Landscape Ecol
DOI 10.1007/s10980-016-0392-8

RESEARCH ARTICLE

Past and predicted future effects of housing growth on open space conservation opportunity areas and habitat connectivity around National Wildlife Refuges

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Received: 13 March 2015 / Accepted: 5 May 2016

Abstract
Context Housing growth can alter suitability of matrix habitats around protected areas, strongly affecting movements of organisms and, consequently, threatening connectivity of protected area networks.
Objectives Our goal was to quantify distribution and growth of housing around the U.S. Fish and Wildlife Service National Wildlife Refuge System. This is important information for conservation planning, particularly given promotion of habitat connectivity as a climate change adaptation measure.
Methods We quantified housing growth from 1940 to 2000 and projected future growth to 2030 within three distances from refuges, identifying very low housing density open space, "opportunity areas" (contiguous areas with <6.17 houses/km^2), both nationally and by USFWS administrative region. Additionally, we quantified number and area of habitat corridors within these opportunity areas in 2000.
Results Our results indicated that the number and area of open space opportunity areas generally decreased with increasing distance from refuges and with the passage of time. Furthermore, total area in habitat corridors was much lower than in opportunity areas. In addition, the number of corridors sometimes exceeded number of opportunity areas as a result of habitat fragmentation, indicating corridors are likely vulnerable to land use change. Finally, regional

Electronic supplementary material The online version of this article (doi:10.1007/s10980-016-0392-8) contains supplementary material, which is available to authorized users.

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Published online: 11 June 2016

differences were strong and indicated some refuges may have experienced so much housing growth already that they are effectively too isolated to adapt to climate change, while others may require extensive habitat restoration work.

Conclusions Wildlife refuges are increasingly isolated by residential housing development, potentially constraining the movement of wildlife and, therefore, their ability to adapt to a changing climate.

Keywords Connectivity · Corridors · Climate change adaptation · Exurban growth · Housing growth

Introduction

Habitat connectivity maintains critical ecological flows and is a key method proposed to mitigate climate change and promote ecological resilience in the face of global change (Scheffer et al. 2001; Carpenter et al. 2006). Protected areas, a main tool for conserving biodiversity, must therefore be viewed in the larger landscape context in which they occur (Hansen and DeFries 2007; Wiens 2009). The condition of matrix habitats, defined here as those areas outside of protected areas, strongly influences connectivity and, by extension, ecological flows to and from protected areas (Lindenmayer and Nix 1993; Fischer and Lindenmayer 2007).

Among land uses, housing growth is a significant threat to biodiversity in the United States (Flather et al. 1998; Hansen et al. 2005), especially because it is commonly associated with infrastructure development activities, which have their own environmental effects (Hawbaker and Radeloff 2004). Habitat changes related to housing affect individual species (Merenlender et al. 2009), community composition of many taxonomic groups (Miller et al. 2003; Pidgeon et al. 2007; Eigenbrod et al. 2008), predation rates (Wilcove 1985), species abundance and distribution (Fahrig and Rytwinski 2009), species invasions (Gavier-Pizarro et al. 2010), and ecological flows (Hawbaker et al. 2006; Patrick and Gibbs 2010). Once land is in residential development, it is unlikely to change to another use (Nusser and Goebel 1997). However, despite the impacts of housing growth, our methods for identifying the location of housing at broad spatial extents are imperfect and residential development often remains undetected (Pidgeon et al. 2007).

Native species diversity and abundance tend to decrease with increased housing density along the rural-to-urban gradient (Blair 1996; Eigenbrod et al. 2008; Gagne and Fahrig 2010a). Low-density rural housing (densities ranging between 6 and 25 houses/km^2) has been a particularly fast-growing land use in the United States (Brown et al. 2005; Hansen et al. 2005). The area of influence of houses in low-density developments is proportionately larger than that of houses in suburban sprawl (Radeloff et al. 2005). In addition, housing growth in recent decades has been notably high near the boundaries of protected areas (Hammer et al. 2009; Radeloff et al. 2010; Wade and Theobald 2010). This growth pattern is driven by the amenity-rich nature of protected areas and is problematic because protected areas are crucial for biodiversity conservation. Housing growth at the boundaries may thus reduce the conservation value of protected areas (Leinwand et al. 2010; Radeloff et al. 2010; Wade and Theobald 2010).

