



Scenarios of future land use change around United States' protected areas



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ABSTRACT

Land use change around protected areas can diminish their conservation value, making it important to predict future land use changes nearby. Our goal was to evaluate future land use changes around protected areas of different types in the United States under different socioeconomic scenarios. We analyzed econometric-based projections of future land use change to capture changes around 1260 protected areas, including National Forests, Parks, Refuges, and Wilderness Areas, from 2001 to 2051, under different land use policies and crop prices. Our results showed that urban expansion around protected areas will continue to be a major threat, and expand by 67% under business-as-usual conditions. Concomitantly, a substantial number of protected areas will lose natural vegetation in their surroundings. National land-use policies or changes in crop prices are not likely to affect the overall pattern of land use, but can have effects in certain regions. Discouraging urbanization through zoning, for example, can reduce future urban pressures around National Forests and Refuges in the East, while the implementation of an afforestation policy can increase the amount of natural vegetation around some Refuges throughout the U.S. On the other hand, increases in crop prices can increase crop/pasture cover around some protected areas, and limit the potential recovery of natural vegetation. Overall, our results highlight that future land-use change around protected areas is likely to be substantial but variable among regions and protected area types. Safeguarding the conservation value of protected areas may require serious consideration of threats and opportunities arising from future land use.

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1. Introduction

One of the main purposes of protected areas is to preserve biodiversity. However, even if protected areas are protected perfectly, change in surrounding land uses might threaten their conservation value (Hansen and DeFries, 2007). Deforestation, agricultural expansion, and urbanization in the vicinity of protected areas typically reduce and fragment available habitats, making protected areas themselves susceptible to species declines (Parks and Harcourt, 2002), introduction of exotic species (Pimentel et al., 2005), and novel disturbances (Pringle, 2000). As protected areas become increasingly isolated everywhere, understanding future

land use changes in the vicinities of protected areas is critical (Radeloff et al., 2010; Beaumont and Duursma, 2012; Wilson et al., 2014).

Projections of future land use change can improve our understanding of the status of protected areas, making it possible to identify both, potential threats and conservation opportunities (Pressey et al., 2007; Fleishman et al., 2011; Davis and Hansen, 2011). For example, while the expansion of urban and croplands around protected areas could increase the levels of threat, situations where land use intensity decreases can provide opportunities for the expansion of natural habitats and increased connectivity around protected areas (Fischer et al., 2006; Hansen and DeFries, 2007; DeFries et al., 2007). In the U.S., knowledge about future land use changes around protected areas is a major need by federal agencies, as both protected areas and their surrounding landscapes are an integral part of conservation agendas (Griffith et al., 2009; Joyce et al., 2009).

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Scenarios projecting how future land use might unfold under alternative socioeconomic conditions can enrich our understanding of human activities around protected areas (Peterson et al., 2003). In particular, knowing the potential outcomes of alternative scenarios can be a powerful tool when making difficult policy decisions (Polasky et al., 2011). Land-use scenarios have proved useful for testing the effect of conservation policies (e.g., payments for land conservation), changes in economic conditions, and changes in population growth on future land use changes (Radeloff et al., 2012; Sleeter et al., 2012), yet our knowledge for protected areas is limited.

In the U.S., most of our knowledge about future land use changes around protected areas is limited to land development, including changes in houses and urban cover (Gude et al., 2007; Radeloff et al., 2010; Wade and Theobald, 2010). Projections of future housing growth suggest that up to 17 million new houses may be built in the vicinity of Wilderness Areas, National Parks, and National Forests between 2000 and 2030 (Radeloff et al., 2010). Such expansion is projected to reduce natural habitats around protected areas by 12% (Wade and Theobald, 2010). However, land development represents only one type of land use, and other land uses such as cropland and pasture could be part of important land-use changes as well. Between 1973 and 2000, for example, the gains in natural vegetation cover from former agricultural lands far exceeded the area of land development (15.8 vs 7.7 million ha; Sleeter et al., 2013).

In addition, National Wildlife Refuges are the only protected areas in the U.S. for which both different land uses and scenarios have been assessed (Hamilton et al., 2013, 2014). While such information is of great value for the federal agency managing Refuges (U.S. Fish and Wildlife Service), extrapolating these lessons to other protected areas is difficult. Refuges represent only 3% of all federal protected areas and they are most frequently found on productive soils at low elevation, which is untypical for most protected areas in the U.S. (Scott et al., 2001) and elsewhere (Joppa and Pfaff, 2009).

Our goal here was to assess future land-use change around protected areas in the conterminous U.S. In particular, we were interested in quantifying future land-use changes around different protected areas and under different land-use scenarios. We focused on National Forests, National Parks, Wilderness Areas, and National Wildlife Refuges (hereafter Forests, Parks, Wilderness Areas, and Refuges), which together represent 66% of all federal protected areas in the U.S. and capture a broad range of geographic distributions, protection levels, and management agencies. Our specific objectives were to:

- i. quantify future land-use changes around different protected areas between 2001 and 2051, and
- ii. compare the effect of alternative land-use scenarios reflecting potential changes in land-use policies and economic conditions

2. Material and methods

2.1. Study area and general approach

We restricted our analysis to a 10 km buffer around protected areas, a distance that has shown useful for evaluating land transformation near protected areas at national scales (Sánchez-Azofeifa et al., 2003; Gaveau et al., 2009), and reliable by our land-use projections. We obtained the perimeters of the protected areas from the Protected Areas Database (PAD-US, CBI Edition Version 1; <http://consbio.org/products/projects/pad-us-cbi-edition>), the USFWS Cadastral database (<http://www.fws.gov/GIS/data/CadastralDB/> from 2013), and Radeloff et al. (2010), for a total of 1260 individual units. We evaluated changes in three

major land uses: urban, crop/pasture combined, and natural vegetation cover (including forests and natural grasslands and shrublands). We did not analyze state protected areas, because difference in designation and status among states prohibits treating them as a uniform type of protected areas across the conterminous U.S. Similarly, we did not include conservation easements, because they tend to be smaller in size than public lands, and our land use data was too coarse to provide meaningful information for conservation easements.

