. The graph depicts the changes relative to the historical period (1950–2005) by mid-century (2041–2070) and end-of-century (2071–2100), and under two emission scenarios from the Intergovernmental Panel on Climate Change, including RCP4.5 (medium-low emissions) and RCP8.5 (high-emissions).

Fig. 4b). At the same time, and under all thresholds, the Pacific Southwest and Southwest administrative regions had the largest number of wildlife refuges projected to experience increases in two or three types of extremes, reinforcing the findings that these regions are projected to see the greatest changes in frequency of extreme weather.

4. Discussion

Land managers need information about future weather conditions in protected areas so they can better prepare for a changing future. We found that wildlife refuges in the U.S. will likely experience substantial changes in the frequency of extreme weather events, namely extreme heat, drought, and false springs. In particular, all wildlife refuges are projected to see increases in extreme heat, and half of the refuges are projected to see increases in frequency of multiple types of extremes. Furthermore, we found notable spatial variation in future extreme weather conditions across the nation, indicating that some wildlife refuges and FWS administrative regions may require more attention than others.

We found that the entire network of wildlife refuges is projected to see 7- to 20-fold increases in the frequency of extreme heat during the spring season. Historical, 20-year extreme heat events are projected to occur every 1–3 years by mid and end-of-century. This is important because high spring temperatures increase heat stress on birds (Jenouvrier, 2013) and reduce bird productivity (Both and Visser, 2001; Drever et al., 2012). Higher temperatures can also decrease water levels and increase vegetation cover in shallow seasonal wetlands (Erwin, 2009; Johnson et al., 2005), potentially reducing breeding success and adult survival for groups such as waterfowl, passerines, and other wildlife groups, and conflicting with the primary FWS mission to "conserve, protect, and enhance…[species] and their habitats" (http://www.fws.gov/who/). Exposure to extreme heat will likely be a common occurrence, and climate change adaptation planning in wildlife refuges should take this into account.

However, extreme heat will not occur alone. We found that almost half of the wildlife refuges are projected to experience increases in the frequency (>20% above the current rate) of droughts or false springs as well, which can exacerbate negative effects on biota caused by heat (Allen et al., 2010; Breitburg et al., 1998). More frequent droughts and extreme heat by mid-century were projected in 26% of all wildlife refuges, mainly in the Southwest and Pacific Southwest FWS administrative regions. These projected drought patterns are consistent with projected changes in mean precipitation during spring from both the CMIP5 models (RCP8.5) and the older CMIP3 models (A2 scenario), as documented in the National Climate Assessment (Walsh et al., 2014). Combined with the increases in annual temperature and reduced precipitation projected for some of these regions (Cook et al., 2015), these refuges may experience increasing bird vulnerability to heat-stress during the breeding season and reduced bird productivity (Bolger et al., 2005), more fires (Westerling et al., 2006), and in the case of wetlands, decreases in water levels or water availability (Allen et al., 2010; Erwin, 2009; Jiménez et al., 2011).

On the other hand, increases in both false springs and extreme heat are most likely in the wildlife refuges of the Mountain Prairie and sections of the Midwest administrative region, affecting ~26% of all wildlife refuges by mid-century. More frequent vegetation damage and reduction in plant productivity associated with false springs, coupled with increasing heat stress on animals at the start of the breeding season, could affect resource availability and populations of wild species in those refuges (Augspurger, 2011; Gu et al., 2008; Parmesan et al., 2000). Although the final response of biota to extremes will depend on multiple factors, our study suggests that a large number of wildlife refuges will likely have to face multiple types of extreme weather in the future.

