


Assessing the Future Vulnerability of Wyoming's Terrestrial Wildlife Species and Habitats

The Nature Conservancy, Wyoming Chapter
Amy Pocewicz, Holly E. Copeland and Lindsey M. Washkoviak

WY Game and Fish Department
Martin B. Grenier

WY Natural Diversity Database, University of Wyoming
Douglas A. Keinath




Acknowledgements

FUNDING for this assessment was provided to The Nature Conservancy's Wyoming Chapter and the Wyoming Game and Fish Department through the Wyoming State Legislature General Fund Appropriations and a US Fish and Wildlife Service Grant Agreement. Additional funding was provided by the Kaplan Family Foundation. This assessment would not have been possible without the assistance of wildlife experts who reviewed initial climate change and disease vulnerability ratings for wildlife species of concern, including Greg Anderson, Tom Christiansen, Terry Creekmore, Stan Harter, Daryl Lutz, Andrea Orabona, Susan Patla, Larry Roberts, Charlotte Snoberger, and Zack Walker of the Wyoming Game and Fish Department and Erik Atkinson of Northwest College. We thank Bryson Webber, formerly of Wyoming Game and Fish Department, for his assistance with the Nature Serve CCVI tool and Jim Platt, of The Nature Conservancy, for assistance with GIS programming. Mike Heiner, Jeff Evans, and Steve Buttrick, of The Nature Conservancy, provided guidance related to the topographic diversity analysis. Kim Johnson and Matt Church, of Fremont County Weed and Pest, and Brian Mealor, of the University of Wyoming, provided assistance related to the invasive species analyses. Finally, we thank, Nicole Korfanta, Bob Lanka, Graham McGaffin, Andrea Orabona, Glenn Pauley, Ian Tator, and Zack Walker for reviewing a draft of this report.

SUGGESTED CITATION FOR THIS REPORT:

Pocewicz, A., H.E. Copeland, M.B. Grenier, D.A. Keinath, and L.M. Waskoviak. 2014. Assessing the future vulnerability of Wyoming's terrestrial wildlife species and habitats. Report prepared by The Nature Conservancy, Wyoming Game and Fish Department and Wyoming Natural Diversity Database.

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Executive Summary

THIS assessment analyzed the vulnerability of 131 terrestrial Species of Greatest Conservation Need (SGCN), 11 terrestrial habitat types, and 44 terrestrial priority areas to climate change, residential and energy development, and wildlife disease, as well as cumulative vulnerability to all three of these stressors. These terrestrial species, habitats, priority areas and challenges to wildlife were identified in Wyoming's 2010 State Wildlife Action Plan (SWAP). Vulnerability assessments are useful for highlighting species or habitats that may be most susceptible to changes or emerging threats. Vulnerability is a function of a species' or habitat's exposure to changes and its resilience to those changes.

We ranked each wildlife species to reflect their anticipated future vulnerability. This species-based assessment resulted in tabular data, in the form of scores and categorical rankings of low, moderate or high, for overall vulnerability and for vulnerability to climate change, development or disease. We used this species-based approach to capture species-specific traits and important differences in responses among species, and we also used a landscape-based approach to identify landscape patterns that may affect many species and habitats. To describe the vulnerability of habitat types and terrestrial priority areas, we first created spatial datasets to represent climate change vulnerability, development vulnerability, and overall vulnerability across Wyoming. These landscape-based estimates of vulnerability were then summarized across each habitat type and terrestrial priority area to determine vulnerability rankings. The landscape-based estimates incorporated exposure and resilience to development and climate change. Resilience was based on three datasets, for which results were also summarized: topographic diversity and water availability, land management status, and landscape integrity. Additionally, we further prioritized which species were most vulnerable by assigning a landscape-based vulnerability ranking to each species, by summarizing landscape-based vulnerability across each species' predicted habitat. This reflected which species had the most vulnerable habitats and incorporated spatial elements of vulnerability that were not part of the species-based rankings.

PHOTO: Laramie Plains © *Randy Craft*

The results prioritized which of Wyoming's 131 terrestrial SGCN may need the most attention based on expected future vulnerability. Fifty-one species were identified as highly or very highly vulnerable and 33 as moderately vulnerable. The factors contributing to species vulnerability varied among taxonomic groups. Amphibians were the most vulnerable taxonomic group (88% highly vulnerable), and most amphibians were highly vulnerable to climate change. No bird species were highly vulnerable to climate change, but birds were the most vulnerable taxonomic group to disease, by number and proportion. Reptiles were the taxa most exposed to development, with nearly half of the species highly vulnerable. Mammals were the least vulnerable taxonomic group, with only one-fifth of mammal species ranked as highly vulnerable, and vulnerability to development, disease, and climate change varied greatly among individual mammal species.

Overall landscape-based vulnerability was highest for wetlands and prairie grasslands. These habitat types had high or moderate vulnerability to both climate change and development, low resilience to development, very limited legal protections and some of the greatest numbers of associated highly vulnerable species. Sagebrush shrublands, desert shrublands, and riparian areas also had high vulnerability, and riparian areas had the second highest number and percentage of associated highly vulnerable species. Spatial patterns in climate change and development vulnerability were similar, suggesting that interactions between these two factors will be important. Greater numbers of habitats and terrestrial priority areas were ranked highly vulnerable to climate change than to development. Of the three types of development considered, residential development contributed the most to species and habitat vulnerability, followed by oil and gas development. However, the greatest percent increases in development exposure to species are expected from wind development.

Our assessment provides new information about the expected impacts from three stressors (climate change, development, and disease) on Wyoming's terrestrial wildlife and their habitats in the future. We hope these results inform the development of conservation strategies aimed at mitigating threats we have identified. These findings can guide activities of the Wyoming Game and Fish Department, public land management agencies, and conservation organizations by highlighting which species and habitats have the greatest conservation needs and where additional information may be needed. Our results could be used to inform the next revision of the SWAP, to help to reevaluate and prioritize Wyoming's list of SGCN, prioritize terrestrial habitat types and priority areas for conservation action, and provide additional information about disease. As resources become increasingly scarce and conservation becomes more complex in the future, this analysis and the results we provide justify expending resources on certain species and habitats based on their anticipated vulnerability and associated conservation needs. Finally, this project provides a template for completing similar analyses and a baseline for interpreting those results when these issues are revisited, as new data becomes available or as conditions change in Wyoming.

PHOTO: LEFT TO RIGHT Mud cracks in a river bed © *Sally Clement;* Natural gas development on the Pinedale Anticline © *Amy Pocewicz*

Introduction

ECOSYSTEMS are changing, which affects wildlife species and their habitats. Vulnerability assessments are useful for highlighting species or habitats that may be susceptible to changes or emerging threats. A vulnerability assessment is a proactive approach for identifying targeted and efficient conservation strategies that can help to prevent declines in sensitive species and the habitats they depend on. Vulnerability assessments focused on climate change have been encouraged by the Association of Fish and Wildlife agencies as part of State Wildlife Action Plan revisions (Association of State Fish and Wildlife Agencies 2009). Climate change vulnerability assessments have been completed in at least nine states (Association of State Fish and Wildlife Agencies 2012), including Michigan, New York, and West Virginia (Byers and Norris 2011, Schlesinger et al. 2011, Hoving et al. 2013).

Vulnerability is a function of a species' or habitat's *exposure* to changes and its *resilience* to those changes (Williams et al. 2008, Dawson et al. 2011, Glick et al. 2011). Exposure is a measure of how much change is likely to be experienced (Glick et al. 2011). Resilience is the ability of a species or habitat to survive and recover from change and is affected by *sensitivity* and *adaptive capacity* (Carpenter et al. 2001, Williams et al. 2008, Magness et al. 2011). Sensitivity is the degree to which a species or habitat is likely to be affected by change. For example, some species may not be tolerant of increases in temperatures. Adaptive capacity reflects the capacity of a species or habitat to accommodate or recover from changes, which for species may mean moving, modifying behavior, or evolutionary adaptation, and for habitats may mean maintaining quality, diversity, and connectivity (Williams et al. 2008, Glick et al. 2011). A species or habitat that is sensitive to changes may or may not have the capacity to adapt to those changes.

Wyoming's 2010 State Wildlife Action Plan identified the five leading challenges to wildlife conservation as rural subdivision and development, energy development, climate change, invasive species, and disruption of historic disturbance regimes (Wyoming Game and Fish Department 2010c). This vulnerability assessment analyzes wildlife vulnerability to three of those challenges: rural subdivision and development (residential development), energy development, and climate change. This assessment incorporates invasive species as a component of habitat integrity and also highlights wildlife disease, which were both identified as important conservation issues in the 2010 SWAP. Disruption of historic disturbance regimes, which includes fire and grazing regimes, was not included because data representing these regimes and how they may affect wildlife habitats in the future were not available statewide.