2.2. Land use projections and scenarios

We used spatially explicit projections of future land use change for 2001–2051 for the conterminous U.S. from Radeloff et al. (2012) as refined in Lawler et al. (2014). These land-use projections are based on an econometric model that reflects observed landowner decisions in response to economic conditions (from Lubowski et al., 2006). The model uses a multinomial logit specification to quantify the probability of changes in urban, crop, pasture, range, and forest lands.

Based on initial land use (from the 2001 National Land Cover Database or 2001 NLCD; Homer et al., 2007), soil type (from the U.S. Soil Survey Geographic database (<http://soils.usda.gov/>), and economic returns to each use (from Lubowski et al., 2006), the model quantifies the probability of changes from the initial land use to any other land use as a function of expected net returns to the different land uses, and the costs of converting from one land use to another. The model was parameterized with 800,000 observations of land use change for the conterminous U.S. during the 1990s from the National Resources Inventory (NRI; <http://www.nrcs.usda.gov/technical/NRI>), together with county-specific net returns (i.e., profits) for each land use. The model makes land-use projections at 100-meter pixel resolution and only private lands are allowed to change use; public lands (as defined by the PAD-US) and wetlands were assumed to remain in the same state. However, the data is intended to be summarized at larger spatial scales such as watersheds (Martinuzzi et al., 2014), large pixels (e.g. 10 km; Lawler et al., 2014), buffers around protected areas (kilometers; Hamilton et al., 2013), or counties for reliable estimates. The economic returns to alternative uses are endogenous and, thus, change during the projection period.

A main value of our econometric model is its ability to simulate the effects of changing assumptions regarding the level of net returns to various land uses, making it possible to explore scenarios of future land-use change. Common forces altering the economic return to land uses include land-use policies (e.g., taxes and subsidies), changes in crop commodity prices, and zoning regulations. Here, we explored four scenarios of future land-use change from Lawler et al. (2014), including:

- *Business As Usual* scenario, with no taxes or subsidies or changes in economic conditions other than those present when the NRI and net return data was collected. Land-use changes under this scenario reflect a continuation of 1990s trends, which were dominated by urbanization and declining cropland.
- *Forest Incentives* scenario, which provides incentives for afforestation and reduced deforestation, similar to carbon sequestration incentives. Landowners are paid \$247/ha/year if they convert land to forest, and are taxed \$247/ha/year for land if they deforest. A \$247/ha/year subsidy translates into a \$50/ton carbon price, a relatively aggressive carbon policy (Lubowski et al., 2006).
- *High Crop Demand* scenario, which assumes substantial growth in the demand for agricultural commodities with concomitant pressures to expand agricultural lands. Crop commodity prices

are assumed to rise by 160% by 2051, resembling a recent period of very high crop commodity prices (2007–2012).

- *Urban Containment* scenario, which reflects the implementation of a nationwide “smart-growth” zoning regulation to reduce urban expansion, by prohibiting the conversion of land to urban in non-metropolitan counties (as defined by the U.S. Census).

Other studies that forecasted land-use changes around protected areas used projections based on assumptions on potential trends in population growth, gross domestic product, and/or land use (e.g., McDonald et al., 2008; Beaumont and Duursma, 2012; Güneralp and Seto, 2013; Wilson et al., 2014). Our projections were solely driven by the economic returns to the different land uses in response to economic conditions, which has shown to be a major driver of land transformation in the U.S. (Lubowski et al., 2008), and we made no assumptions about future population growth or land use trends. Both approaches are valid, but we chose to base our analysis on an econometric model, because this allowed us to simulate the effects of tax- and subsidy-based policies. Appendix A1 provides further information on the econometric model and scenarios.

Finally, our estimates of future land-use change are projections, not predictions. Following Intergovernmental Panel on Climate Change convention, a projection is a description of the future and the set of assumptions leading to it, as opposed to a prediction or forecast, which is a statement about the likelihood of a particular future outcome. Our business-as-usual scenario reflects what the landscape would look like by 2051 if the economic relationships determining land-use changes during the 1990s were to persist in the future. We do not assume that economic relationships that prevailed during the 1990s are actually what will persist or have persisted. The reference scenario is a way of constructing a view of the future against which we can test the influences of policy changes, and learn about the consequences for future land use changes (Martinuzzi et al., 2013; Hamilton et al., 2013; Lawler et al., 2014).

2.3. Specific approaches

First, we described the initial land-use conditions around protected areas, corresponding to 2001. We extracted land use from the 2001 NLCD and quantified the total area (km²) of urban, crop/pasture, and natural vegetation cover within 10 km of our protected areas. We summarized 2001 land use at two scales: around all of our protected areas combined (i.e., total land use in 2001), and around each type of protected area separately (i.e., Forests, Refuges, Parks, and Wilderness Areas). One reason why we looked at the protected areas of each agency separately was

that we expected that their management responses to land use change in their surroundings might differ.

Second, we quantified future land-use changes using the land-use projections. For each scenario, we quantified the total area (ha) and proportion (%) of urban, crop/pasture and natural vegetation around protected areas in 2051, and calculated the differences relative to 2001 amounts to estimate change (see Appendix A2 for an example). We summarized land-use change around all of our protected areas combined, and for each type of protected area separately (i.e., Forests, Refuges, etc.). We also compared the previous values of future land-use change around protected areas with those projected for the conterminous U.S. by our model.