Identifying priority regions for conservation action is important for agencies managing large protected area networks, such as the FWS (Griffith et al., 2009). At the administrative region level, the Southwest and Pacific Southwest administrative regions had the greatest number of wildlife refuges with projected increases in multiple types of springtime extremes. This is mostly due to larger increases in the frequency of springtime drought compared to other regions, as extreme heat is projected to increase similarly everywhere. This is important because of the effect of these types of extremes on wildlife populations. For example, migratory birds already show strong, negative responses to droughts in these regions (Albright et al., 2010; Cruz-McDonnell and Wolf, 2015), and population models for a local endangered species (the Coachella Valley fringe-toed lizard, *Uma inornata*) project rapid population declines with increasing drought frequency (Barrows et al., 2010). In the southwestern US, summer monsoons provide most of the precipitation, but March typically includes some precipitation (Finkelstein and Truppi, 1991), and less rain in this month may exacerbate negative effects of increased heatwave frequency on spring nesting birds. For the NWRS, an increase in drought conditions in the Southwest and Pacific Southwest has the potential to act as a barrier to neotropical and short distance migrants during spring, due to reduced food availability. The southwestern U.S. is a hotspot for future increases in droughts (Cook et al., 2015), and our study suggests that this area warrants major attention for managers of wildlife refuges.

The negative impacts of springtime drought are not limited to the southwestern portion of the U.S. Regionally, increased drought in the southern Great Plains is likely to strongly negatively affect avian habitat quality (e.g., in much of Texas, which experiences its highest precipitation in the month of May; National Drought Mitigation Center, 2016). Similarly the lower Mississippi Valley and Gulf Coast States experience highest rainfall in the spring months (Finkelstein and Truppi, 1991), and productivity of plants, and thus habitat quality is likely to suffer in response to increased frequency of springtime drought.

At the same time, there was great spatial variation in extreme weather conditions within administrative regions. For instance, we found that all FWS administrative regions had wildlife refuges with projected increases in the frequency of multiple types of extremes (our proxy for increasing threat) that were not evident in the medians at the administrative region level. For conservation planning, this means that a single management strategy is not likely to work within most FWS administrative regions, and that planners could take spatial variation into account when guiding conservation actions within administrative regions. Our findings, thus, highlight the importance of visualizing changes both at the administrative region and individual wildlife refuge level for identifying priority areas, and revealed that all FWS administrative regions may have to deal with threats and stressors affecting wildlife refuges to some degree.

Extreme weather conditions that come on too hard and fast or those exceeding the natural limits of species for too long may require mitigation and adaptation ahead of the expected event to ameliorate their consequences. Mitigation and adaptation are key components of climate change planning in protected areas, including for the NWRS (Czech et al., 2014; Griffith et al., 2009), and our study can provide further insights into both strategies. Landscape management can enhance the resistance of biota to extreme weather events and provide opportunities for mitigation. For example, larger patches of woodland habitat and riparian vegetation can reduce sensitivity of butterfly and bird populations to drought events (Nimmo et al., 2015; Oliver et al., 2013), continued access to food could help wildlife withstand false springs (Gutie et al., 2015), and availability of microhabitats, such as tree holes, can reduce exposure to climate extremes by frogs and lizards (Scheffers et al., 2014). The NWRS has a long history of manipulating water levels to support water birds, and our study suggests that water levels and the ability to manage them may be less of a management concern for north-central refuges, but more so for southern and southwestern refuges, because of the projected increase in drought conditions there. On the other hand, management actions focused on facilitating adaptation to climate change can benefit greatly from understanding how species distributions may change under future climates (Lawler, 2009). The spatial datasets of extreme spring weather generated in this study can be used for modeling species distributions and vulnerabilities to guide adaptive management efforts (Davison et al., 2012). Considering the high levels of exposure to future changes that we found, both mitigation and adaptation may be important for future planning in the NWRS. Preparing resources ahead of anticipated outbreaks of extreme weather-induced disease, fire, and species invasion could be possible. For example, unfavorable weather effects might be mitigated through forest thinning, pre-emptive and controlled burning of grasslands, or supplementation of limiting resources. Additionally, given the role hunting has as an important recreational activity within the NWRS, coordinating harvest policy in concert with anticipated effects of extreme events on harvestable populations may increase population resilience, or at least prevent exacerbation of one problem by another. Our weather projections for each wildlife refuge are included in Appendix B to facilitate this planning.

