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De-extinction potential under climate change: Extensive mismatch between historic and future habitat suitability for three candidate birds

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ABSTRACT

De-extinction is becoming potentially feasible for restoring extinct species in the wild, but research is required to determine the likelihood of success in light of contemporary and future environmental change. We assessed 1900–2100 change in suitable climate and land cover in the historic range of Carolina parakeet (*Conuropsis carolinensis*), ivory-billed woodpecker (*Campephilus principalis*) and passenger pigeon (*Ectopistes migratorius*), in North America. Parakeet and woodpecker historic range currently remains climatically-favourable, but intensified land use has broadly reduced habitat in contemporary landscapes. For passenger pigeon, more substantive loss in climate and land cover suitability exists in both the historic full range and primary breeding range. Long-term climate and land cover projections suggest that improved habitat suitability and increased potential future distribution outside historic ranges are likely for each de-extinction candidate. While such changes could improve probability of success for de-extinction programs, extensive mismatch between historic and future habitat suitability highlights the potential risks of reviving species that may colonize novel geographic space. To date, potential long-term negative effects of de-extinction programs to ecosystems outside historic ranges have not been elucidated, making this a priority concern for any serious proposal. To address whether benefits of reinstating extinct species to historic ecosystems outweigh risks to extant species outside their historic range will require extensive ecological, social and economic analyses that extend beyond that conducted to-date for this potentially transformational conservation tool.

1. Introduction

Extinction represents the permanent loss of a species, marked by the death of the last remaining individual. However, recent technological advances in synthetic biology have clouded this definition (Church and Regis, 2012; Folch et al., 2009), allowing for the possibility of bringing back extinct species (Sherkow and Greely, 2013). Reviving lost species can be beneficial for restoring natural ecosystems, as extinct species may have played an important role in ecological community dynamics (Ellsworth and McComb, 2003). Although restoration of extinct species (i.e., 'de-extinction' sensu Seddon et al., 2014) certainly has potential benefits to native communities and ecosystems, several important factors must be weighed prior to any attempted re-establishment (Jorgensen, 2013). Despite the recent surge in publications discussing ethical and conservation-related issues surrounding the revival of extinct species (Sandler, 2014; Seddon et al., 2014), there have not been rigorous empirical evaluations of restoration potential in contemporary and future environmental conditions.

One important factor determining the potential for success of de-extinction programs is the availability of habitat to support recovering populations (Armstrong and Seddon, 2008). With climate change, regions of the extinct species' documented former range may no longer be climatically suitable, and intensified land use over the past century (Klein Goldewijk et al., 2011) may further limit the availability of habitat. Similar to protocols for assessing potential for reintroducing endangered species (IUCN, 2013), changes in habitat suitability and likely areas of occupation should be examined before the revival and re-establishment of extinct species is seriously considered. In particular, long timespan since extinction from the wild will increase the likelihood that climate and land use change will have irreversibly altered natural environments, thereby reducing the likelihood of successful re-establishment. In some cases environmental change may be sufficiently substantive as to call into doubt the validity of resurrecting certain extinct species, at least within their indigenous range. Further, in many regions there is inadequate protection of natural spaces (Jenkins et al., 2015), meaning that

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any attempt at species resurrection could face serious challenges in terms of protecting individuals and their habitats. Accordingly, to maximize the likelihood of successful resurrection, a primary goal should include determining the optimal location and extent of occupancy for a potential reintroduction program, based on current and future environmental suitability and protection.

A primary concern surrounding de-extinction is the potential negative consequences it poses to extant biodiversity (Jorgensen, 2013). Climate change and contemporary land use patterns have elicited range shifts for numerous species (Parmesan and Yohe, 2003), and such shifts would logically be expected by species that are re-established via de-extinction. Therefore, re-established populations of extinct species may not only cause conflicts with existing species within their indigenous range, but also to species and ecosystems occurring beyond their previous range limits. Predicting the expansion of suitable climate and land-use space beyond the extinct species' former distribution will provide insight into the potential that candidates will become established in geographic regions and ecosystems that historically did not contain the species. Such establishment could be problematic if candidates negatively impact biodiversity through competitive interactions or ecosystem changes, but this facet of the de-extinction debate has not been considered in detail.

The Carolina parakeet (*Conuropsis carolinensis*), ivory-billed woodpecker (*Campephilus principalis*) and passenger pigeon (*Ectopistes migratorius*) are three historically wide-ranging North American bird species that went extinct in the first half of the 20th century; each has been mentioned as a serious candidate for de-extinction and re-establishment in the wild (Seddon et al., 2014; longnow.org/revive/candidates). In this study, we modelled the historic environmental niche of each species and projected its potential future distribution beyond previously known range limits. We estimate the change in suitable area for each species caused by climate change alone, as well as when environmental suitability is restricted by contemporary land use practices. By projecting habitat suitability beyond documented range limits for each species, we: 1) Assess the potential for these candidates to colonize areas where they did not occur previously; and 2) Identify possible release sites taking into account the location of future suitable habitat. Overall, this research provides a general framework illustrating how to consider changing habitat and climate when assessing de-extinction potential of a given species.