Prior research has only reported average housing densities in the surroundings of protected areas, rather than the spatial distribution of housing at protected area boundaries (Gaston et al. 2008; Joppa et al. 2008). The spatial distribution of housing is important because comparable densities of housing in the surroundings of protected areas may vary in their configuration. Widely dispersed housing is much more likely to isolate refuges, while more clustered housing may still allow connectivity and the persistence of ecological flows critical to resilience of natural systems and wildlife populations. Given concerns that climate change will likely exacerbate other stressors that include urbanization, habitat loss, and habitat fragmentation, there is high interest in maintaining and/or restoring habitat connectivity. The USFWS is interested in maintaining, or through targeted restoration, improving connectivity for the NWRS as an adaptation measure for climate change (Griffith et al. 2009). Evaluating the current and future state of areas without housing and habitat corridors surrounding the National Wildlife Refuges is thus a necessary step in conservation planning aimed at improving resilience and climate adaptation (Griffith et al. 2009; Hamilton et al. 2013).

We evaluated the spatial distribution of housing around the NWRS in the conterminous United States. We posed four questions:

- How has the pattern of very low-density housing around National Wildlife Refuges changed over time?
- Does the current and future pattern of housing provide opportunity areas within which habitat could be created to allow species to migrate among National Wildlife Refuges across the United States?
- What is the current status of habitat corridors within existing very low-density housing opportunity areas?
- How does the status of very low-density housing opportunity areas and corridors vary among the administrative regions by which the NWRS is organized and managed?

Methods

Study area

The U.S. National Wildlife Refuge System (NWRS) is unique among federal lands in that its primary focus is on wildlife conservation in contrast with other federal lands (e.g., U.S. Forest Service, Bureau of Land Management, and National Park Service). Additionally, the NWRS has a stated goal of maintaining the biological integrity of the refuge system (Meretsky et al. 2006), which is complicated by the fact that many of the refuges occur in a matrix of intensive land uses such as agriculture (Scott et al. 2004). We evaluated housing growth around Refuges in the contiguous 48 United States. We only evaluated NWRS lands that were specifically designated as refuges in the USFWS cadastral database (http://www.fws.gov/GIS/data/CadastralDB/), and excluded lands that are not directly managed by USFWS (i.e., cooperatively managed lands). This resulted in a set of 455 refuges. We analyzed the NWRS as a whole, and each of the 7 administrative regions in the conterminous United States.

Extent of analyses

We modeled housing and housing growth at different spatial and temporal scales around the refuges to quantify how the number and size of very low density housing opportunity areas changed over the past 60 years and may change in the future. Housing was analyzed within 5, 25, and 75 km of each refuge. Some areas fell within the analyzed extents of multiple refuges due to their proximity (e.g., some housing was within 75 km of two or more refuges). These areas were only counted once for the refuge system as a whole and once within each region, but potentially more than once for different refuges or regions. In addition to spatial extent, we analyzed historical (1940, 1970, and 2000) and projected (2030) housing density at each distance (5, 25, 75 km) from refuges.

The spatial analysis extent was based on our previous work evaluating change around the NWRS (Hamilton et al. 2013) and allowed us to evaluate a range of distances given that body size and habit are known to generally affect dispersal distances of animals (Sutherland et al. 2000). In addition, the maximum distance reflected the distance from refuges within which most USFWS private land habitat restoration projects have been completed under the 25-year-old program called "Partners for Fish and Wildlife", which has restored over 1,000,000 acres of wetland as of 2010 (http://www.fws.gov/partners/).

Housing data

We obtained housing data from the 2000 U.S. Decennial Census at the partial block group level, the smallest unit for which information on the age of housing units is released by the U.S. Census Bureau. Based on the age of housing units and historic county-level housing totals, it is possible to backcast housing density for each decade from 1940 to 1990 (Radeloff et al. 2001; Hammer et al. 2004). However, the Census Bureau does not provide spatial boundaries for partial block groups. Thus, to generate the spatial boundaries of partial block groups we aggregated the census blocks within each partial block group (Hammer et al. 2004). The partial block groups allowed for more refined analysis because they are typically an order of magnitude smaller than block groups.

Forecasting of future housing densities is possible by extrapolating 1990s housing growth rates and adjusting these estimates based on county-level population projections from Woods & Poole Economics (http://www.woodsandpoole.com/), as was done by Radeloff et al. (2010). The Woods and Poole projections were based on a cohort-component model based on calculated fertility and mortality in each population forecast area (i.e., a county), as amended by labor demand (to accommodate immigration). We applied county-specific household sizes to convert population growth to housing unit growth, an adjustment accounting for high frequencies of vacant housing units in areas with high proportions of seasonal housing (Radeloff et al. 2010).

The backcasting and forecasting follow from Hammer et al. (2004) and Radeloff et al. (2010), respectively. As such, we provide a synopsis of methods as supplemental material.