Our study was also subject to some limitations. We focused on spring extreme heat, droughts, and false springs, but other types of extreme weather can also threaten the NWRS. For example, more intense and frequent rainfall, as projected for the Midwest and Northeast (Walsh et al., 2014), could increase the frequency of floods and alter the composition of aquatic and riparian communities (Czech et al., 2014), creating additional challenges for managing lands. However, modeling floods was beyond the scope of our study. In addition, we modeled the probabilities of different types of extreme weather events separately and then visualized all together, but we did not explicitly model the probabilities of co-occurrence of multiple types of extremes. Doing so would be important for better understanding synergies and intensifying effects of multiple types of extremes on the NWRS. At the same time, interactions between temperature and snow cover affect herpetofauna, but we did not model these effects here. Further, the extended Spring Index used to estimate flower emergence in this study was designed as a general spring phenological model for temperate and subtropical ecosystems (Schwartz et al., 2013), but more detailed, species-specific models may be required for particular regions with different annual cycles (e.g. deserts). Furthermore, our patterns of extreme weather change apply only to the spring season, and may be different for other seasons (Walsh et al., 2014). Similarly, some protected areas could also experience large species turnover under low levels of climate change, and vice versa (Langdon and Lawler, 2015), but we did not model species distributions here. Meanwhile, other activities such as land use around protected areas can strongly affect the ability of biota to respond to future climate changes (Hamilton et al., 2016). For example, wildlife refuges in parts of the Eastern U.S. and on the West Coast are projected to see high rates of urban expansion in their surrounding lands (Martinuzzi et al., 2015). Similarly, sea level rise is projected to threaten wildlife refuges in coastal areas, but we did not include sea level rise here. Hence, our study provides a first approximation of the exposure of the NWRS to future changes in extreme weather and potential threats.

Climate conditions are changing in protected areas around the globe (Monahan and Fisichelli, 2014; van Wilgen et al., 2016) and the NWRS is one of the cornerstones for plant and animal protection in the U.S. Our study showed that future changes in extreme weather events could threaten the ability of wildlife refuges to function in this role. Those involved in management and mitigation efforts in the NWRS may need to consider the potential consequences of future changes in extreme weather, as well as the notable spatial variation in predicted changes across the US.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2016.07.007.

Acknowledgments

We gratefully acknowledge support for this research by the NASA Biodiversity and Ecological Forecasting Program under grant NNH10ZDA001N-BIOCLIM-12. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Any use of trade, product, or firm names are for descriptive purposes only and do not imply endorsement by the U.S. Government.

References

Albright, T.P., Pidgeon, A.M., Rittenhouse, C.D., Clayton, M.K., Flather, C.H., Culbert, P.D., Wardlow, B.D., Radeloff, V.C., 2010. Effects of drought on avian community structure. Glob. Chang. Biol. 16, 2158–2170. http://dx.doi.org/10.1111/j.1365-2486.2009.02120.x.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., Mcdowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H.T., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684. http://dx.doi.org/10.1016/j.foreco.2009.09.001.

Allstadt, A.J., Vavrus, S.J., Heglund, P.J., Pidgeon, A.M., Thogmartin, W.E., Radeloff, V.C., 2015. Changes in spring onset and false springs in the conterminous U.S. during the 21st century. Environ. Res. Lett. 10, 104008.

Augspurger, C.K., 2011. Frost damage and its cascading negative effects on *Aesculus glabra*. Plant Ecol. 212, 1193–1203. http://dx.doi.org/10.1007/s11258-011-9897-z.

Augspurger, C.K., 2013. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: spring damage risk is increasing. Ecology 94, 41–50.

Barrows, C.W., Rotenberry, J.T., Allen, M.F., 2010. Assessing sensitivity to climate change and drought variability of a sand dune endemic lizard. Biol. Conserv. 143, 731–736. http://dx.doi.org/10.1016/j.biocon.2009.12.013.

Bateman, B.L., Pidgeon, A.M., Radeloff, V.C., Allstadt, A.J., Akc, H.R., Thogmartin, W.E., Vavrus, S.J., Heglund, P.J., 2015. The importance of range edges for an irruptive species during extreme weather events. Landsc. Ecol. 30, 1095–1110. http://dx.doi.org/10.1007/s10980-015-0212-6.

Bolger, D.T., Patten, M.A., Bostock, D.C., 2005. Avian reproductive failure in response to an extreme climatic event. Oecologia 142, 398–406. http://dx.doi.org/10.1007/s00442-004-1734-9.

Both, C., Visser, M.E., 2001. Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. Nature 411, 296–298. http://dx.doi.org/10.1038/35077063.