Rural subdivision and associated low-density residential development has been steadily increasing across the western United States for decades (Johnson and Beale 1994, Theobald 2005, Gude et al. 2006). Natural amenities and increases in second homes have contributed to this growth in Wyoming (Gude et al. 2006, Taylor and Lanning 2012). The result has been a dramatic increase in fragmentation of previously large ranches into 20-40 acre "ranchettes" for suburban or rural residences (Hulme et al. 2009). Residential development is expected to continue increasing in Wyoming, with an estimated 11 percent increase in new rural homes expected between 2010 and 2030 under a moderate growth scenario (Wyoming Housing Database Partnership 2010, Copeland et al. 2013). Subdivision and residential development can lead to reduced, fragmented and degraded habitat for wildlife populations (Theobald et al. 1997, Odell and Knight 2001, Hansen and Rotella 2002, Maestas et al. 2003, Wood et al. 2014). In Wyoming, the private lands that are developed for rural housing often include low elevation lands along rivers that provide important wildlife habitat and migration corridors (Hulme et al. 2009).

In addition to residential development, new energy development is rapidly occurring throughout the western United States due in part to both rising demand and interest in domestic energy production related to national security concerns. In the Intermountain West, for example, oil and gas development doubled between 1990 and 2007 (Naugle et al. 2011). Wyoming, in particular, has been at the epicenter of western energy development, leading in coal, oil and gas, and uranium production. Wyoming produces 40% of US coal, leading the nation in coal production, produces over 2 million cubic feet of natural gas annually, and produced 54.7 million barrels of oil in 2011 (US Energy Information Administration 2013). In addition to fossil fuels, Wyoming is 8th in the US for wind resources and had 957 turbines amounting to 1415 megawatts of installed capacity in 2012 (US Energy Information Administration 2013). Many studies examining the link between energy development and wildlife populations and habitat use in Wyoming have found a negative relationship, in the form of decreased abundance (Gilbert and Chalfoun 2011), directly mortality (Arnett et al. 2007, Pagel et al. 2013), habitat selection away from development (Holloran 2005, Walker et al. 2007, Doherty et al. 2008, Pruett et al. 2009, Sawyer et al. 2009), or altered migration patterns (Sawyer et al. 2013), which warrants concern. More is known about species' responses to oil and gas development than wind development simply because fossil fuel development has been occurring in Wyoming for over 100 years and large-scale wind development projects are relatively new. This study focused on the vulnerability of Wyoming's wildlife species and their habitats to oil and gas and wind development due to the known impacts to species and the high rate of development cited above.

There has been a significant change in Wyoming's recent climate, with an increasing number of warm years, less frequent episodes of extremely low winter temperatures, and prolonged intervals of low winter precipitation (Shuman 2012). Statewide from 1951-2006, annual mean temperatures increased (p-value=0.057) (Girvetz et al. 2009). Historic temperature trends have been linked with very high confidence to changes in natural systems (Intergovernmental Panel on Climate Change (IPCC) 2007). In this assessment we used historic trend data in combination with projections, to focus on areas already experiencing change and because of the known and inherent uncertainties with climate models that forecast changes into the future (Copeland et al. 2010, Magness et al. 2011). Increasingly, studies have examined impacts of climate on species and habitats, including development of models that predict future species ranges or habitats (Pearson and Dawson 2003). However, rather than focusing on potential species' range shifts, which require high resolution spatial data that is species-specific, we chose to highlight places and species that may be affected by climate change.

This assessment builds upon work already completed, "Assessing the Vulnerability of Wildlife to Energy Development" (AVWED) across Wyoming (Keinath et al. In preparation). There are also similarities to Rapid Ecoregional Assessments (REAs) that are being completed by the Bureau of Land Management (BLM) for three ecoregions occurring in Wyoming (http://www.blm.gov/wo/st/en/prog/more/ Landscape_Approach/reas.html). The REAs are intended to inform BLM management decisions by identifying priority areas for conservation, restoration and development and will assess where change agents, including development, climate change, invasive species, wildfire, and forest insects and disease, overlap with ecological systems and a limited number of wildlife species. The REAs will not describe vulnerability specifically and include only a subset of Wyoming's Species of Greatest Conservation Need (SGCN). The REAs may fill gaps not addressed by this assessment, including wildfire and forest insects and disease.

The Wyoming Game and Fish Department, The Nature Conservancy and the Wyoming Natural Diversity Database partnered to complete this vulnerability assessment, which considers vulnerability of 131 terrestrial SGCN, 11 habitats, and 44 terrestrial priority areas to climate change, development, and disease, as well as cumulative vulnerability to all three of these stressors. By considering cumulative vulnerability to multiple stressors, the assessment is more comprehensive than previous vulnerability assessments completed in support of State Wildlife Action Plan revisions that have focused exclusively on climate change. This Wyoming-focused assessment was designed specifically to assess the future vulnerability of Wyoming's terrestrial SGCN and their habitats, with the intent of informing the next revision of Wyoming's State Wildlife Action Plan.

Methods

ANALYSIS APPROACH OVERVIEW

We assessed the anticipated future vulnerability of 131 terrestrial vertebrate SGCN and 55 focal landscapes (11 terrestrial habitat types and 44 terrestrial priority areas), as identified in Wyoming's 2010 State Wildlife Action Plan (Wyoming Game and Fish Department 2010c). For each species, we evaluated vulnerability to climate change, energy and residential development, and wildlife disease. These three components of vulnerability were synthesized into an overall vulnerability ranking (Figure 1a). The species-based assessment resulted in tabular data, in the form of scores and categorical rankings. We also assigned these tabular values to the predicted habitat for each species, to show the locations where many vulnerable species occur. For each focal landscape, we evaluated vulnerability to climate change and development using statewide spatial datasets representing these components of vulnerability, and we also synthesized the results into an overall vulnerability ranking (Figure 1b). Additionally, we summarized this landscape-based vulnerability across the predicted habitat for each species. By combining species-based and landscape-based approaches, we were able to further prioritize vulnerable species (i.e., identify highly vulnerable species also occurring in highly vulnerable landscapes) and identify places where large numbers of vulnerable species occur in vulnerable habitats. Detailed methods describing each of these analyses are provided in the following sections.