Finally, we quantified and mapped land-use changes at the scale of individual protected areas ($n = 1260$). We evaluated changes in urban, crop/pasture, and natural vegetation cover around each individual protected area by 2051, and summarized them by type (Forests, Parks, etc.) and scenario. This allowed us to identify variations within the different types of protected areas, as well as regional patterns of land-use change. At the scale of the individual protected areas, we expressed the extent of future land-use change relative to size of the buffer (i.e., as a percent area of the surrounding landscape). The buffer included all terrestrial lands (private and public) and excluded pixels covered by water/wetlands.

3. Results

3.1. Initial land use conditions around protected areas

In 2001, natural vegetation was the most common land use around our protected areas (64% cover), followed by crop/pasture (14%; Table 1). There were notable differences among protected area types. Refuges had the greatest proportion of human land uses within 10 km (crop/pasture plus urban; 32%), followed by Forests (13%) and then Parks and Wilderness Areas (5–6%). Urban areas made up only a small percentage of the land uses around these protected areas (2–7%), yet these small percentages still represented impressive absolute numbers. For example, Refuges and Forests, the protected areas with the most urban cover, each had 2.9 million ha of urban lands within 10 km (Table 1).

3.2. Projected land use changes for all protected areas combined

In total, 12–16% of the land around the protected areas was projected to change in land use by 2051. These changes, however, resulted in small changes to the original proportions of the different land uses. Under the *Business As Usual* scenario, for example, urban cover was projected to expand an area equivalent to 3% of the total buffer area, while crop/pasture and natural vegetation

Table 1
Description of the different protected areas considered in this study, and their surrounding land cover in 2001. National Forests are managed by the U.S. Forest Service, National Parks by the National Park Service, Wildlife Refuges by the U.S. Fish and Wildlife Service, and Wilderness Areas by various agencies (mostly U.S. Forest Service and Bureau of Land Management).

	All Protected Areas	National Forests	National Parks	Wildlife Refuges	Wilderness Areas
Amount	1260	151	46	461	602
Total area ^a	112,346,268	81,067,497	7,764,712	4,979,078	18,534,980
Median size ^a	8430	518,948	80,571	2457	10,216
Buffer area ^a	124,645,974	74,319,048	10,907,730	41,910,602	47,580,787
Natural vegetation cover ^b	80,305,266 (64%)	58,099,144 (78%)	7,572,982 (69%)	16,060,451 (38%)	40,651,542 (85%)
Crop/pasture cover ^b	17,089,510 (14%)	6,759,446 (9%)	329,043 (3%)	10,389,618 (25%)	1,275,831 (3%)
Urban cover ^b	6,005,937 (5%)	2,910,730 (4%)	327,957 (3%)	2,919,218 (7%)	955,372 (2%)
Other land cover ^{b,c}	21,245,261 (17%)	6,549,728 (9%)	2,677,748 (25%)	12,541,316 (30%)	4,698,042 (10%)
Private lands ^b	89,315,314 (72%)	51,339,680 (69%)	5,126,744 (47%)	34,141,499 (81%)	14,511,802 (30%)

^a In hectares.

^b Within the 10-km buffer (ha), and as the proportion of the entire buffer area (%).

^c Includes wetlands and water.