Breitburg, D., Baxter, J., Hatfield, C., Howarth, R., Jones, C., Lovett, G., Wigand, C., 1998. Understanding effects of multiple stressors: ideas and challenges. In: Pace, M., Groffman, P. (Eds.), Successes, Limitations, and Frontiers in Ecosystem Science SE - 17. Springer New York, pp. 416–431 http://dx.doi.org/10.1007/978-1-4612-1724-4_17.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sánchez, G., Peñuelas, J., 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. Proc. Natl. Acad. Sci. U. S. A. 108, 1474–1478. http://dx.doi.org/10.1073/pnas.1010070108.

Cook, B.I., Ault, T.R., Smerdon, J.E., 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Sci. Adv. 1, e1400082.

Cruz-McDonnell, K.K., Wolf, B.O., 2015. Rapid warming and drought negatively impact population size and reproductive dynamics of an avian predator in the arid southwest. Glob. Chang. Biol. http://dx.doi.org/10.1111/gcb.13092.

Czech, B., Covington, S., Crimmins, T.M., Ericson, J.A., Flather, C., Gale, M., Gerst, K., Higgins, M., Kaib, M., Marino, E., Moran, T., Morton, J., Niemuth, N., Peckett, H., Savignano, D., Saperstein, L., Skorupa, S., Wagener, E., Wilen, B., Wolfe, B., 2014. Planning for Climate Change on the National Wildlife Refuge System (Washington, DC).

Dale, V., Joyce, L., Mcnulty, S., Neilson, R., Ayres, M., Flannigan, M., Hanson, P., Irland, L., Lugo, A., Peterson, C., Simberloff, D., Swanson, F., Stocks, B., M., W., 2001. Climate change and forest disturbances. Bioscience 51, 723–734.

Davison, J.E., Coe, S., Finch, D., Rowland, E., Friggens, M., Graumlich, L.J., 2012. Bringing indices of species vulnerability to climate change into geographic space: an assessment across the Coronado national forest. Biodivers. Conserv. 21, 189–204. http://dx.doi.org/10.1007/s10531-011-0175-0.

Drever, M.C., Clark, R.G., Derksen, C., Slattery, S.M., Toose, P., Nudds, T.D., 2012. Population vulnerability to climate change linked to timing of breeding in boreal ducks. Glob. Chang. Biol. 18, 480–492. http://dx.doi.org/10.1111/j.1365-2486.2011.02541.x.

Erwin, K.L., 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl. Ecol. Manag. 17, 71–84. http://dx.doi.org/10.1007/s11273-008-9119-1.

Filewod, B., Thomas, S., 2014. Impacts of a spring heat wave on canopy processes in a northern hardwood forest. Glob. Chang. Biol. 20, 360–371. http://dx.doi.org/10.1111/gcb.12354.

Finkelstein, P.L., Truppi, L.E., 1991. Spatial-distribution of precipitation seasonality in the United-States. J. Clim. 4, 373–385. http://dx.doi.org/10.1175/1520-0442(1991)004<0373:sdopsi>2.0.co;2.

Garcia, R.A., Cabeza, M., Rahbek, C., Araújo, M.B., 2014. Multiple dimension of climate change and their implications for biodiversity. Science 344, 1247579. http://dx.doi.org/10.1126/science.1247579.

Griffith, B., Scott, J.M., Adamcik, R., Ashe, D., Czech, B., Fischman, R., Gonzalez, P., Lawler, J., McGuire, A.D., Pidgorna, A., 2009. Climate change adaptation for the US National Wildlife Refuge System. Environ. Manag. 44, 1043–1052. http://dx.doi.org/10.1007/s00267-009-9323-7.

Gu, L., Hanson, P.J., Post, W.M.A.C., Dale, P., 2008. The 2007 eastern US spring freeze: increased cold damage in a warming world? Bioscience 58, 253–262.

Gutie, J.S., Senner, N.R., Verhoeven, M.A., Masero, A., Tibbitts, T.L., Hooijmeijer, J.C.E.W., Kentie, R., Piersma, T., 2015. When Siberia came to the Netherland: the response of continental black-tailed godwits to a rare spring weather event. J. Appl. Ecol. 84, 1164–1176. http://dx.doi.org/10.1111/1365-2656.12381.