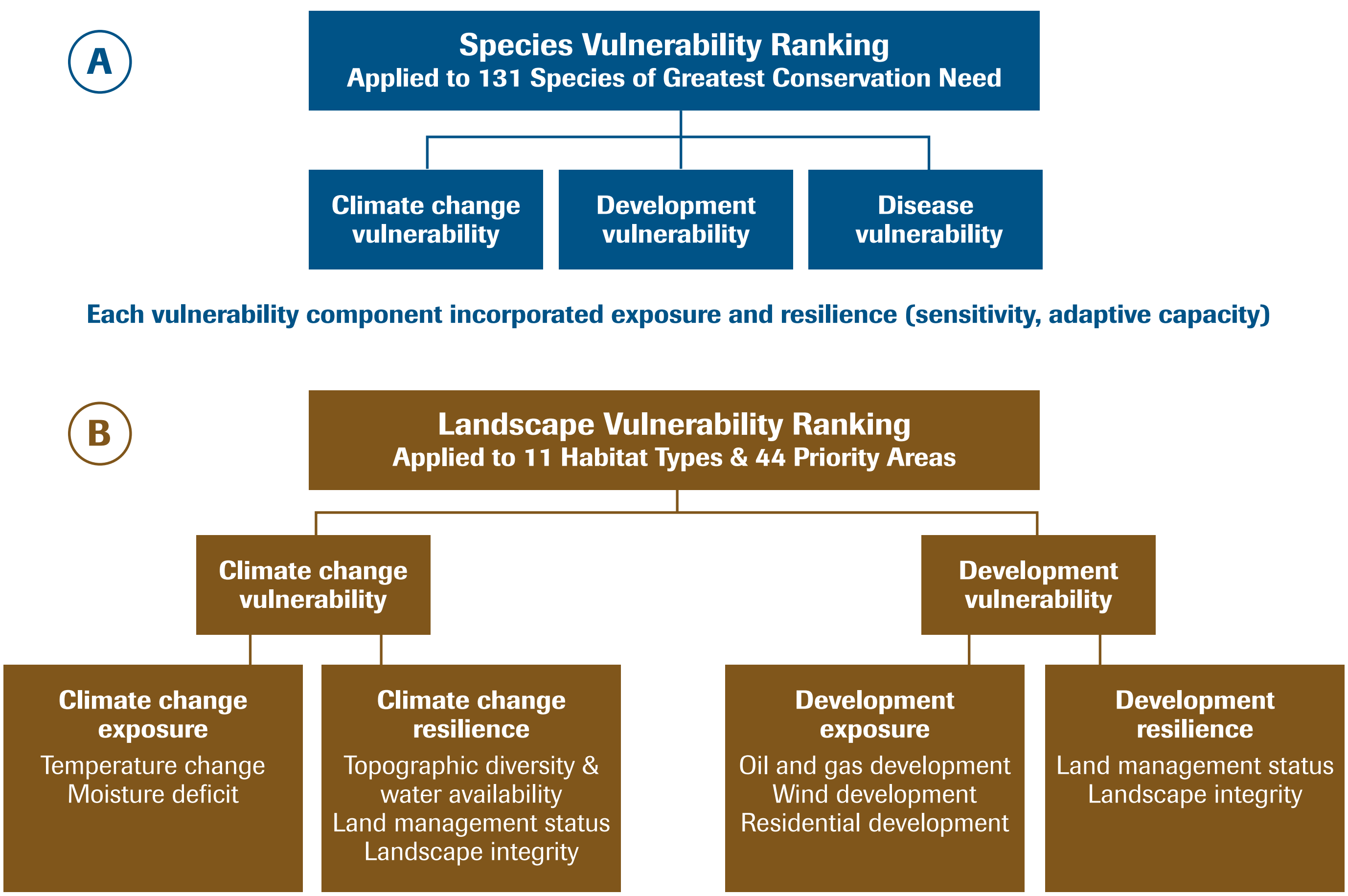


Figure 1. The vulnerability assessment included (A) species-based and (B) landscape-based analyses. For each species (A), vulnerability to climate change, development, and disease were evaluated and synthesized into one species vulnerability ranking. For each focal landscape (habitat type or terrestrial priority area) (B), climate change and development vulnerability were evaluated and synthesized into one landscape vulnerability ranking. Climate change and development vulnerability were each calculated as exposure minus resilience. The component datasets for exposure and resilience are shown in lighter text.

This vulnerability assessment is unique, because we considered multiple stressors (i.e., climate change, development, and disease) and used both species- and landscape-based approaches. The two approaches have rarely been combined in a single study (Kittel et al. 2011). Some climate change vulnerability assessments have focused on species (Crossman et al. 2012, Davison et al. 2012) and others on landscapes (Klausmeyer et al. 2011, Magness et al. 2011). We chose a dual approach to capture species-specific traits as well as landscape patterns that affect many species and habitats. Approaches that only use species-specific data assume that species vulnerability will apply more broadly to systems, and landscape approaches that ignore species-specific data may miss important differences in responses among species.

Factors influencing vulnerability were treated differently between the species and landscape-based analyses. Disease was only considered in the species-based approach, because diseases are specific to individual wildlife species. Climate change was included in both approaches but differed in its implementation. The species-based approach considered how changes in temperature or moisture could affect each species and their sensitivity and ability to adapt to potential changes. The landscape-based approach considered patterns of change in temperature and moisture across the state and how land management status, landscape integrity (i.e., degree to which habitats are intact and undisturbed), topographic diversity and water availability could facilitate resilience to climate changes. Oil and gas, wind, and residential development were included in both approaches using models describing their existing and anticipated distribution across Wyoming (Copeland et al. 2013).

Evaluating and quantifying uncertainty and confidence are an important component of any modeling exercise. Uncertainty in this study arose from the dynamic and nonlinear nature of natural systems and from potential errors in datasets used in the analyses. Where feasible, uncertainty or confidence was incorporated in the methods and expressed in the presentation of results. However, it is possible that the vulnerability of some species or focal landscapes will be greater or less than that reflected in this assessment. The intent of the assessment was not to provide absolute measures of vulnerability, but rather relative scores that can identify potential concerns and inform the prioritization of conservation actions. That said, the cumulative effect of all sources of uncertainty and bias could not be calculated and is unknown.

SPECIES VULNERABILITY

We ranked each of Wyoming's 131 SGCN to reflect their anticipated future vulnerability. The overall ranking combined scores reflecting vulnerability to climate change, energy and residential development, and wildlife disease (Figure 1a). Each vulnerability component incorporated exposure and resilience (sensitivity and adaptive capacity). For climate change, development and disease, a vulnerability ranking of low, moderate or high was assigned to each species, using methods provided in the following sections. We ranked each of the three components of vulnerability individually and then combined them into an overall rank, because each component was calculated using different scoring methods. A total vulnerability score was determined by summing the three individual ranks, by assigning values to low (1), moderate (2) and high (3) categories. These summed scores were then categorized into overall ranks of low (3-4), moderate (5), high (6-7), or very high (8-9). For example, a low rank for disease, moderate rank for climate change, and high rank for development resulted in a total vulnerability score of six and an overall vulnerability rank of high, while a low rank for development, low rank for disease, and moderate rank for climate change resulted in a total vulnerability score of four and an overall vulnerability rank of low. The overall vulnerability ranks were intended to highlight those species that may be the most vulnerable, but the individual contributing stressors will be most relevant to developing strategies to address threats. It is possible that the magnitude of effect may differ among the three stressors. However, we assigned each an equal weight, because we had no data to support weighting them differently and weighting would likely vary by species.

We further prioritized which species were most vulnerable by assigning a landscape-based vulnerability ranking to each species. This ranking reflected which species had the most vulnerable habitats and incorporated spatial elements of vulnerability that were not part of the species-based rankings. This ranking is independent of the species-based ranking described above. Landscape-based vulnerability was calculated across Wyoming as described in the Landscape Vulnerability methods section. We calculated the percentage of each species' medium or high predicted probability of occurrence (Keinath et al. 2010) that was categorized as high vulnerability to assign a low, moderate or high rank, as follows: low (<10%), moderate (10-33%), and high (>33%). We used one-third of the predicted habitat area as the cutoff for the high category, because given the large sizes of most species distributions, one-third of the land area could have a significant impact. Additionally, this threshold resulted in a reasonable distribution of categorizations among the species.

Additionally, we created maps that synthesized species-based vulnerability rankings across multiple species to highlight locations where many vulnerable species occur. We combined these maps with a landscape-based vulnerability map, to identify the locations across Wyoming where the largest concentrations of sensitive species are most vulnerable. The categorical species-based vulnerability rankings were converted to numerical scores, corresponding to low (1), moderate (2), high (3), and very high (4) ranks. The score for each species was assigned to each raster cell having a medium or high predicted probability of that species' occurrence (Keinath et al. 2010). The values corresponding with each raster cell were averaged across all 131 species and taxonomic groups (i.e. bird, mammal, amphibian, and reptile). These mean scores represent a "cross-species vulnerability index" (CSVI) (Davison et al. 2012). The CSVI is useful to visualize where the predicted habitats occur for the most vulnerable species; however, it does not show where within those predicted habitats threats are most likely to occur. Across all species and for each taxonomic group, we intersected locations with mean CSVI values of 0.30 or greater with locations where overall landscape vulnerability was ranked as high to show where habitats may be most vulnerable. The cutoff value of 0.30 represented the low end of the middle third of CSVI data across all species.

Climate Change

We applied Nature Serve's Climate Change Vulnerability Index version 2.1 (CCVI; www.natureserve.org/climatechange), which uses an evaluative framework to assign a relative score reflecting climate change vulnerability for each species based on multiple intrinsic and extrinsic factors related to indirect exposure, sensitivity or adaptive capacity (Young et al. 2013). The CCVI is a rapid assessment tool to distinguish species likely to be most vulnerable to climate changes and has been applied in several other state wildlife assessments (Byers and Norris 2011, Schlesinger et al. 2011, Wildlife Action Plan Team 2012, Hoving et al. 2013). The CCVI assigns a non-spatial score to each species. To calculate vulnerability, this score is adjusted based on the magnitude of direct exposure to projected climate change. To estimate direct exposure, we used projected temperature and moisture change for the 2050's (Hamon AET:PET Moisture Metric), which was selected because it is far enough in the future to detect significant changes, but not so far into the future that temperature projections from climate models diverge (Young et al. 2013). For these future climate datasets and to represent future climate and historical thermal and hydrological niches, we used data specifications recommended by Nature Serve. Downscaled climate datasets (Maurer et al. 2007) were downloaded from Climate Wizard (Girvetz et al. 2009). All climate data were summarized across the medium or high predicted probability of each species' occurrence (Keinath et al. 2010).

Each species was assigned scores for natural history traits related to indirect exposure, sensitivity, and adaptive capacity (Young et al. 2013). Indirect exposure included distribution relative to natural habitat barriers or anthropogenic barriers. Sensitivity and adaptive capacity included dispersal ability, historical and physiological thermal and hydrological niches (i.e., temperature and moisture the species is accustomed to), dependence on ice or snow, physical habitat specificity, reliance on other species that may be affected by climate change, diet versatility, and occurrence of recent genetic bottlenecks. Size of population and range are not explicitly considered within the CCVI, to avoid causing most sensitive species to be scored as vulnerable to climate change; CCVI is meant to be complementary to conservation status. There is also an option to use actual or modeled responses to climate change, but we did not have the data available to do so.