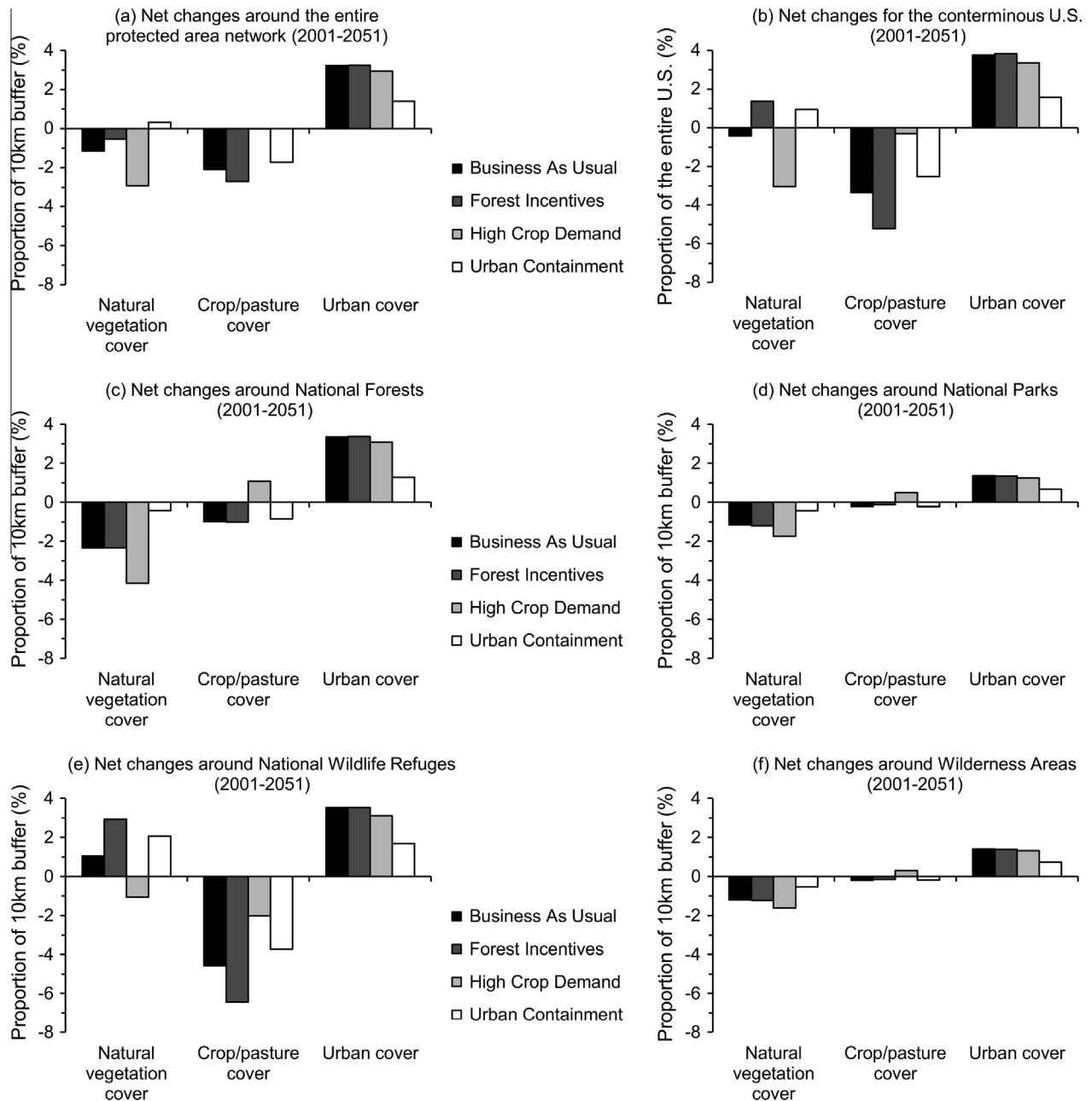


Fig. 1. Changes in the proportions of the different land uses around protected areas between 2001 and 2051, and under alternative scenarios. Land-use proportions are expressed as percentage relative to the entire buffer area. Panel (a) shows the results around our protected areas combined; panel (b) for the conterminous U.S. as a whole; and panels (c–f) around the different protected areas.

cover were projected to decline (2% and 1%; Fig. 1a). At this scale of analysis, the other scenarios showed little variation. Under the *High Crop Demand* scenario, for example, the proportion of crop/pasture was projected to stay constant (instead of decreasing), and under the *Urban Containment* scenario, urban expansion was projected to be half of that under *Business as Usual* (Fig. 1a).

Although net changes in land use were small, relative to the entire buffer area, they affected substantial areas. For example, the future increase in urban cover projected under the *Business As Usual* scenario, equivalent to 3% of the buffer area, translated into 4 million ha of urban cover, or 67% urban growth relative to 2001 amounts (Table 2). This rate of urban expansion around our protected areas was more or less equal to the one projected for the conterminous U.S. (Table 2)

3.3. Projected land-use changes by protected areas designation

Among the different protected areas, Refuges and Forests were projected to see the greatest changes in surrounding land use across scenarios, affecting 12–18% of the pixels, compared to 4–6% for Parks and Wilderness Areas (and 16–21% for the conterminous U.S.; see Appendix A3). Similar to the results for all protected areas combined, the projected changes altered very little the proportions of the different land uses. Refuges, for example, were projected to see a small decline in the proportion of surrounding crop/pasture cover across scenarios (e.g., 4% under *Business As Usual*), coupled with a net expansion of both urban cover (3%) and natural vegetation (1%; Fig. 1e). Forests, on the other hand, were projected to see a net expansion of urban cover (3% under

Table 2
Projected land-use change from 2001 to 2051 around protected areas under alternative scenarios, relative to 2001 amounts.

Land use class	Change 2001–2051 (ha and percent change)							
	Business As Usual		Forest Incentives		High Crop Demand		Urban Containment	
<i>Around all Protected Areas</i>								
Natural vegetation	–1,442,507	–2	–678,150	–1	–3,644,829	–5	402,543	1
Crop/pasture	–2,601,756	–15	–3,376,578	–20	–14,271	0	–2,151,140	–13
Urban	4,044,263	67	4,054,729	68	3,659,101	61	1,748,598	29
<i>Around National Forests</i>								
Natural vegetation	–1,747,677	–3	–1,742,466	–3	–3,079,948	–5	–319,704	–1
Crop/pasture	–741,043	–11	–756,488	–11	796,674	12	–637,142	–9
Urban	2,488,720	86	2,498,954	86	2,283,274	78	956,846	33
<i>Around National Parks</i>								
Natural vegetation	–124,640	–2	–131,268	–2	–188,424	–2	–48,627	–1
Crop/pasture	–23,864	–7	–15,236	–5	53,894	16	–24,314	–7
Urban	148,504	45	146,504	45	134,529	41	72,942	22
<i>Around Wildlife Refuges</i>								
Natural vegetation	439,581	3	1,224,068	8	–449,953	–3	864,727	5
Crop/pasture	–1,913,497	–18	–2,701,584	–26	–847,328	–8	–1,565,987	–15
Urban	1,473,916	50	1,477,516	51	1,297,280	44	701,259	24
<i>Around Wilderness Areas</i>								
Natural vegetation	–576,285	–1	–589,602	–1	–768,976	–2	–259,798	–1
Crop/pasture	–94,778	–7	–74,642	–6	141,492	11	–89,473	–7
Urban	671,063	70	664,245	70	627,484	66	349,271	37
<i>Conterminous U.S.</i>								
Natural vegetation	–3,332,544	–1	10,810,794	2	–23,827,803	–5	7,485,953	2
Crop/pasture	–26,158,151	–14	–40,779,367	–22	–2,360,221	–1	–19,715,667	–11
Urban	29,490,696	71	29,968,573	72	26,188,023	63	12,229,714	29

Business As Usual), but net declines in both natural vegetation and crop/cover (Fig. 1c). Parks and Wilderness Areas showed practically no change in land use at this level of analysis (0–2% difference; Fig. 1d and f).

There were some differences among scenarios for the different protected areas, but these differences were still small relative to the entire buffer area. Under the *Forest Incentives* scenario, for example, the proportion of natural vegetation cover around Refuges was projected to increase relative to the *Business as Usual* scenario (2% more); while it remained unchanged for the other protected areas (Fig. 1). The *High Crop Demand* scenario, on the other hand, was projected to expand somewhat the amount of crop/pasture around Forests, but to reduce the amount of natural vegetation around Refuges. Finally, the *Urban Containment* scenario was projected to reduce the rates of urban expansion around both Refuges and Forests. Parks and Wilderness Areas showed practically no change in the proportion of the different land uses across scenarios.