Guttman, N.B., 1999. Accepting the standardized precipitation index: a calculation algorithm. J. Am. Water Resour. Assoc. 35, 311–322.

Hamilton, C.M., Martinuzzi, S., Plantinga, A.J., Radeloff, V.C., Lewis, D.J., Thogmartin, W.E., Heglund, P.J., Pidgeon, A.M., 2013. Current and future land use around a nationwide protected area network. PLoS One 8, e55737. http://dx.doi.org/10.1371/journal.pone.0055737.

Hamilton, C.M., Baumann, M., Pidgeon, A.M., Helmers, D.P., Thogmartin, W.E., Heglund, P.J., Radeloff, V.C., 2016. Past and predicted future effects of housing growth on open space conservation opportunity areas and habitat connectivity around National Wildlife Refuges. Landsc. Ecol. http://dx.doi.org/10.1007/s10980-016-0392-8.

Hannah, L., 2008. Protected areas and climate change. Ann. N. Y. Acad. Sci. 212, 201–212. http://dx.doi.org/10.1196/annals.1439.009.

Hole, D.G., Willis, S., Pain, D.J., Fishpool, L.D., Butchart, S.H.M., Collingham, Y., Rahbek, C., Huntley, B., 2009. Projected impacts of climate change on a continent-wide protected area network. Ecol. Lett. 12, 420–431. http://dx.doi.org/10.1111/j.1461-0248.2009.01297.x.

Hufkens, K., Friedl, M.A., Keenan, T.F., Sonnentag, O., 2012. Ecological impacts of a widespread frost event following early spring leaf-out. Glob. Chang. Biol. 18, 2365–2377. http://dx.doi.org/10.1111/j.1365-2486.2012.02712.x.

Inouye, D.W., 2008. Effects of climate change on phenology, frost damage, and flora abundance of montane wildflowers. Ecology 89, 353–362.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Jenouvrier, S., 2013. Impacts of climate change on avian populations. Glob. Chang. Biol. 19, 2036–2057. http://dx.doi.org/10.1111/gcb.12195.

Jiménez, M.A., Jaksic, F.M., Armesto, J.J., Gaxiola, A., Meserve, P.L., Kelt, D.A., Gutiérrez, J.R., 2011. Extreme climatic events change the dynamics and invasibility of semi-arid annual plant communities. Ecol. Lett. 14, 1227–1235. http://dx.doi.org/10.1111/j.1461-0248.2011.01693.x.

Johnson, W.C., Millett, B.V., Gilmanov, T., Voldseth, R.A., Guntenspergen, G.R., Naugle, D.E., 2005. Vulnerability of northern prairie wetlands to climate change. Bioscience 55, 863–872.

Langdon, J.G.R., Lawler, J.J., 2015. Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. Ecosphere 6, 1–14.

Lawler, J.J., 2009. Climate change adaptation strategies for resource management and conservation planning. Ann. N. Y. Acad. Sci. 98, 79–98. http://dx.doi.org/10.1111/j.1749-6632.2009.04147.x.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., Ackerly, D.D., 2009. The velocity of climate change. Nature 462, 1052–1055. http://dx.doi.org/10.1038/nature08649.

Marino, G.P., Kaiser, D.P., Gu, L., Ricciuto, D.M., 2011. Reconstruction of false spring occurrences over the southeastern United States, 1901–2007: an increasing risk of spring freeze damage? Environ. Res. Lett. 6, 024015. http://dx.doi.org/10.1088/1748-9326/6/2/024015.

Martinuzzi, S., Radeloff, V.C., Joppa, L.N., Hamilton, C.M., Helmers, D.P., Plantinga, A.J., Lewis, D.J., 2015. Scenarios of future land use change around United States' protected areas. Biol. Conserv. 184, 446–455. http://dx.doi.org/10.1016/j.biocon.2015.02.015.

Maurer, E.P., Brekke, L., Pruitt, T., Duffy, P.B., 2007. Fine-resolution climate projections enhance regional climate change impact studies. EOS, Trans. Am. Geophys. Union 88, 504.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology Vol. 17. American Meteorological Society, Boston, MA, USA No. 22.