We reviewed available literature for each of the 131 species prior to scoring them using the CCVI. For mammals, we reviewed each species account available from the American Society of Mammalogists (www.asmjournals.org). Only the Wyoming Pocket Gopher was not represented, so we relied on accounts of closely related species (Verts and Caraway

1999). We also supplemented information contained within each species account when more information was needed, such as for the American Pika (Kruezer and Huntly 2003, Morrison and Hik 2007, Beever et al. 2008, Galbreath et al. 2010). We also used technical conservation assessments when available (Beauvais 2006b, Keinath and Beauvais 2006). For birds, we used The Birds of North America online resources (http://bna.birds.cornell.edu/bna/) and supplemented these with technical conservation assessments and peer-reviewed literature specific to climate change, when available (Crick 2004, Beauvais 2006a, Gienapp 2008). For reptiles and amphibians, we relied primarily on experts (Z. Walker, Wyoming Game and Fish Department, personal communication) for inputs into the CCVI, and we also consulted peer-reviewed literature (Gibbon et al. 2000, Walther et al. 2002). Once preliminary results were compiled, we initiated a review by wildlife biologists from the Wyoming Game and Fish Department having expertise in specific taxonomic groups (i.e., mammals, birds, reptiles, and amphibians). Some species received reviews by multiple experts (e.g., American Marten, Northern Goshawk, Greater Sage-Grouse). When discrepancies or errors were identified by the experts, we reviewed existing literature together to identify specific criteria for that species. In situations where the interpretation of the literature differed or when data was lacking, we used expert opinion to resolve the issue.

The index resulted in five vulnerability classes, which we reduced to three rankings (shown in parentheses): Extremely Vulnerable (High), Highly Vulnerable (High), Moderately Vulnerable (Moderate), Not Vulnerable/Presumed Stable (Low), and Not Vulnerable/Increase Likely (Low). A measure of confidence was provided when the scorer selected more than one level for a specific scoring factor, through simulations with the multiple scores. Confidence was low in cases with less than 60% agreement (Young et al. 2013).

Energy and Residential Development

The development score included oil and gas, wind energy, and residential housing development. The primary score used in the vulnerability ranking was based on existing (2010) and projected (2030) development combined for these three types. For comparison, we also calculated a score based on existing development only. We represented existing development using point datasets of oil and gas wells (Wyoming Oil and Gas Conservation Commission 2010), wind turbines (O'Donnell and Fancher 2010), and houses (Copeland et al. 2013). Future development projections were based on spatial models representing the likelihood of potential development, combined with published growth projections used to populate the highest probability locations with oil and gas well, wind turbine or house points, while excluding those areas where each development type would be legally prohibited (Copeland et al. 2013).

We used the point datasets representing existing or projected development to generate disturbance footprints where the maximum disturbance occurred at development points (i.e. wells, turbines, houses) and decayed logistically to zero over a distance of 1 km to capture species' sensitivity to disturbance (Benitez-Lopez et al. 2010, Keinath et al. In preparation). We created an existing and cumulative (existing + projected) disturbance footprint for each of the three development types. We combined the points for each of the three development types to calculate the overall disturbance footprint, to avoid double-counting different types of disturbances that overlapped in some locations. Next, for each species, we multiplied the probability of the species' occurrence, represented by habitat suitability maps (Keinath et al. 2010), by the disturbance footprint in each map cell. This resulted in a development exposure score for each species, which represents the proportion of that species' potential distribution exposed to development, weighted by the relative probability of occurrence and disturbance intensity (Keinath et al. In preparation). The score ranges from zero, for a species whose habitat does not overlap with development, to an upper limit near one for a species whose habitat is entirely encompassed by projected high-density development.

The development score differed from the climate change and disease scores by assuming that all species have the same level of sensitivity to development. Species-specific estimates of sensitivity to development were not available across the 131 species considered. This exposure-based score may underestimate vulnerability to development for species that are more sensitive, or conversely, overestimate vulnerability to development for species that are less sensitive. The exposure score did not lend itself to biologically-based breaks for low, moderate, and high categories so we assigned a relative ranking, where the lowest 25% of the values were low, the highest 25% of values were high, and values ranging falling between the 25 and 75th quartiles were moderate (to reflect uncertainty). These statistical cut points emphasize the highest and lowest exposure values; however, occurrence in the moderate category does not indicate that a species is less sensitive to development than a species in the high category. Rather, it indicates a difference in exposure to development. Since vulnerability is a direct function of exposure and sensitivity, wildlife species with higher exposures to development have a greater likelihood of being vulnerable. The primary vulnerability score and ranking was based on cumulative development across the three types, but we also present results for existing development, the 20-year change in development, and for each development type.

Wildlife Disease

For wildlife diseases, we developed an approach similar to the CCVI, which uses an evaluative framework to assign a relative vulnerability score for each species. The scoring for wildlife disease vulnerability included sensitivity risk, exposure risk, and adaptive capacity (Appendix B). Sensitivity risk measured how sensitive populations are to the disease of interest, including how often the disease is fatal for a significant portion of the population and whether low genetic variation within a population might increase sensitivity (O'Brien and Evermann 1988, Altizer et al. 2003, Spielman et al. 2004). Exposure risk measured the how widespread the species is in both Wyoming and North America, to what degree the disease overlaps with those species distributions, and the connectivity of individual populations that may facilitate exposure to disease (Hess 1994, 1996). Adaptive capacity was represented by the effectiveness of natural adaptive responses (i.e., sero-conversion), life history strategy (e.g., longevity, age at sexual maturity), capacity to recolonize infected areas, and the feasibility of direct management intervention via prophylaxis vaccination or indirect management via access restrictions and gear disinfections.

Wildlife diseases are stochastic events, often with severe and devastating impacts that are not additive – because a species is vulnerable to one disease it does not have an increased probability of being infected by another disease. Accordingly, we ranked diseases independently for each species and constrained our analysis by not considering wildlife diseases that had little potential to affect populations at a large scale (e.g., rabies in bats). Therefore, we present only results for the disease that posed the greatest risk to each species, though we considered all the diseases that we had identified as important to a particular taxonomic group. It is worth noting that some diseases (e.g., West-Nile virus) may be emerging issues for specific species (e.g., Bald Eagle). As impacts from emerging issues may not be fully known, it is possible that some errors exist in our rankings and that as a result, another disease may have ranked higher. Nevertheless, because this approach relied on identifying the single biggest disease threat to persistence of each species, we believe it is robust to these types of omissions.

We first identified which wildlife diseases were major threats to each taxonomic group and had the potential to occur in Wyoming (Kreeger et al. 2011). For mammals, we considered six diseases: chronic wasting disease, pneumonia, sarcoptic mange, sylvatic plague, tularemia, and white-nose syndrome. For birds, we considered five diseases: aspergillosis, avian pox, avian cholera, botulism (Type E and Type C), and West-Nile virus. For amphibians and reptiles, we only considered chytrid fungus and ranavirus. To evaluate risk and impacts to each mammal species, we reviewed available peer-reviewed articles and books (Williams and Barker 2008, Kreeger et al. 2011), along with Mammalian Species accounts (www.asmjournals.org). For birds, we reviewed reports and books (Friend and Franson 1999, Nicholoff 2003, Kreeger et al. 2011) and consulted online resources retrieved from the Center for Disease Control (www.cdc.gov) and The Birds of North America (http://bna.birds.cornell.edu/bna/). For amphibians and reptiles, we relied on expert input. Within each group, some species were not known to be susceptible to any of the wildlife diseases that we had identified. In these situations, we attempted to identify alternate diseases but were unable to identify any that met our initial criteria. Consequently, for these species, we assigned a disease vulnerability score of 0.

Every wildlife disease for each species was assigned a numerical score, which was compiled from the sum of sensitivity and exposure risk minus adaptive capacity (Appendix B). In cases where species were affected by multiple diseases, we based that species' final ranking on the highest-scoring disease. The numerical scores were then assigned a ranking. Lacking precedence for defining this breakdown (e.g., low, moderate, high), we identified natural breaks in the results and used those as a reference for assigning categorical values, resulting in disease vulnerability rankings of low (<13), moderate (13.1 to 20.9) and high (>21). Three wildlife disease experts provided either initial input or review of our framework and preliminary results. When discrepancies or errors were identified by the experts, we reviewed existing literature together for the specific criterion for that species. In situations where data were lacking in the literature, we used expert opinion to resolve the issue.

LANDSCAPE VULNERABILITY

To assess landscape vulnerability, we first calculated spatially-explicit estimates of exposure to development, exposure to climate change, resilience to development, and resilience to climate change across Wyoming. These calculations (described in the following sections), resulted in 30-m resolution raster maps of Wyoming, where cell values ranged from 0 (minimal exposure or resilience) to 1 (maximal exposure or resilience). These datasets were then used to calculate development vulnerability, climate change vulnerability, and overall vulnerability (development + climate change). Each of the resulting datasets were then summarized for each focal landscape, including 11 habitat types (Figure 2) and 44 priority areas (Figure 3), as described on page 20 under "Landscape Vulnerability Calculations".