Housing summary and corridor analysis

We conducted the analysis using ArcGIS 10.1 (ESRI, Redlands, California). From the Census data, we extracted those areas that had fewer than 6.17 housing units/km^2 (i.e., 1 house/40 acres) across the United States. We designated these areas as very low-density housing in accordance with the wildland-urban interface definition (USDA and USDI 2001; Radeloff et al. 2005). We then extracted areas of very low-density housing at each distance around the National Wildlife Refuges (5, 25, 75 km). Continuous areas of very low density housing that reached from a National Wildlife Refuge boundary to the outer boundary at a given distance (e.g., 5 km) were designated "open space conservation opportunity areas" (hereafter, opportunity areas; Table 1). Our reasoning was that very low-density housing may allow movement for some species that are sensitive to human activity but not particularly sensitive to a modified landscape or may present the opportunity to re-create or restore habitat for species with stricter habitat requirements. We then summarized the number of opportunity areas and the percent of the area within a certain distance from a refuge that was composed of opportunity area (opportunity area proportion = opportunity area/buffer area) for each refuge and summarized the total number of opportunity areas, the mean number of opportunity areas, and the average proportion of buffer area comprised of opportunity areas around refuges at all buffer extents and at each time step both nationally and regionally for the refuge system.

Finally, we used ArcGIS to identify habitat in all opportunity areas at each distance for the 2000 era. Within opportunity areas, we identified habitat corridors that reached from the border of the wildlife refuge to the full extent of the specified buffer. We reclassified the 2006 National Land Cover Dataset (Fry et al. 2011) to reflect only potential wildlife habitat, including open water (class 11), forest (classes 41, 42, 43), shrubland (classes 52), grassland (class 71), and wetlands (classes 90 and 95). All of these land cover classes were aggregated and designated "habitat". We identified continuous corridors via GDAL (http://www.gdal.org/) using an 8-neighbor rule. Within the opportunity areas, we summarized the number of corridors, the mean number of corridors, and the average proportion of buffer area comprised of corridor (corridor proportion = corridor area/buffer area) around refuges at all buffer extents both nationally and regionally. In our analyses, habitat corridors could only be a subset of opportunity areas (i.e., in all cases, corridor area and proportion was by definition equal to, or less than opportunity area and proportion).

Results

Opportunity areas

The mean number of opportunity areas per refuge declined with increasing distance from National Wildlife

Table 1 Definition of terms used throughout the document to describe the analyses and results

Term	Definition
Buffer	All land around a refuge within a given extent of analysis (e.g., 5, 25, or 75 km)
Open space conservation opportunity area (opportunity area)	Any contiguous areas of very low density housing (i.e., <6.17 houses/km^2) that touched both the wildlife refuge and a buffer boundary at a given extent of analysis
Corridor	Any contiguous areas of habitat (within a conservation opportunity area) that touched both the National Wildlife Refuge and a buffer boundary at a given extent of analysis. In our analyses, it was not possible to have corridors outside of conservation opportunity areas

Refuges within each time-step, and it also declined with advancing decades (Table 1; Figs. 1, 2). However, there was one notable exception: the mean number of opportunity areas increased slightly from 1940 to 2000 at the 5-km buffer extent, then decreased from 2000 to 2030. Variation in the mean number of opportunity areas was very small among time steps (less than a 4 % difference), compared to the level of variation among the different extents of analysis (up to a 30 % difference).

The mean proportion of area around refuges that was composed of conservation opportunity areas decreased over time at each extent (Table 3). However, among spatial extents at a given time, the pattern differed. In 1940 and 1970, the maximum proportion of opportunity area occurred within 25 km (Table 3). In 2000 and 2030, the proportion of land in conservation opportunity areas decreased with increasing analysis extent (e.g., from 5 to 75 km). The highest mean proportions of area in opportunity area for the entire refuge system were all in 1940, with 0.86 at 25 km being the highest for any combinations of year and analysis extent, and approximately 0.60 at 75 km in 2030 being the lowest. Most NWRs retained at least one pathway in 2030 over the 75 km distance, but 23 were projected to have zero opportunity areas by then (Fig. 2).

Corridors

The number of habitat corridors in the 2000 era decreased with increasing extent of analysis, mirroring the pattern of opportunity areas (Table 2; Fig. 2). The mean number of corridors at 5 km was actually higher than the mean number of opportunity areas, indicating instances of multiple corridors within a single pathway (Table 2). The mean number of corridors per refuge declined precipitously with increasing analysis extent, however, decreasing to 0.84 and 0.54 corridors per refuge at 25 and 75 km, respectively (Table 2), a 40 % greater decline than for opportunity areas (Table 2; Fig. 2). Additionally, the number of refuges with no habitat corridors increased substantially with increasing extent of analysis (Fig. 2).

The mean proportion of buffer area composed of habitat corridor in in the 2000 era was far lower than the mean buffer area composed of opportunity area (Table 3). In fact, the values were approximately half of the opportunity area values at 5 km, becoming much lower at 25 and 75 km. The mean corridor area was less than 25 % of the comparable mean opportunity area at 75 km.