When comparing the rates of future land use change relative to 2001 amounts, the most notable result was that lands around Forests were projected to see higher rates of urban expansion than the Conterminous U.S. (86% vs. 71%), while the other protected areas were projected to see similar or lower rates (45–70%; Table 2).

3.4. Individual protected areas and spatial patterns

At the level of individual protected areas ($n = 1260$; presented in Figs. 2–4), the effects of future land use change around protected areas, and changing scenarios, became more evident. Overall, our results showed a higher proportion of Refuges affected by future land-use changes, followed by National Forests, National Parks, and finally Wilderness Areas (see pie charts in Figs. 2–4).

Under the *Business As Usual* scenario, 30% of the Refuges showed an increase in natural vegetation cover in their vicinity, while 20–30% of the Forests, Parks, and Refuges, and 10% of the Wilderness Areas experienced net declines (Fig. 2). Refuges with the greatest changes in surrounding land use were located along the East and West coasts, and along the Mississippi river valley (Figs. 2–4).

Refuges along the coasts were projected to see an expansion of urban cover (5–15% of the buffer area), and reductions in both natural vegetation and crop/pastures (5–15%). Refuges along the Mississippi, instead, were projected to see an expansion of both urban cover and natural vegetation, and a strong decline in crop/pasture cover (Fig. 3). On the other hand, Forests with the greatest changes in surrounding land use were located in the Southeast and some parts of the West. These Forests also had a net increase in surrounding urban cover (Fig. 4), with some decreases in crop/pasture (for those in the Southeast), and declines in natural vegetation (e.g., in the West). Finally, Parks and Wilderness Areas with the greatest changes in surrounding land use were located in the eastern part of the U.S., the West coast, and some parts of the interior West. Projected changes for Parks and Wilderness in these regions included typically urban expansion and decrease in natural vegetation (Figs. 2 and 4).

The scenarios revealed considerable local variation and different effects for the different protected areas. Under the *Forests Incentives* scenario, Refuges along the Mississippi were projected to see a further expansion of natural vegetation cover (see Fig. 2). Under the *High Crop Demand* scenario, the number of Forests experiencing a net decline in natural vegetation was projected to increase from 28% to 40%, mainly in the Southeast and West. For Refuges, the *High Crop Demand* scenario was projected to reduce the expansion of natural vegetation along the Mississippi, and increase the amount of crop/pasture in other regions. Finally, the *Urban Containment* scenario was projected to reduce future urban expansion around many Refuges and Forests (see pie charts in Fig. 4), and facilitate the expansion of natural vegetation around some Forests in the Southeast.

4. Discussion

Identifying potential threats to protected areas requires knowledge of future land-use changes in their vicinity (Hansen and DeFries, 2007). Our study suggests that urban expansion will continue to be a major threat to protected areas in the U.S., and that a