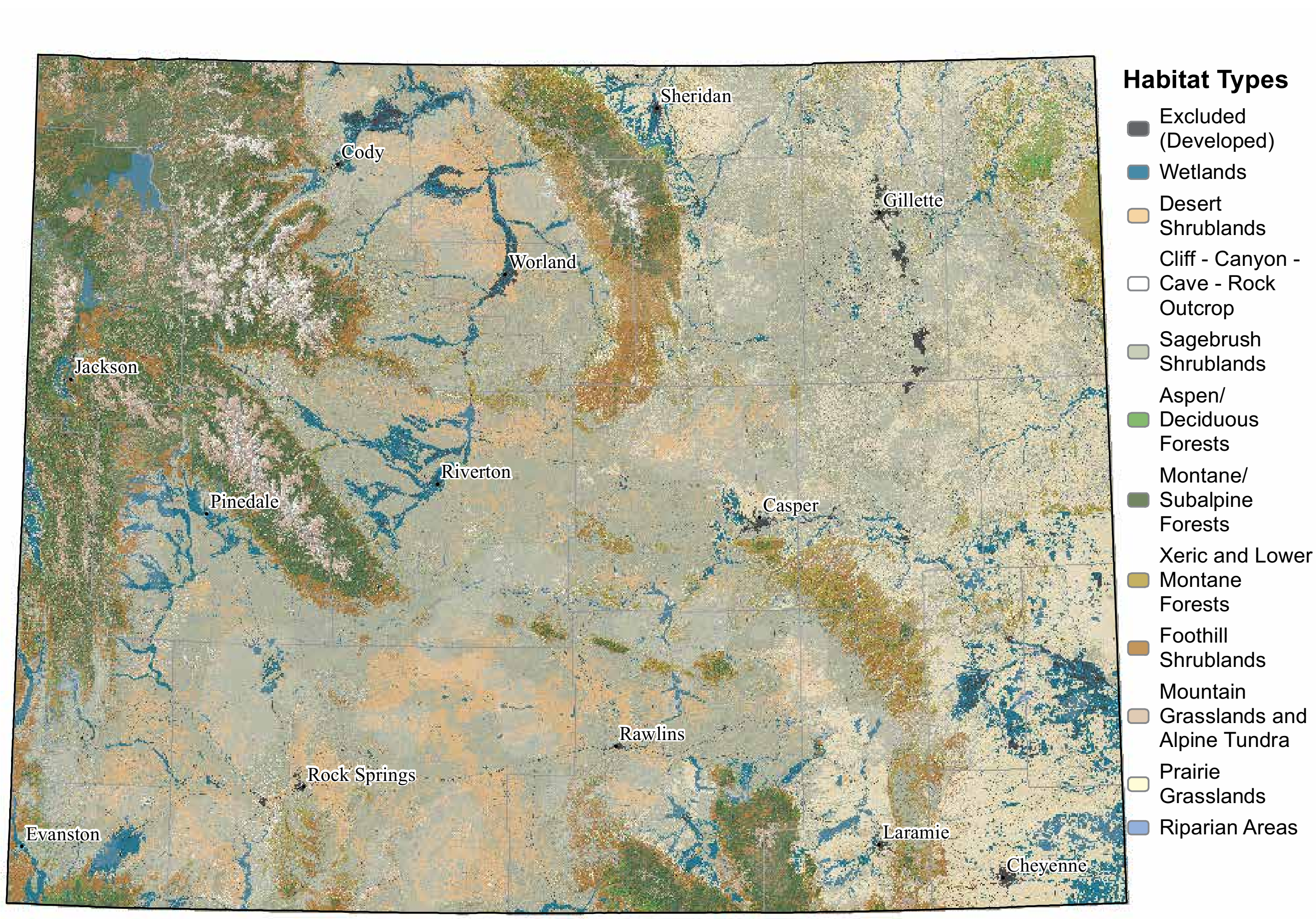
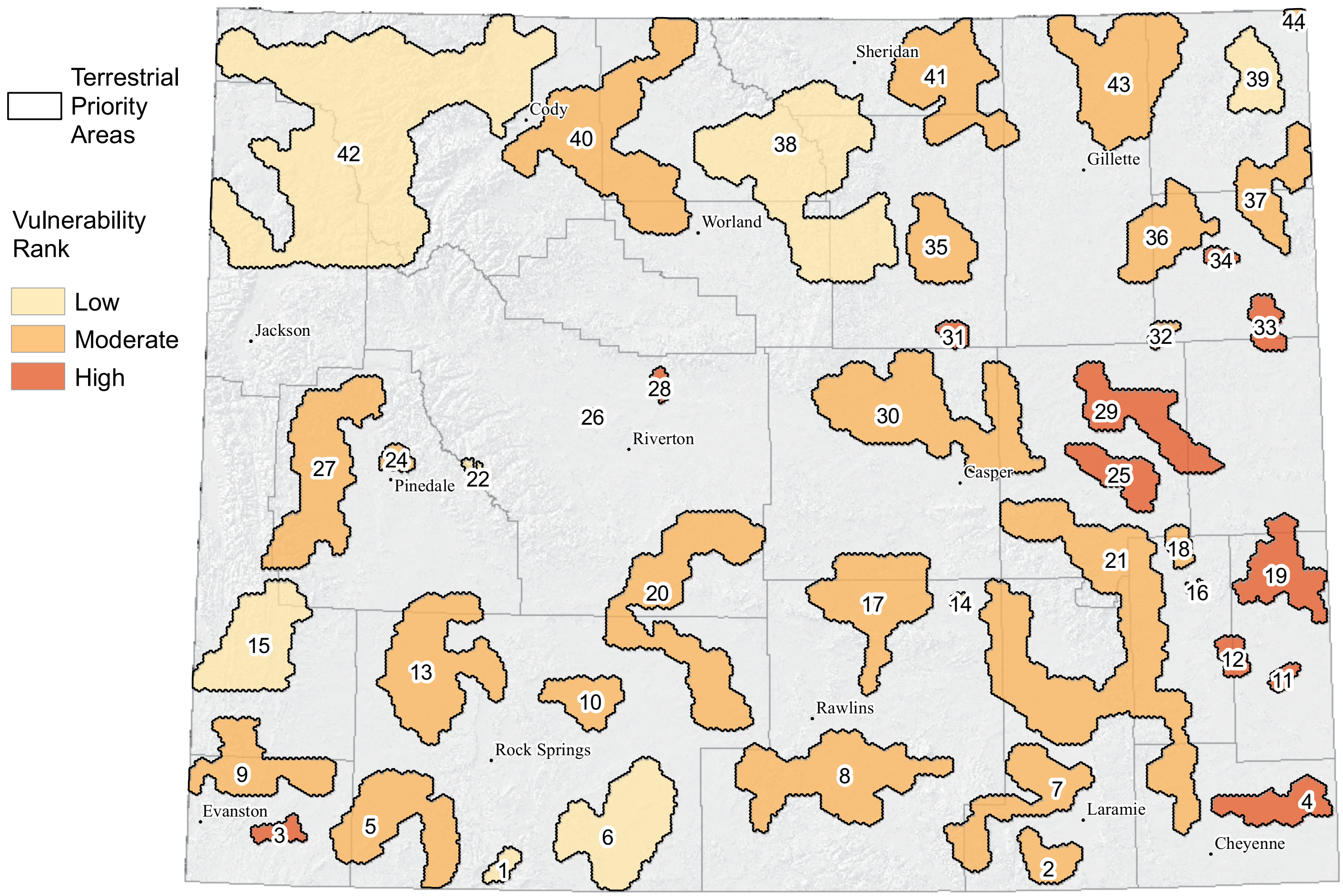


Figure 2. Terrestrial habitat types of Wyoming, as identified in Wyoming's 2010 State Wildlife Action Plan. County boundaries are displayed in gray.

Figure 3. Terrestrial priority areas, as identified in Wyoming's 2010 State Wildlife Action Plan. The 44 priority areas are labeled with numbers to facilitate cross-referencing with vulnerability results for each area. Vulnerability ranks are based on the percentage of each priority area that is highly vulnerable.. County boundaries are displayed in gray.



Development Exposure

Exposure to development represents the relative impact of development on the landscape and was calculated for all 30-m raster cells across Wyoming. Cell values ranged from 0, which reflects minimal potential for impact, to 1, which reflects complete conversion of native habitat.

Development exposure included oil and gas, wind energy, and residential housing development, and used the same datasets applied in the species-based analysis, as described in the previous "Species Vulnerability" section. Exposure was cumulative and included existing (2010) and projected (2030) development combined for the three development types. To create the cumulative development exposure dataset, we combined the points for each of the three development types and generated a raster dataset where the maximum disturbance (value=1) occurred at development points (i.e. wells, turbines, houses) and decayed logistically to zero over a distance of 1 km (Keinath et al. In preparation). These methods were repeated for the oil and gas, wind and residential data points separately to create individual exposure maps.