Monahan, W.B., Fisichelli, N.A., 2014. Climate exposure of US national parks in a new era of change. PLoS One 9, e101302. http://dx.doi.org/10.1371/journal.pone.0101302.

National Drought Mitigation Center, 2016. Onal Drought Mitigation Center [WWW Document]. (URL http://drought.unl.edu/ranchplan/DroughtBasics/GeographyDrought/TimingofPrecipitation.aspx).

Nimmo, D.G., Haslem, A., Radford, J.Q., Hall, M., Bennett, A.F., 2015. Riparian tree cover enhances the resistance and stability of woodland bird communities during an extreme climatic event. J. Appl. Ecol. http://dx.doi.org/10.1111/1365-2664.12535.

Nixon, C.M., McClain, M.W., 1969. Squirrel population decline following a late spring frost. J. Wildl. Manag. 33, 353–357. http://dx.doi.org/10.2307/3799835.

Oliver, T.H., Brereton, T., Roy, D.B., 2013. Population resilience to an extreme drought is influenced by habitat area and fragmentation in the local landscape. Ecography (Cop.) 36, 579–586. http://dx.doi.org/10.1111/j.1600-0587.2012.07665.x.

Parmesan, C., Root, T.L., Willig, M.R., 2000. Impacts of extreme weather and climate on terrestrial biota. Bull. Am. Meteorol. Soc. 91, 443–450.

Reclamation, 2014. Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Needs. Denver, Colorado.

Reyer, C.P.O., Leuzinger, S., Rammig, A., Pereira, I.Z.I.A., 2013. A plant's perspective of extremes: terrestrial plant responses to changing climatic variability. Glob. Chang. Biol. 19, 75–89. http://dx.doi.org/10.1111/gcb.12023.

Sakai, A., Larcher, W., 1987. Frost Survival of Plants: Responses and Adaptation to Freezing Stress. Springer-Verlag, Berlin, Heidelberg.

Scheffers, B.R., Edwards, D.P., Diesmos, A., Williams, S.E., Evans, T.A., 2014. Microhabitats reduce animal's exposure to climate extremes. Glob. Chang. Biol. 20, 495–503. http://dx.doi.org/10.1111/gcb.12439.

Schwartz, M.D., 1993. Assessing the onset of spring: a climatological perspective. Phys. Geogr. 1, 536–550.

Schwartz, M.D., Ault, R., Betancourt, J.L., 2013. Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices. Int. J. Climatol. 33, 2917–2922. http://dx.doi.org/10.1002/joc.3625.

Scriven, S.A., Hodgson, J.A., Mcclean, C.J., Hill, J.K., 2015. Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. Biol. Conserv. 184, 414–423. http://dx.doi.org/10.1016/j.biocon.2015.02.018.

Thurow, T.L., Taylor, C.A., 1999. Viewpoint: the role of drought in range management. J. Range Manag. 52, 413–419. http://dx.doi.org/10.2307/4003766.

van Wilgen, N.J., Goodall, V., Holness, S., Chown, L., Mcgeoch, M.A., 2016. Rising temperatures and changing rainfall patterns in South Africa's national parks. Int. J. Climatol. 36. http://dx.doi.org/10.1002/joc.4377.

Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., Thorne, P., Vose, R., Wehner, M., Willis, J., Anderson, D., Doney, S., Feely, R., Hennon, P., Kharin, V., Knutson, T., Landerer, F., Lenton, T., Kennedy, J., Somerville, R., 2014. Ch. 2: our changing climate. In: Melillo, J.M., Richmond, T.C., Yohe, G.W. (Eds.), Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, pp. 19–67 http://dx.doi.org/10.7930/J0KW5CXT.

Walther, G., 2010. Community and ecosystem responses to recent climate change. Philos. Trans. R. Soc. B 365, 2019–2024. http://dx.doi.org/10.1098/rstb.2010.0021.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943. http://dx.doi.org/10.1126/science.1128834.

Wiens, J.A., Seavy, N.E., Jongsomjit, D., 2011. Protected areas in climate space: what will the future bring? Biol. Conserv. 144, 2119–2125. http://dx.doi.org/10.1016/j.biocon.2011.05.002.

World Meteorological Association, 2009. Press Release No. 872. Experts Agree on a Universal Drought Index to Cope With Climate Risks.