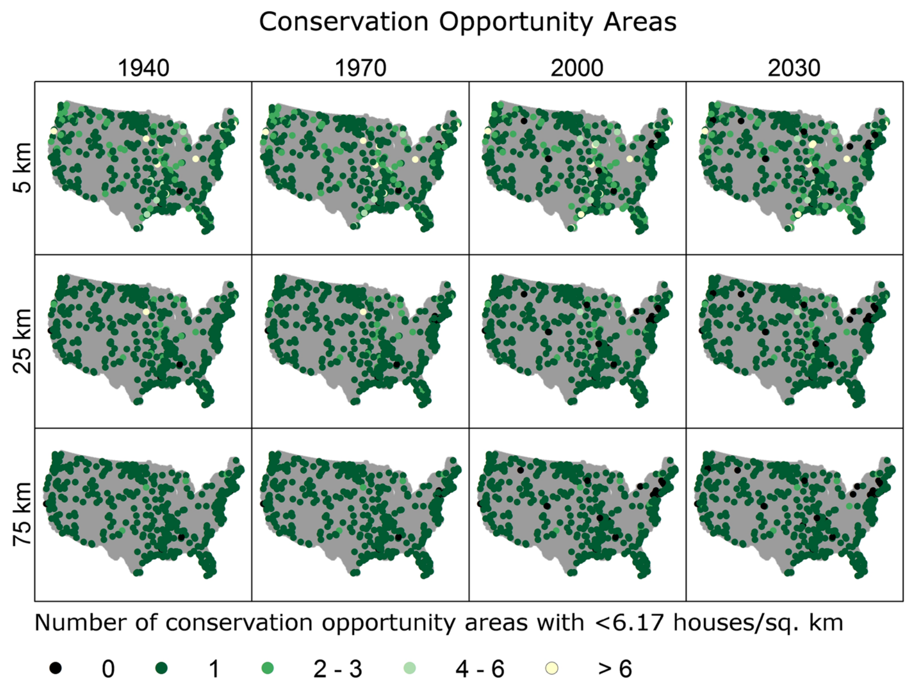

Fig. 1 The number of conservation opportunity areas around each refuges at all spatial extents of analysis and all time steps