Climate Change Exposure

Exposure to climate change represents the relative impact of changes in temperature and moisture on the landscape and was calculated for all 30-m raster cells across Wyoming. Cell values ranged from 0, which reflects minimal potential for change, to 1, which reflects a maximum change in climate conditions. We used two metrics, annual mean temperature change rate (°C/yr) from 1951-2006 and projected moisture deficit, to evaluate the exposure of Wyoming's habitats to climate change (Figure 4a, b). We chose a metric quantifying moisture stress, where evaporative demand is higher than precipitation, to focus on areas likely to be significantly drier than the current climate (Copeland et al. 2010). Precipitation alone is highly variable, and past trends in precipitation across Wyoming have not been statistically significant (Girvetz et al. 2009). Moisture deficit was calculated as potential evapotranspiration (PET) minus precipitation (in mm), summed annually, and was set to zero if precipitation was greater than PET. We used departure of 2040-2069 moisture from the 1961-1990 record, using the IPCC's A2 emissions scenario and an ensemble of 15 climate models. This time frame was chosen to be consistent with recommended datasets that we used to populate the Nature Serve CCVI tool and because 2050 is far enough into the future for significant changes to have occurred, while projections from various climate models begin to diverge beyond 2050 (Young et al. 2013).

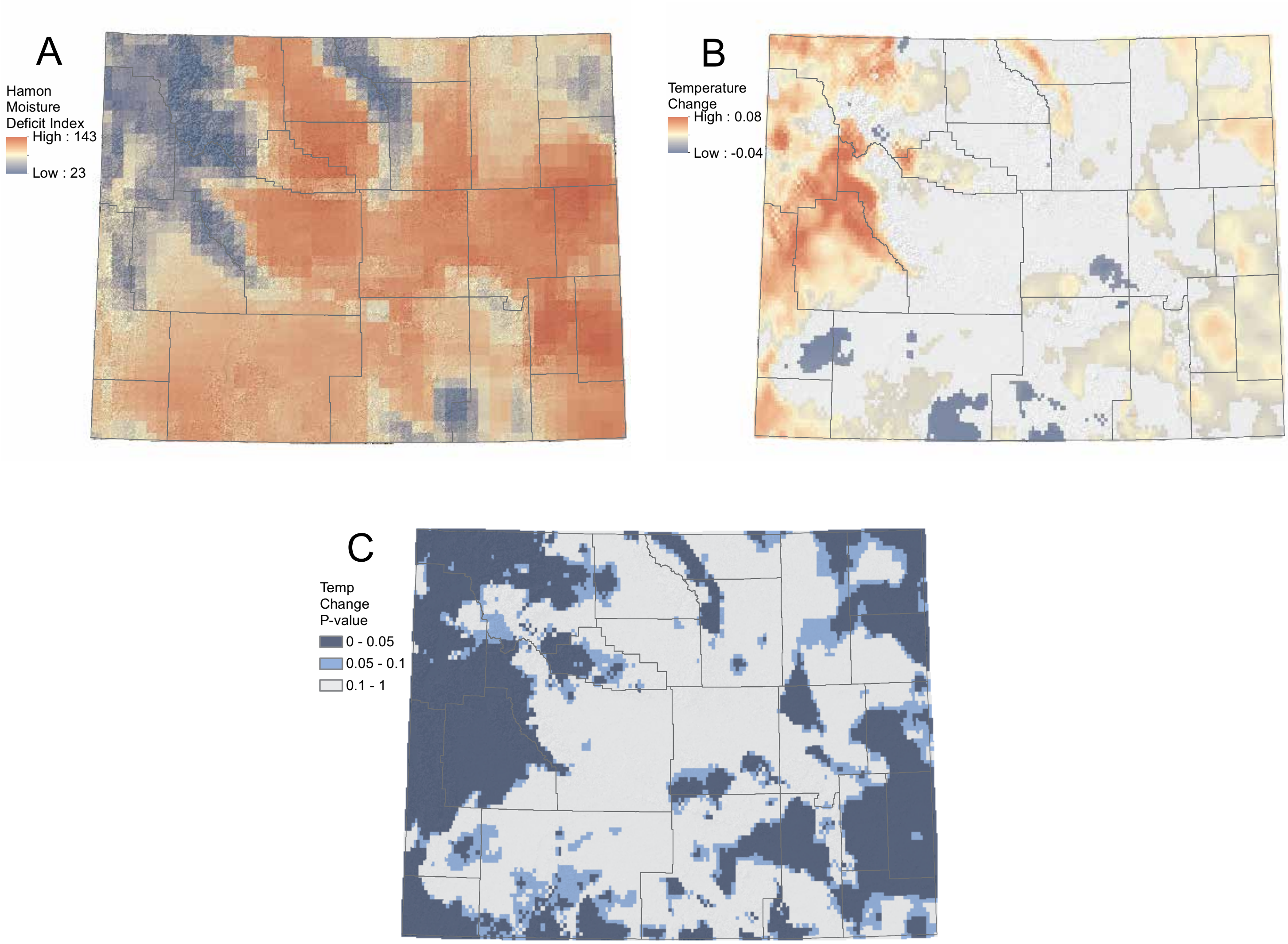


Figure 4. Climate change exposure was calculated using the (A) projected Hamon Moisture Deficit Index (mm) and (B) the historical annual mean temperature change rate (°C/yr). Locations with low statistical confidence in temperature change rate (C), a p-value >0.1, were excluded from the analysis. Temperature data are not shown (appear as light gray) in panel B for the locations with low statistical confidence.

The temperature change and moisture deficit raster data were downloaded from Climate Wizard (Girvetz et al. 2009), which uses 4-km Parameter-elevation Regression on Independent Slopes (PRISM) data for US historical climate data and 12-km North America future projections from General Circulation Models (GCMs) downsampled from the global model data (Maurer et al. 2007). Climate Wizard also provided a spatial representation of statistical confidence for the temperature change data. Other historical and projected climate datasets, extrapolated using different modeling approaches, are also available for Wyoming (Hijmans et al. 2005, Rehfeldt 2006). We compared annual historical mean temperature datasets among PRISM, Bioclim, and Rehfeldt datasets and patterns were nearly identical. We used PRISM-based datasets because they offered variables well-suited for our analysis that can be easily accessed and explored by the public through the Climate Wizard website (www.climatewizard.org).

To represent climate exposure we combined the temperature and moisture deficit raster data (Figure 4). First, we adjusted temperature change by removing data from areas with low statistical confidence (p-value >0.1) (Figure 4c). We then grouped each climate dataset into 10 bins, where the first bin represented the lowest 10% of scores and the tenth bin represented scores that were greater than 90% of the scores. We binned the scores into these 10 quantiles so that the lowest and highest values were equivalent between the datasets. In the areas of the state with high confidence in temperature data, we summed the binned temperature and moisture deficit rasters and normalized the sum to range from 0 to 1. In the areas of the state having low temperature confidence, exposure was represented solely by the moisture deficit dataset.

Climate Change and Development Resilience

Resilience represents the relative ability of habitats within a landscape to survive or recover from a change. Resilience was calculated separately for development and climate change for all 30-m raster cells across Wyoming. Cell values ranged from 0, which reflects minimal resilience, to 1, which reflects maximal resilience. Resilience was calculated from three datasets: topographic diversity and water availability, land management status, and landscape integrity. Each resilience dataset ranged in value from 0 to 1 (1=highest resilience). Resilience to development was represented using land management status and landscape integrity, while resilience to climate change was represented using all three datasets. Topographic diversity and water availability provide resilience to changes in climate specifically (Ackerly et al. 2010). Land management status and landscape integrity reflect the level of management protection and habitat intactness and have relevance for wildlife habitat resilience to both development and climate change. For both development and climate change, the two or three resilience datasets were each grouped into 10 quantile bins before they were summed so that the lowest and highest values were equivalent between the two datasets. For climate change resilience, we assigned equal weight to the topographic diversity dataset and the other two landscape conditions combined due to the importance of topographic diversity and water availability for buffering against climate change.

Topographic Diversity and Water Availability

The datasets we used to represent climate exposure were derived from coarse-scale models, but the climate conditions experienced by wildlife species and their habitats in particular locations may differ from these coarse-scale climate model estimates (Luoto and Heikkinen 2008, Randin et al. 2009, Willis and Bhagwat 2009). Fine-scale spatial heterogeneity in climate conditions provides an important buffer against climate change (Ackerly et al. 2010). Local variability in climate, due to topographic diversity, can promote population stability and increase the persistence of plant and animal species (Weiss et al. 1998, Luoto and Heikkinen 2008, Randin et al. 2009, Oliver et al. 2010). This buffer against climate effects is the result of having many combinations of temperature and moisture within a local area, as occurs in mountainous areas. We therefore included the buffering effect of topographic diversity in our calculation of resilience to climate change, which we represented at two spatial scales (Anderson et al. 2012, Anderson et al. 2014). We captured major differences in topography and local climate settings using landform diversity, and to capture finer scale differences we used microclimate diversity. Including fine-scale topographic diversity also allowed us to adjust the climate vulnerability index to account for the limitations of the coarse-scale climate exposure dataset.