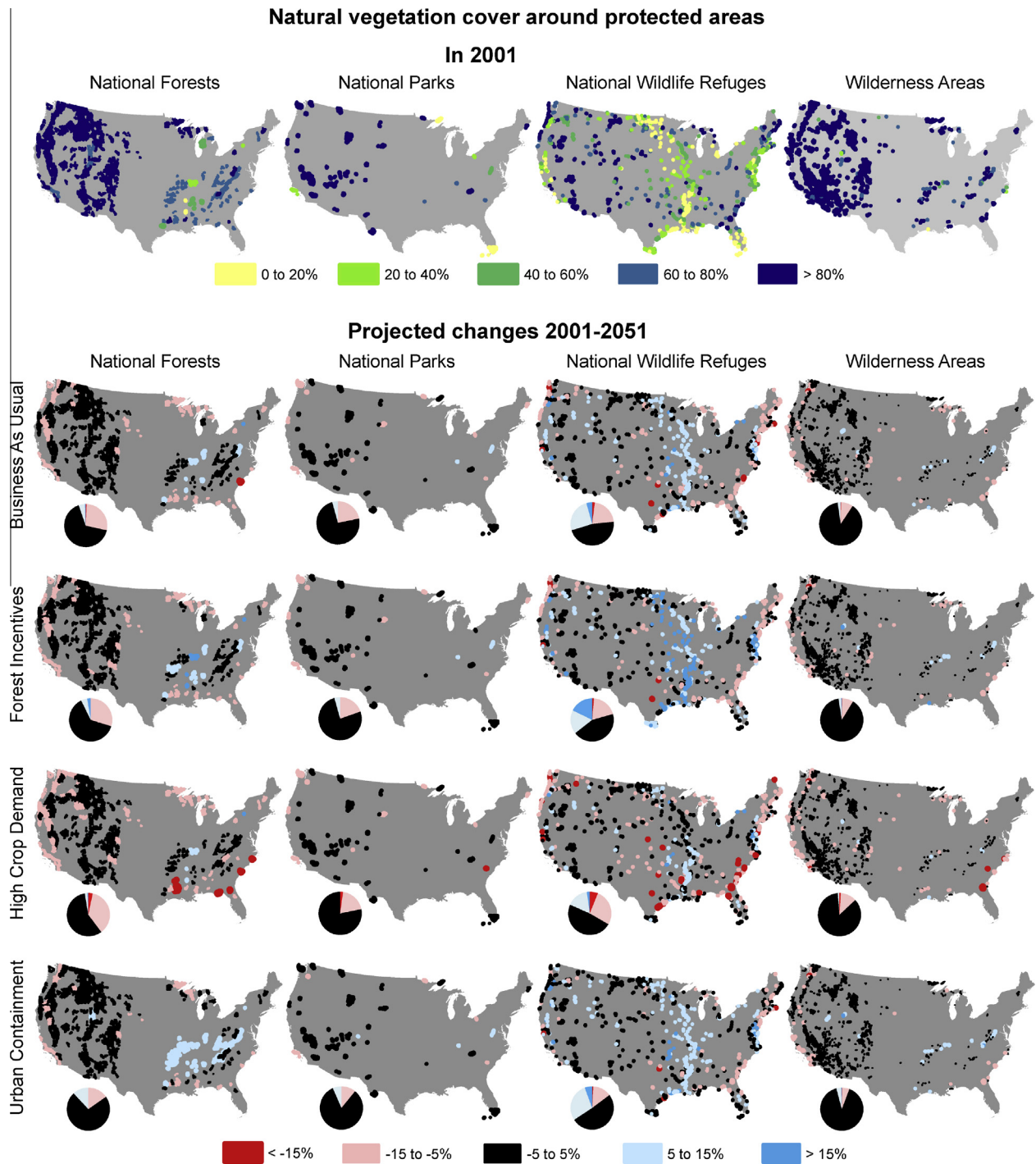


Fig. 2. Natural vegetation cover around individual protected areas in 2001 (top), and projected changes by 2051 under alternative scenarios of future land-use change (bottom), and within 10 km of each protected area. The map displays individual protected areas with some of them magnified for the purpose of visualization. The pie charts show the number of individual protected areas in each land-use change category. Values supporting the pie charts are included in [Appendix A4](#).

substantial number of protected areas are likely to see some level of decline in surrounding natural vegetation as a result of future land use change. The implementation of land use policies or changes in crop prices are not likely to change the overall pattern of future land use around protected areas, but can have important consequences at the scale of individual protected areas or regions.

Our study revealed that future land-use changes will affect protected areas differently. Future land-use changes are likely to be more pronounced around Refuges, followed by Forests, Parks,

and ultimately Wilderness Areas. This is explained in part by the geographic distribution of the different protected areas. Refuges occur typically in lowland areas, within an agricultural matrix, and are surrounded by private lands, while Wilderness Areas, tend to be embedded in public lands and are often located in mountainous areas, making them more isolated and protected from human land uses (Table 1). These findings are important as our knowledge on this topic was previously restricted to Refuges (Hamilton et al., 2013, 2014).

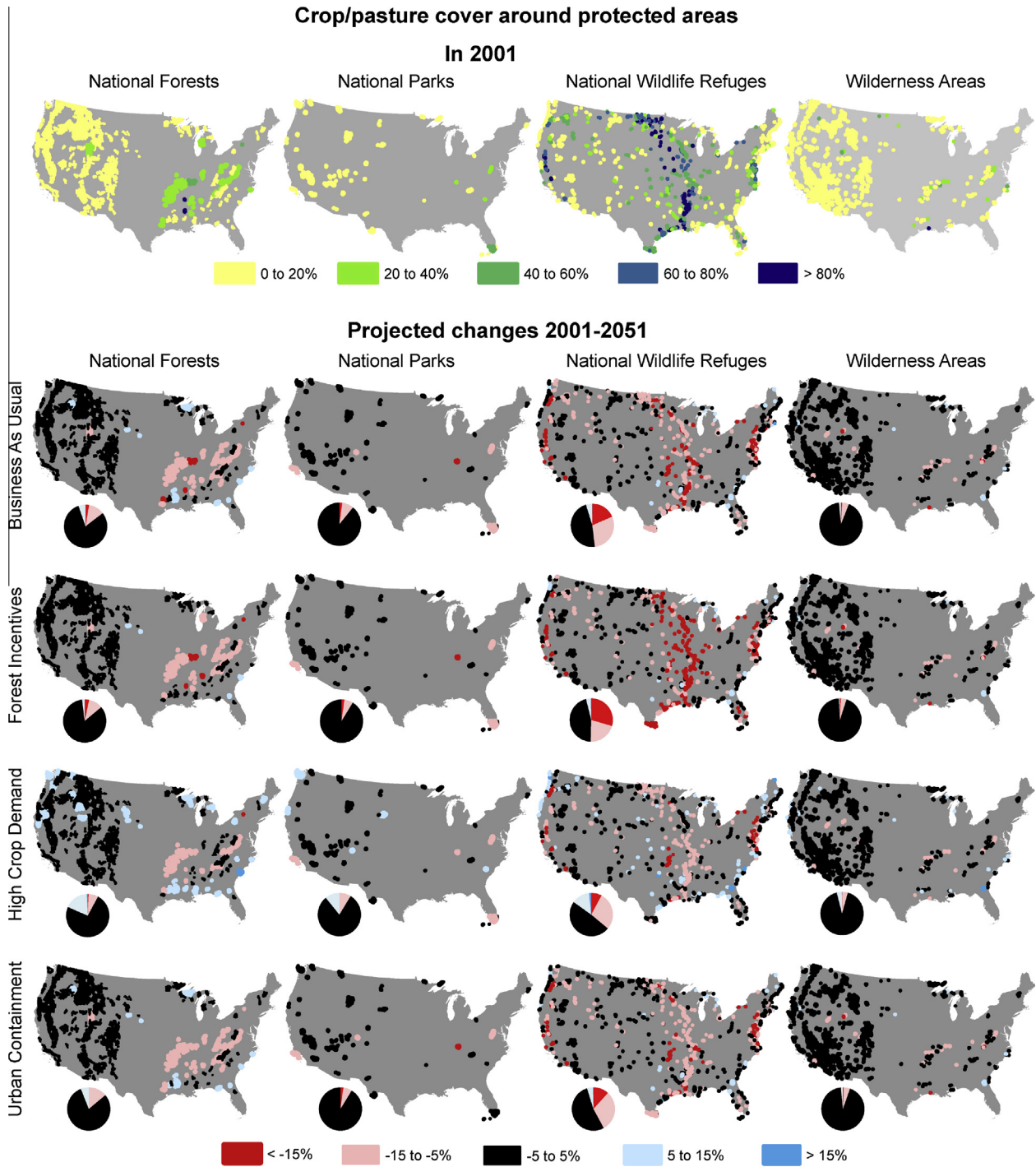


Fig. 3. Crop/pasture cover around individual protected areas in 2001 (top), and projected changes by 2051 under alternative scenarios of future land-use change (bottom), and within 10 km of each protected area. The map displays individual protected areas with some of them magnified for the purpose of visualization. The pie charts show the number of individual protected areas in each land-use change category. Values supporting the pie charts are included in [Appendix A4](#).