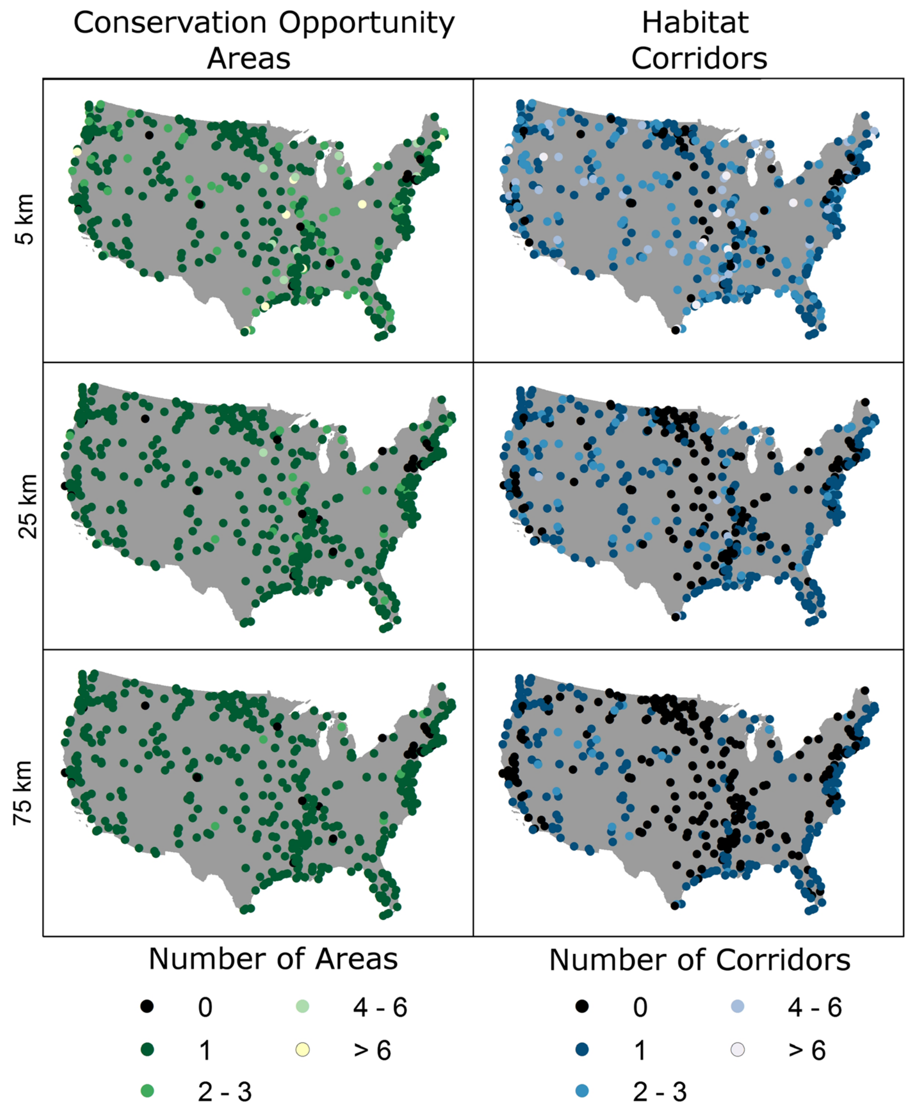

Fig. 2 The number of conservation opportunity areas around each refuge in 2000 and the number of habitat corridors around each refuge based on 2006 National Land Cover Data

Regional variation

Refuges with zero opportunity areas were not distributed evenly across the nation or even within regions, and largely occurred in the Northeast (Figs. 1, 2, 3). Refuges with one opportunity area were widely distributed but those with more than one opportunity area were clustered in the Mississippi River region, Gulf Coast, and Florida, though there were widely scattered refuges with 2 to 3 opportunity areas, particularly at the 5 km distance. Across all spatial extents, the number of opportunity areas per refuge declined, with declines in the western and northeastern United States being the most notable.

Habitat corridors were also not distributed evenly and, once again, were far more numerous and widespread at the 5 km distance, decreasing with increasing extent of analysis (Figs. 2, 4). The pattern at 5 km was similar to the opportunity area patterns, where refuges with 1 to 2 corridors were relatively widespread, except in the northeast. However, at 25 and 75 km, the pattern became much different with almost no refuges with corridors found in the Mississippi River Valley, Great Plains, and Central Valley of California (Figs. 2, 3, 4). These patterns had three distinct characteristics. First, there were very few opportunity areas to a distance of 75 km east of the Mississippi River from the Mid-Atlantic region northward. Where opportunity areas existed, they were relatively small and narrow (Figs. 3, 5). Second, the Mississippi and Ohio River valleys as well as the Northern Great Plains had a high number and proportional area of opportunity areas but almost no habitat corridors beyond several small ones in the Lower Mississippi Valley (Fig. 5). Third, nearly all of the habitat corridors that extended 75 km from refuges were found in the Western Great Plains, Rocky Mountains, and the Intermountain West, with a cluster of several corridors along the Columbia River and along the Pacific Northwest Coast. These three differences were exemplified in different USFWS administrative regions (Figs. 3, 4). USFWS Region 5 has very limited amounts of land in opportunity areas or corridors (Figs. 2, 3, 4). Region 4 has open opportunity areas in Central and Southern Florida, as well as in the Lower Mississippi River Valley. There are also extensive areas within Region 3 and the eastern halves of Regions 2 and 6 that provide opportunity areas but much of this is in use for agriculture or pasture and would likely require substantial restoration. The western halves of Regions 2 and 6, and large areas within Regions 1 and 8, have extensive corridor areas. In fact, the majority of the corridors in these areas occupied a very large percentage of the buffer areas. In addition, there are opportunity areas in the Central Valley of California and in Eastern Washington, but very little area in corridor (Figs. 3, 4).

Table 2 Mean number of opportunity areas per refuge at each time step and spatial extent of analysis and the mean number of corridors in the 2000 era

Distance	1940	1970	2000	2030	In corridor
5	1.36	1.38	1.4	1.38	1.78
25	1.05	1.05	1.02	1.00	0.84
75	1.00	1.00	0.97	0.96	0.54

Table 3 Mean proportion of landscape area per refuge composed of opportunity area at each time step and spatial extent of analysis with the mean proportion in corridors in the 2000 era

Distance	1940	1970	2000	2030	In corridor
5	0.85	0.80	0.70	0.65	0.40
25	0.86	0.81	0.69	0.64	0.26
75	0.83	0.77	0.65	0.60	0.14