We defined and mapped landforms from a 30-m National Elevation Dataset DEM based on a cluster analysis of elevation, the Compound Topographic Index (CTI) (Moore et al. 1993, Gessler et al. 1995), the Heat Load Index (McCune and Keon 2002) and terrain ruggedness (Sappington et al. 2007). The CTI and Heat Load Index were calculated in ArcGIS using the Geomorphometry and Gradient Metrics Toolbox (Cushman et al. 2010). We defined the landforms using the four topographic datasets and a migrating means clustering procedure, using the Iso Cluster algorithm and maximum likelihood classification in ArcGIS (Ball and Hall 1965, Richards 1986). We used the k-medoids clustering algorithm with the 'clara' model to help identify the optimal number of clusters, which was identified as seven (Kaufman and Rousseeuw 1990, Maechler et al. 2014). This resulted in a coarse-scale representation of characteristic landforms across Wyoming (Figure 5a). Landform diversity was measured as the variety of landform classes occurring within a 2-km rectangular window around each raster cell, calculated on a 90-m resolution version of the landform dataset (Figure 5c). A 2-km window was chosen because it maximized the cell-to-cell variation in landform variety.

Microclimate diversity was based on the CTI and Heat Load Index. The CTI represents locations that accumulate moisture, and the Heat Load Index represents the relative temperatures of locations, based on solar radiation, aspect and slope. For each dataset, we calculated microclimate diversity in the area surrounding each raster cell using the standard deviation in a 250-m window around each CTI cell and a 2-km window around each Heat Load cell. These window sizes were chosen because they maximized the cell-to-cell variation in each index. For each diversity index, we calculated 10 quantile bins. The 10-bin datasets for CTI and Heat Load were summed and normalized from 0 to 1 to represent microclimate diversity (Figure 5d).

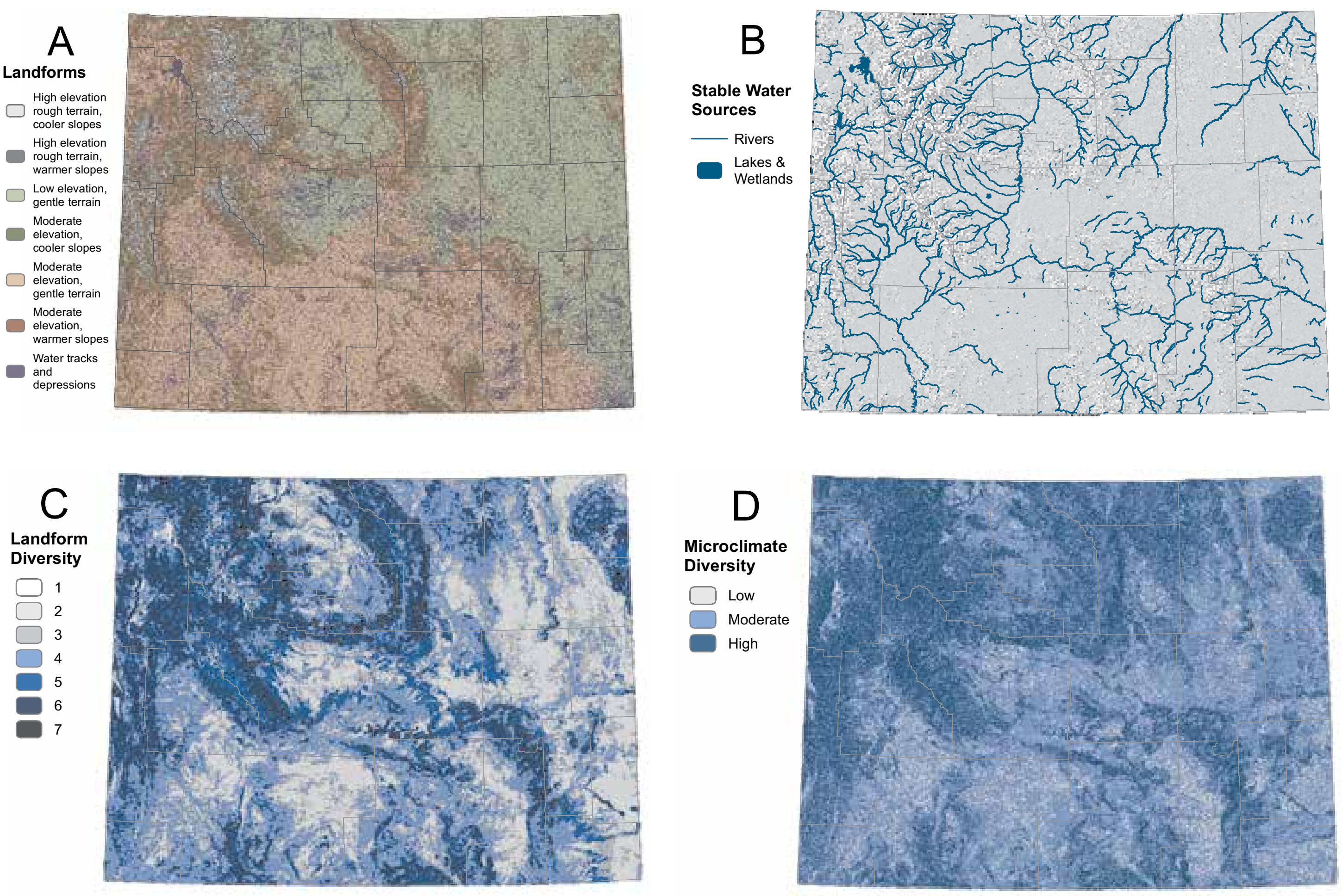


Figure 5. The component datasets of topographic diversity and water availability were coarse-scale landform diversity (C), calculated from seven major landforms (A), fine-scale microclimate diversity (D), and the distance to stable water sources (B). Streams are not contiguous because only perennial segments of some streams were selected.

Many wildlife species are very dependent on water sources. Droughts may become more frequent as the climate changes, and reliable sources of water may be very important. Therefore, we also included distance to stable water sources as a factor that may buffer against the effects of climate change (Klausmeyer et al. 2011). We included lakes and permanent wetlands over 100 ha in size (Klausmeyer et al. 2011) and major rivers and perennial streams order 3 and higher (Figure 5b), as mapped in the National Hydrography Dataset and the National Wetlands Inventory (U.S. Geological Survey 2009, U.S. Fish and Wildlife Service 2010). We calculated the Euclidean distance to each of these water features in ArcGIS and assigned a value of 1 to the water source and decreased values linearly to 0 at distances of 15 km or greater.

The final dataset representing topographic diversity and water availability (Figure 6a) was created by summing the landform diversity, microclimate diversity, and distance to water raster datasets, and the product was normalized to range from 0 to 1. The three input datasets were equally weighted, and each was grouped into 10 quantile bins before summing.

Land Management Status

We described land management across Wyoming using GAP land management status codes (Table 1, Figure 6b), which are a measure of intent to manage for and conserve biodiversity (Scott et al. 1993, US Geological Survey Gap Analysis Program 2010). We applied a recent GAP analysis dataset (US Geological Survey Gap Analysis Program 2010), with the following modifications. The land status definitions used in the 2010 GAP analysis did not include lands that have temporary legal protections or designations that afford limited legal protections. Therefore, we added a new category – status 2b – which