2. Methods

2.1. Study species

The Carolina parakeet ranged broadly throughout the eastern United States, from southern Florida to potentially as far north as New York. The distribution of the species was linked to cypress/sycamore rivers and swamps (Snyder and Russell, 2002). Many aspects of this species' biology are unknown, including the primary driver of its extinction, which could be due to overharvesting, deforestation, and/or disease (Snyder and Russell, 2002). The range of ivory-billed woodpecker was restricted to the southeastern United States, mainly from North Carolina to Florida and west to eastern Texas and Arkansas. This species required large patches of mature bottomland forest with substantial deadwood, which provided adequate quantities of their primary food source, beetle larvae (Jackson, 2002). Declines of this species are linked to the increase in deforestation within their historic range (Jackson, 2002). Passenger pigeon primarily occurred east of the Rocky Mountains, from the Gulf of Mexico to James Bay. The passenger pigeon's breeding range extended across the eastern deciduous forest. Estimated at the time of European settlement as numbering 3–5 billion individuals (Blockstein, 2002), the passenger pigeon was once the most abundant land bird in North America. Strong hunting pressure and nest site disturbance likely drove it to extinction in the early 20th century (Stanton, 2014). These species were chosen for our analysis because of their inclusion in current de-extinction proposals (Seddon et al., 2014; longnow.org/revive/candidates), as opposed to ease of resurrection or ecological benefits.

2.2. Model development

We modelled environmental suitability for each species and calculated changes in suitability between historic, current, and future climates using the program MaxEnt (Phillips et al., 2006). We collected information on species' historic presence from freely accessible databases and published material (see Supporting Information), and related presence with historic climate data from Natural Resource Canada (McKenney et al., 2011). We used monthly climate averaged over 1901–1930 to represent historic climate, and included: Maximum Temperature, Minimum Temperature and Precipitation in the modelling exercise (see below). The historic model was projected onto averaged climate data from 1971–2000 to model current environmental suitability, and two general circulation models (GCM) were applied using the A2 scenario to forecast suitability into the future (short term: 2041–2070; long-term: 2071–2100). Notably, the A2 scenario is the most liberal climate projection, but it is increasingly seen as the best reflection of current patterns in global carbon emissions (Beaumont et al., 2008; Raupach et al., 2007). Future climate data were also obtained from Natural Resource Canada (McKenney et al., 2011). To account for variation among GCMs, we created a final environmental suitability map for each species by taking mean environmental suitability value from each separate GCM (see Supporting Information for detailed modelling methods and evaluation).

2.3. Passenger pigeon breeding range

Given the migratory behaviour of the passenger pigeon, we developed two models for this species: one representing the full distribution, the other, their primary breeding ground. To model changes in suitable environment in the primary breeding range, we selected presence records from our full set of species occurrence data that were identified as either egg or nest, or had a collection date between March and June, which coincided with the breeding period for the species (Blockstein, 2002). As with each species' full range, we further removed records that fell more than 100 km outside the primary breeding range to address outliers and likely errors in geographic location of records (adapted from Blockstein, 2002). We calculated climate for the breeding season by averaging values for the primary breeding months (March–June) for each period mentioned above.

2.4. Changes in habitat suitability and protected areas

To calculate changes in environmental suitability, we used a two-threshold approach for converting continuous models into binary suitable/unsuitable values (Milanovich et al., 2010; see Supporting Information). This approach allowed us to obtain a range of climate change impacts on historic suitability. We also restricted climatic suitability for each species by removing any climatically-suitable grid cell that fell in arctic, tundra or desert ecosystems, as determined by the EPA (United States Environmental Protection Agency) information of ecoregion classes (Omernik, 1987), as well as cells classified as lakes (based on the HYDE 3.1 dataset; see below). Using these binary models for each species we calculated loss of suitable area within the indigenous range and gain of suitable area outside the indigenous range.

We further estimated change in suitability caused by land use change for the time periods 1900, 2000, 2070, and 2100. We removed suitable grid cells that had >50% of the area classified as cropland, pastureland, or urban area determined from the HYDE 3.1 dataset (Klein Goldewijk et al., 2011), which were land use types determined to be unsuitable for restoring natural ecosystems.

We identified protected areas using the IUCN World database on Protected Areas, (WDPA; www.wdpa.org), the Protected Areas Database of the United States (PAD-US; www.protectedlands.net), and