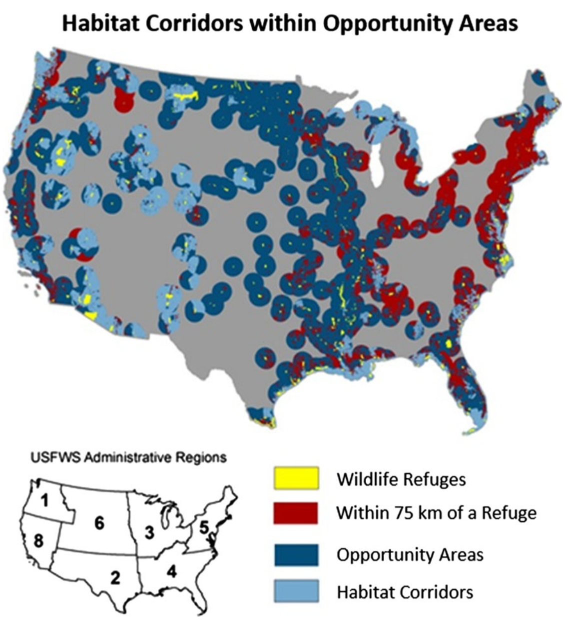

Fig. 3 Visualization of conditions at 75 km around each refuge in 2000. Buffer zones, conservation opportunity areas, and habitat corridors at 75 km are shown for all refuges

Discussion

We evaluated the past, current, and predicted future effects of housing growth on conservation opportunity areas around the National Wildlife Refuge System from 1940 to 2030, identified current habitat corridors, and identified regional variation in the patterns of opportunities and threats for the connectivity of wildlife refuges with habitat in their surroundings. The opportunities and threats are important to managers and policy makers because they highlight where the mitigation of climate change with habitat corridors need may be possible given strong regional and local variation. Our results highlight that we should be acting now, in order to protect connectivity since opportunities will become much more limited in the future.

Our results indicated that there are large regional differences in opportunities for restoring connectivity,