4.1. Land use scenarios and potential threats

Projections under *Business As Usual* conditions (i.e. following 1990s trends) resulted in substantial changes in land use around individual protected areas, characterized typically by urban expansion, decrease in crop/pasture cover, and decrease in natural vegetation. Urbanization emerged as a major threat under our *Business As Usual* and most of our scenarios, reinforcing recent findings on future urban growth impacts on protected areas (Radeloff et al., 2010; Wade and Theobald, 2010), and highlighting the need

to seriously consider urban growth in future planning for protected areas. This problem is not limited to the U.S., and many regions around the world will likely experience significant increase in urban land use around protected areas (McDonald et al., 2008; Güneralp and Seto, 2013) and other habitat conversions due to land-use change (Beaumont and Duursma, 2012).

Under *Business As Usual* conditions, changes in crop/pasture lands did not emerge as a major threat. The 1990s conditions reflected in our baseline scenario were characterized by low crop prices and declines in agriculture. However crop prices in the

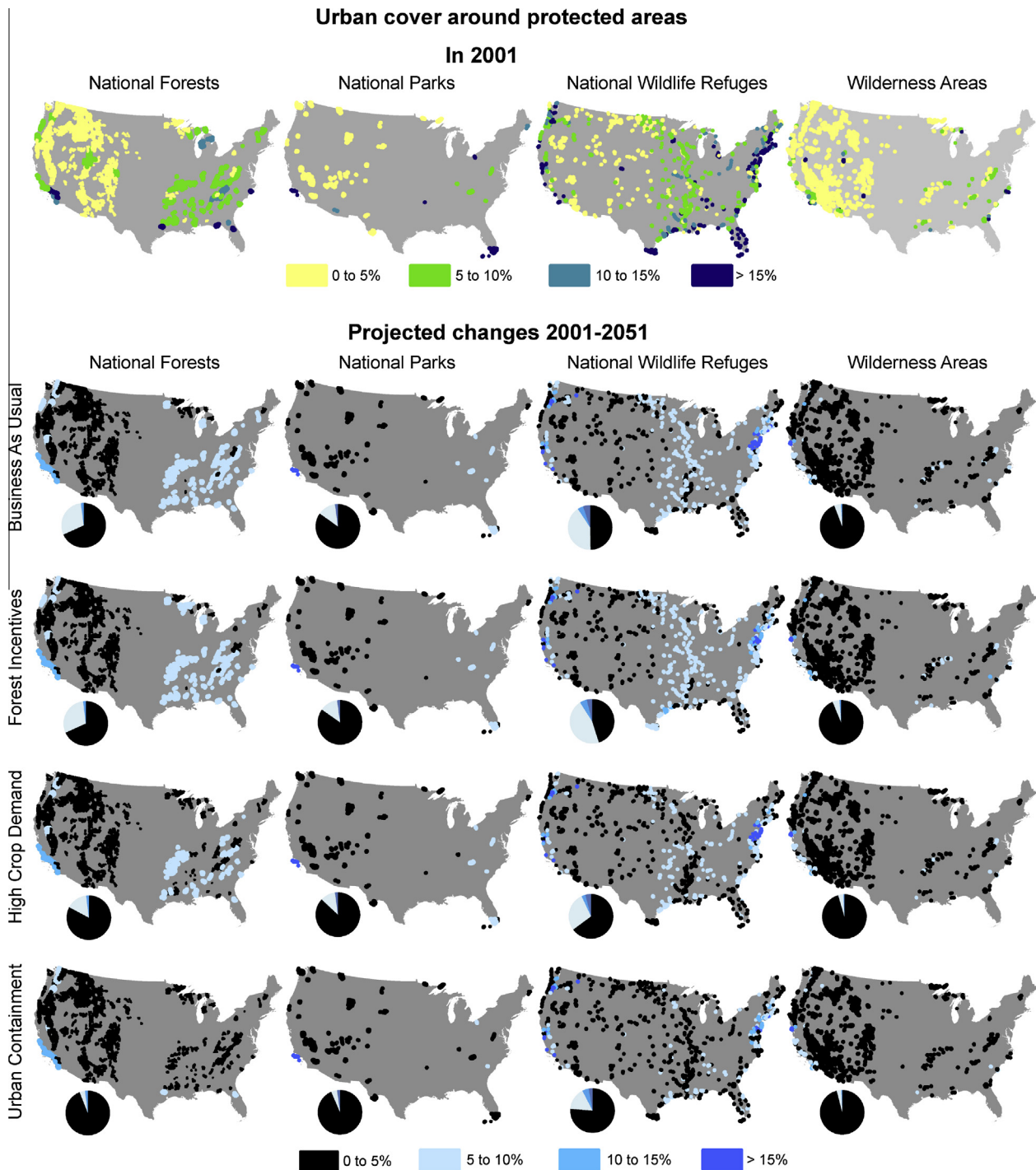


Fig. 4. Urban cover around individual protected areas in 2001 (top), and projected changes by 2051 under alternative scenarios of future land-use change (bottom), and within 10 km of each protected area. The map displays individual protected areas with some of them magnified for the purpose of visualization. The pie charts show the number of individual protected areas in each land-use change category. Values supporting the pie charts are included in [Appendix A4](#).