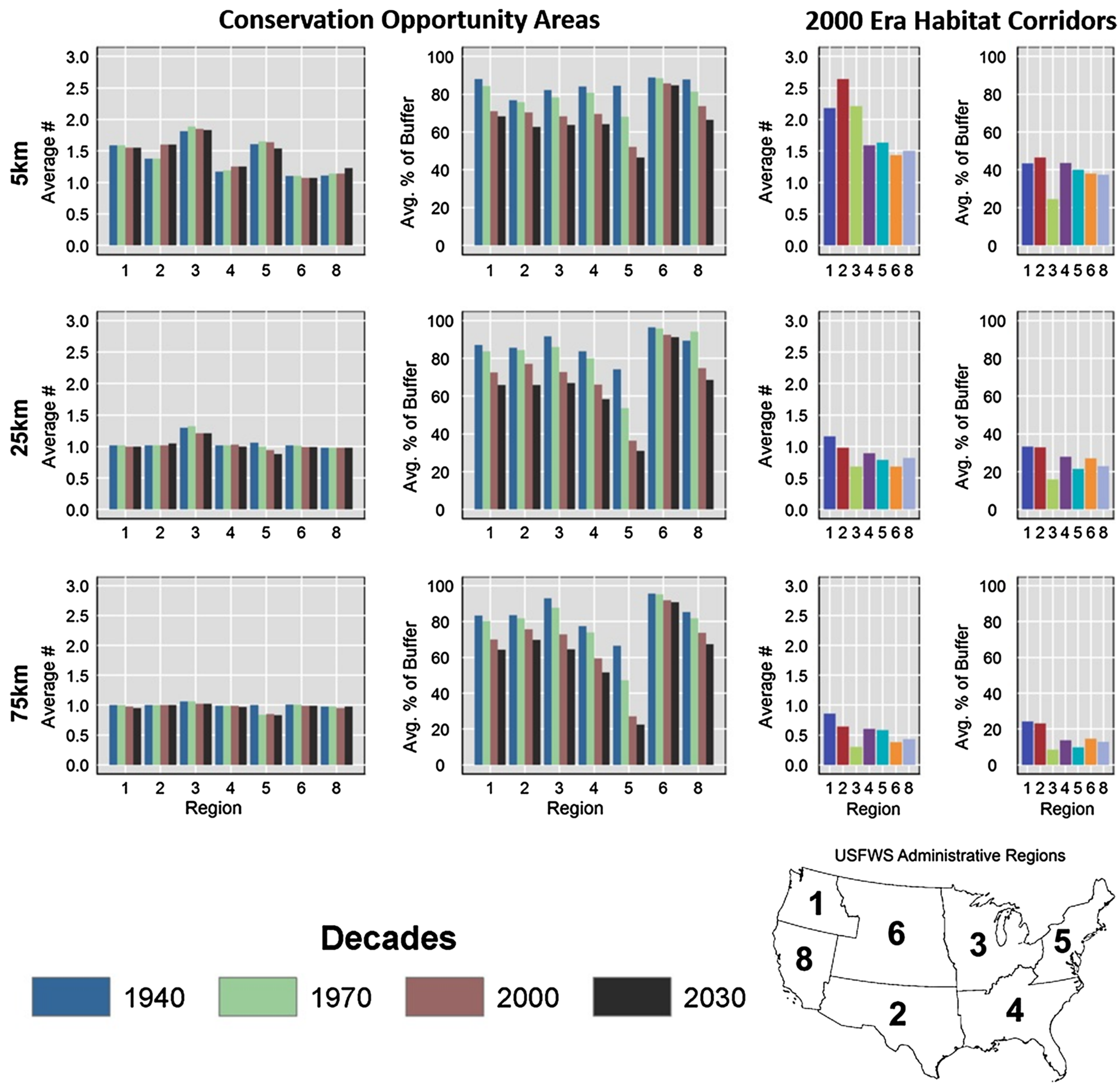

Fig. 4 Regional change in the average number of opportunity areas and proportion of buffer in conservation opportunity area across time steps and regional variation in the average number of corridors and proportion of buffer in corridor in the 2000 era

but only few opportunities east of the Appalachian Mountains, even at relatively limited extents, because of the prevalence of residential land use. Many areas in the eastern United States already lack far-reaching corridors that could function as climate mitigation tools. Those refuges found in the Mississippi Valley and northern Great Plains have opportunities but will require significant restoration efforts because many of the open spaces in the agriculture-dominated Midwest contain very little habitat. In addition, many refuges in the western Great Plains, Intermountain West, and some areas of the Pacific Northwest are currently secure. Finally, our results show that opportunities and threats can vary widely even within a given administrative region. Our findings concur with other studies that have found housing growth to be a significant threat to protected areas, leading to isolation and disruption of ecological flows (Hansen and DeFries 2007; Radeloff et al. 2010; Wade and Theobald 2010).

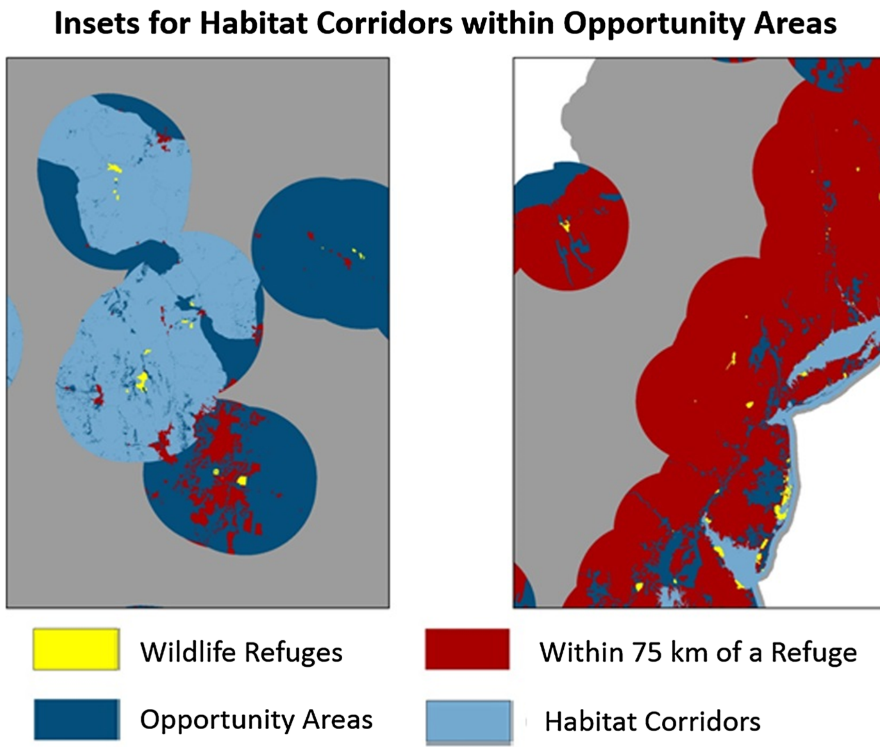

Fig. 5 Example of the variability in amount and configuration of conservation opportunity areas and habitat corridors around refuge in the western Great Plains/foothills of the Rocky Mountains (*left*) and the northeastern United States (*right*). The *left* map is centered near Denver, CO and the *right* is centered near New York, NY

Our findings that opportunity areas and corridors surrounding refuges will decrease in coming decades supports other findings suggesting that residential development has, and will continue to, spread at low density throughout rural areas and will limit the effectiveness of protected areas (Brown et al. 2005; Wade and Theobald 2010). However, it appears that the predicted rate of open space lost to development in the vicinity of refuges is not as rapid as some projections have suggested (Wade and Theobald 2010). Nevertheless, the amount of habitat corridors was significantly lower than the amount of opportunity area present on the landscape. In places where there is very little land in corridor, there may be opportunities to recreate or restore additional corridors and to expand the size of existing corridors. However, doing so would require concerted management efforts.

The within-administrative region variability was also high in some cases. For example, the NWRs in the eastern halves of Regions 2 and 6 often had opportunity areas but no corridors, in contrast to NWRs in the western halves of these regions, which generally had habitat corridors and not just opportunity areas. We were not surprised to find that changes were strongly regional in nature. Other work on land use and housing change has demonstrated that total changes and rates and patterns of changes vary widely across the U.S. (Radeloff et al. 2010; Hamilton et al. 2013). Land use changes are typically strongly tied to socioeconomic processes within ecoregions (Sohl et al. 2010; Radeloff et al. 2012), highlighting the need for integrating social and ecological sciences in order to improve the effectiveness of conservation efforts (Dale et al. 2005; Liu et al. 2007).

Perhaps most alarming among our results were the extremely limited opportunities to restore habitat corridors in the northeastern U.S. The majority of corridors and opportunity areas found in that region were associated with coastal waters, river channels, or large water bodies (e.g. the Finger Lakes in New York State, Fig. 5). There was very little terrestrial buffer area that met our definition of opportunity areas. These results indicate that there are likely to be many areas in which the window of opportunity to restore and secure corridors is rapidly disappearing or where habitat corridors are not a feasible mitigation strategy for climate change adaptation. Our results indicate that unassisted migration may not be possible in many instances for species with poor dispersal capability, or for those species who cannot disperse in water. In addition, the small proportion of area around refuges composed of corridors should be concerning. Such low proportions of the landscape in a contiguous corridor are likely to have very high edge densities which reduces the suitability of habitat and increases susceptibility to invasion by exotic species (Friesen et al. 1995; Fischer and Lindenmayer 2007; Predick and Turner 2008).

While our results had some worrying implications, the worst may be related to climate change itself. Even in areas where our results indicated that corridors or opportunities to restore corridors exist, those opportunities may not have the capacity to address shifting climatic condition for species migration. The velocity of climate change (i.e., the rate at which suitable environmental conditions are shifting across the landscape) may outpace our capacity to connect remaining habitat (Veloz et al. 2011; Williams et al. 2012).

There are several limitations and concerns related to our analyses. First, we selected one housing density threshold to identify opportunity areas, but the most appropriate threshold may differ among species. The low value we used was conservative, since even very low densities of residential development can affect habitat quality and biodiversity (Pidgeon et al. 2007; Gagne and Fahrig 2010a, b). Second, our estimation of corridors and connectivity evaluates structural connectivity (landscape configuration only) while ignoring functional connectivity (a species' response to a landscape; Tischendorf and Fahrig 2000). For instance, many species vary in their ability to move across features such as roads (Carr and Fahrig 2001; Fahrig and Rytwinski 2009). While we excluded roads from our definition of habitat, conversion of linear features such as roads into a raster such as we used in our analyses is likely to result in "cracks" in the linear features (Rothley 2005). We did not address this in our analyses, and that may have led sometimes to an overestimate of structural connectivity. Finally, there were instances where some refuges showed an increase in the number of opportunity areas. This result is potentially confusing, and occurred when a previously larger opportunity area was fragmented into two (or more) smaller areas, with an overall loss of area with very low density housing.

Conclusions

In terms of management implications, our results indicate that addressing climate change impacts to wildlife with habitat corridors will vary in difficulty and effectiveness. Some regions appear to be well-situated for the use of habitat corridors to mitigate the effects of climate change, as has been proposed (Griffith et al. 2009). However, habitat loss in all forms, not just to housing growth, is still the main driver of biodiversity loss (Sala et al. 2000; van Vuuren et al. 2006) and has affected the presence of corridors on the landscape. Policy makers may wish to account for regional and local variation to maximize the effectiveness of climate change mitigation with a variety of techniques. While some areas appear to have limited capacity to address large range shifts for species with limited vagility, there may be opportunities to improve habitat connectivity and quality at localized scales even in areas where corridors do not exist or do not reach great distances. Our results demonstrate the need to work closely with private landowners and other private and public land managers to promote wildlife friendly landscape-scale planning and implementation. Specifying the variety of private and public entities that could be coordinating on this work is too cumbersome for a nationwide analysis such as this. However, working with local partners and neighboring land owners can still do much to improve the quality and effectiveness of many protected areas. The Department of Interior Landscape Conservation Cooperatives could be effective as coordinators of this work. In addition, our analyses projected to 2030 demonstrate the urgency of working with private landowners and other public and private land managers to secure these opportunity areas while they still exist.

Acknowledgments This research was supported by the U.S. Geological Survey/U.S. Fish and Wildlife Service Science Support Program Partnership. We very much appreciate the helpful comments of anonymous reviewers and the patience of the editorial staff of this journal, which greatly helped to improve an earlier version of this manuscript. Any use of trade,

firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This publication represents the views of the authors and does not necessarily represent the views of the U.S. Fish and Wildlife Service.

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