U.S. after 2000 were higher than in the 1990s. Our *High Crop Demand* scenario, which incorporated higher crop prices, suggest that the combination of high urbanization rates and high crop prices may increase the isolation of protected areas in the future, particularly along the East Coast and some parts of the West, and reduce the chances for Refuges to restore natural vegetation in their vicinity. Recent increases in crop prices are threatening natural habitats in the U.S. (Wright and Wimberly, 2013), and our results show that changes in crop prices could have negative

consequences for all protected area types, not just Refuges (Hamilton et al., 2014).

The implementation of economic incentives aimed at increasing carbon sequestration had little effect on the amount of natural vegetation around protected areas. This is because this scenario had its largest effect in regions with highly-productive agricultural lands (e.g. Midwest; Lawler et al., 2014), and these lands are not typically found next to protected areas in the U.S. As a result, Refuges along the Mississippi river valley were practically the only

protected areas to see a substantial increase in natural vegetation, as the afforestation policies significantly reduced the amount of agricultural lands in this region. The conversion of crop/pasture lands back into natural vegetation cover may provide opportunities for the recovery of natural habitats and increase connectivity around Refuges (Bowen et al., 2007; Baeza and Estades, 2010), even if these are in form of managed forests (Brockerhoff et al., 2008). Maintaining habitat connectivity around Refuges is one of the major challenges faced by the U.S. Fish and Wildlife (Meretsky et al., 2006), and our results suggested that, at least for some regions, incentives for carbon sequestration may provide some opportunities to do so.

Efficient urban planning is critical for a sustainable future in the U.S. beyond just protected areas. Our simulation of a national policy to limit urban growth (*Urban Containment* scenario), reduced the rates of urbanization around protected areas by about one-half. This translated into less human encroachment around protected areas, and in some cases, opportunities for the expansion of surrounding natural vegetation (some National Forests in the Southeast). Although the likelihood of this national “smart-growth” scenario is very remote (urban growth policies in the U.S. are formulated largely at the state- and county-level), it shows that concentrating urbanization near cities could have benefits for protected areas.

4.2. Limitations

We measured land-use change within 10 km as a proxy for the immediate area of influence around protected areas. However, we realize that the choice of a given buffer size should ultimately depend on the ecological process under consideration (see Hansen et al., 2011), and that no single buffer size is likely appropriate for all scientific questions. For Refuges, land-use patterns were very similar within 5, 25, and 75 km (Hamilton et al., 2013). In addition, we did not consider other aspects of land-use changes that are important for biodiversity, such as changes in fragmentation and connectivity (Piekielek and Hansen, 2012) because our land use model is not suitable for evaluating detailed changes in landscape fragmentation. Further, by combining some land-use classes we may have masked some important results. For example, the *High Crop Demand* increased the conversion of pasture into croplands, but this was not highlighted in our analysis because we combined crop and pastures into a single class. Importantly, croplands have higher land use intensity than pastures, which are sometimes in a semi-natural state. Finally, our study was not designed to identify the underlying causes for differences in land-use change patterns among the different types of protected areas, and that makes it difficult to state with certainty why housing growth was higher near Forests than the other types of protected areas. However, many Forests are located in counties with high amenity values and that fosters population and housing growth (Johnson and Stewart, 2007), whereas many Refuges are wetlands in the agriculturally-dominated Midwest and Plains, i.e., areas that are not as attractive for housing development.

4.3. Implications for management

Our summaries of future land use changes set the stage for understanding the consequences of future land-use decisions, and provide novel geospatial information to guide regional conservation strategies. Overall, our study revealed that future land-use changes are likely to be a common challenge for those managing Refuges and Forests as they will affect many individual protected areas, while it may be a more localized issue for managers of Parks and Wilderness Areas. In the case of protected areas with high future urban growth under most scenarios (including

Refuges along the Mississippi and in the California, Northwest, and Northeast coasts; Forests in Southeast and Pacific coasts; Wilderness Areas in California; and Parks in the East), management efforts should try to concentrate development away from crucial habitats (Gonzalez-Abraham et al., 2007). In the case of protected areas in agricultural landscapes, e.g., Refuges along the Mississippi and some Forests in the Southeast, management actions should focus on protecting corridors and crucial habitats and maintaining structural complexity (e.g., Fischer et al., 2006; DeFries et al., 2007). This could be done, for example, via land-use regulations at the county- or state-level, ultimately helping to mitigate threats from outside.

Importantly, our results showed that land-use changes have a strong spatial pattern, suggesting that multi-agency regional coordination efforts are needed to mitigate the consequences of land-use change and maintain connectivity among protected areas. In the Southeast, for example, efforts should focus on concentrating urban growth and limiting low-density housing development. In the Pacific Northwest, managers may want to address urban growth particularly around coastal forests, while keeping in mind that these areas could also experience crop/expansion if agricultural commodity prices rise. In the Midwest, managers need to take into consideration that the landscapes around their protected areas are highly sensitive to changing economic conditions, making rapid changes likely, but also offering opportunities for incentive-based conservation programs. Regional partnerships such as the Landscape Conservation Cooperatives could facilitate regional coordination efforts among agencies, protected areas managers, regional planning authorities, and private land owners to ensure proper function of protected areas. Finally, adding climate projections could enhance our understanding of the impacts of global change on protected areas even further (Hansen et al., 2014).

Overall, our results showed that there are no easy answers for managing the lands around protected areas, partly because of the strong trend toward more intensive land uses (e.g., urban), and partly because there are considerable regional differences (see also Piekielek and Hansen, 2012), yet knowing the potential outcomes of alternative scenarios can be a powerful tool to inform policy decisions. Under all the scenarios that we simulated, land-use change is likely to continue to threaten protected areas.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biocon.2015.02.015>.

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