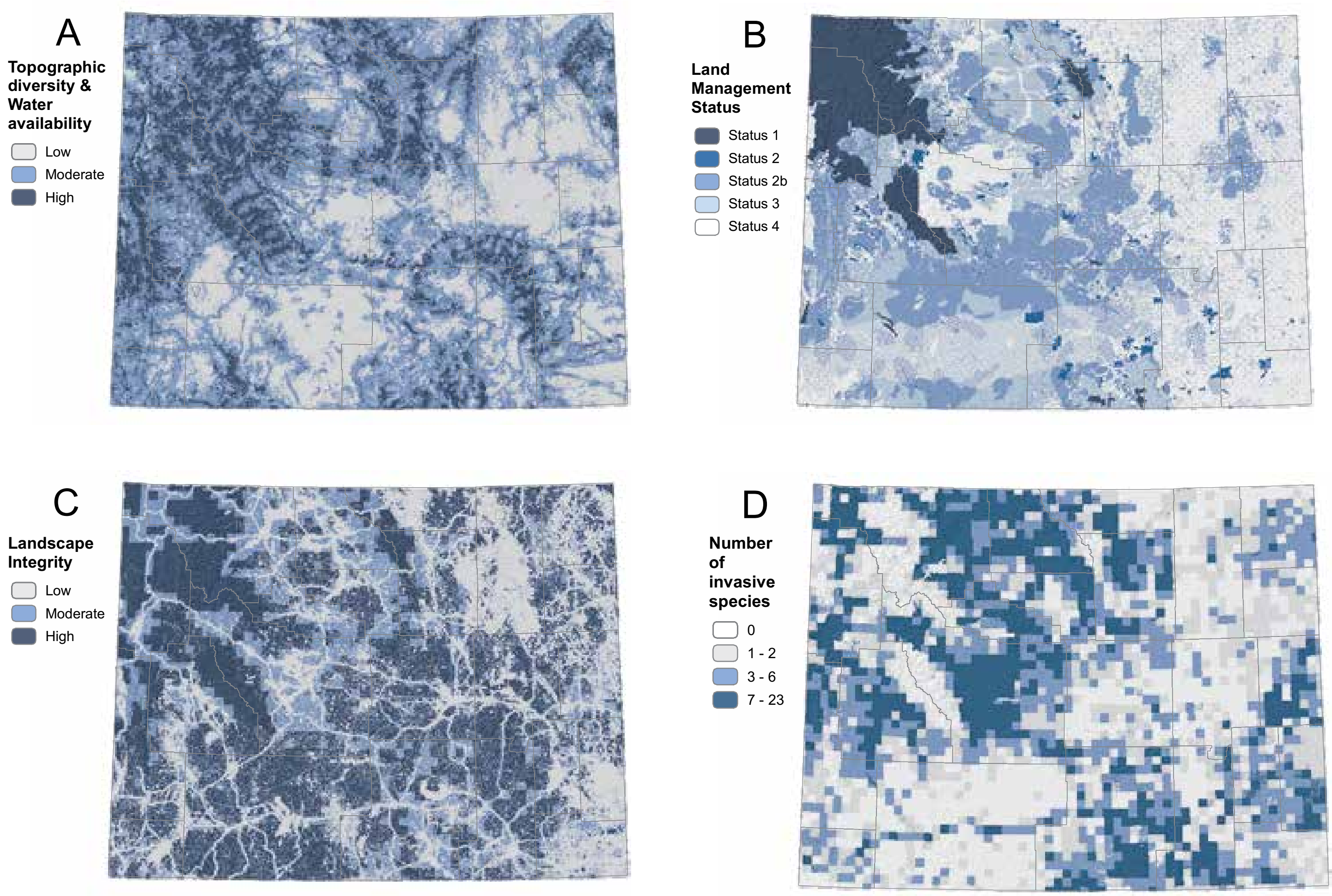


Figure 6. The component datasets of resilience to climate change and development were (A) topographic diversity and water availability, (B) land management status, and (C) landscape integrity. Invasive plant species diversity (D) was incorporated into the landscape integrity dataset.

we defined as areas having temporary protection from conversion of natural land cover or legally-mandated restrictions that limit extractive uses. The recent GAP analysis categorized BLM Areas of Critical Environmental Concern (ACEC) and Wilderness Study Areas (WSA) as either status 2 or 3, but we categorized all of these in the new status 2b. Status 2b also included Sage-Grouse Core Areas (State of Wyoming Executive Department 2011) and 'no surface occupancy' designations for oil and gas development gathered from Forest Service and BLM field offices, neither of which have been previously included in Wyoming GAP analyses but which afford legal restrictions on development. Within sage-grouse core areas, we included only public lands or private lands with federal minerals under status 2b, because the core area policy does not have jurisdiction over oil and gas development on private lands having private minerals, which comprise ~ 20% of the core areas. Land use types within the core areas were not differentiated. Other modifications included the categorization of all wilderness areas and national wildlife refuges as status 1 and the categorization of all conservation easements and wildlife habitat management areas as status 2. We also applied updated versions of datasets representing conservation easements (Copeland and Browning 2013) and BLM ACECs and WSAs (U. S. Bureau of Land Management 2013).

In order to assign land management status scores to focal landscapes, we assigned a relative "resilience support" score to each land management status category that reflected our estimate of that status' ability to support resilient wildlife habitats (Table 1). We assumed that the high level of protections afforded by GAP status 1 would maintain high resilience, with a resilience support score equal to 1. For status 4 lands, there is high uncertainty whether these lands might facilitate resilience, so these lands were assigned a score of 0. For the remaining three categories, we assigned scores consistent with land use practices typical of that status (Table 1).

Table 1. GAP land management status categories assigned to Wyoming lands and our estimate of the probability that each status will support the resilience of wildlife habitats. [1] *Definitions are from USGS GAP (2010) with exception of Status 2b.*

GAP status	GAP status definition[1]	Management designations included	Resilience support score
1	An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management.	Wilderness Areas, Nature Conservancy Preserves, National Wildlife Refuges, National Parks	1
2	An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.1	State Wildlife Habitat Management Areas, State Parks, Conservation Easements	0.75
2b	An area having temporary protection from conversion of natural land cover or legally-mandated restrictions that limit extractive uses (i.e., oil and gas development, wind development, mining).	Sage-grouse core areas, BLM Areas of Critical Environmental Concern and Wilderness Study Areas, No Surface Occupancy designations	0.5
3	An area having permanent protection from conversion of natural land cover for the majority of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging, OHV recreation) or localized intense type (e.g., mining). It also confers protection to federally listed endangered and threatened species throughout the area.	Publicly managed lands with management plans in place, including Forest Service, Bureau of Land Management, Bureau of Reclamation, State Trust Lands	0.25
4	There are no known institutional mandates or legally recognized easements or deed restrictions held by the managing entity to prevent conversion of natural habitat types to anthropogenic habitat types. The area generally allows conversion to unnatural land cover throughout or management intent is unknown.	All other lands not assigned a different land management status.	0

Landscape Integrity

Landscape integrity was represented as the inverse of human disturbance (Figure 6c). We used a human disturbance dataset that included existing cultivated and hay lands, oil and gas pipelines, oil and gas wells, transmission lines, residential development, roads, surface mines, and wind turbines. This dataset was also used as part of terrestrial priority area identification in the 2010 State Wildlife Action Plan (Wyoming Game and Fish Department 2010c). A decay function was applied to each of the disturbance features that reflected the distance from the feature at which disturbance to wildlife is expected (Theobald 2003, Holloran 2005, Neely et al. 2006, Benitez-Lopez et al. 2010). The distances were categorized as abrupt (250 m), moderate-abrupt (600 m), moderate (1250 m), and gradual (2000 m) (Neely et al. 2006) (Table 2). After the distance decay function was applied, each feature was multiplied by a relative weight reflecting development intensity (Table 2) (Neely et al. 2006). Further details on these calculations are provided in Neely et al. (2006). The final raster datasets were summed and normalized to range from 0 to 1. Invasive species were incorporated as an available measure of vegetation condition and because of their potential effects on wildlife habitats (Litt and Pearson 2013). The invasive species raster dataset described below was added to the disturbance dataset with a weight equivalent to that of pipelines. A decay function was not applied to the invasive species dataset, because the data were already presented at a coarse spatial scale. Values in the final landscape integrity dataset ranged between 0 and 1 (1=high).

Table 2. Disturbance features represented in the landscape integrity dataset.

Disturbance feature	Weight	Decay distance (m)	Data source
Urban development – High/Medium	500	2000	Davidson et al. 2009
Urban development - Low	300	2000	Davidson et al. 2009
Roads – Primary/Secondary	500	1250	Tiger/Line Files 2009
Roads – Local/Primitive	300	250	Tiger/Line Files 2009
Oil and gas wells – Active	400	1250	Wyoming Oil and Gas Conservation Commission 2010
Oil and gas wells - Inactive	200	600	Wyoming Oil and Gas Conservation Commission 2010
Surface mines – Active	500	1250	Active mine permits, Wyoming DEQ 2010
Surface mines – Inactive	300	1250	Reclaimed open pit mines, Wyoming DEQ 2007
Wind turbines	400	1250	O'Donnell and Fancher 2010
Pipelines	100	250	Wyoming Pipeline Authority, 2010
Transmission	200	600	US Geological Survey, 2004
Cultivated and hay lands	300	600	Davidson et al. 2009
Invasive plant species	100	Dataset scale	Described in this report

The invasive species component of landscape integrity was based on mapped data representing invasive plant species diversity across Wyoming. Presence of 24 of Wyoming's 25 designated noxious weed species (http://www.wyoweed.org/statelist.htm) was mapped in 2012 at a 9.6-km resolution across the state (Wyoming Weed and Pest Council 2012). The 24 species were Canada Thistle (*Cirsium arvense* L.), Common Burdock (*Arctium minus* (Hill) Bernh.), Common St. John's Wort (*Hypericum perforatum* L.), Common Tansy (*Tanacetum vulgare*), Dalmatian Toadflax (*Linaria dalmatica* (L.) Mill.), Diffuse Knapweed (*Centaurea diffusa* Lam.), Dyers Woad (*Isatis tinctoria* L.), Field Bindweed (*Convolvulus arvensis* L.), Houndstongue (*Cynoglossum officinale* L.), Leafy Spurge (*Euphorbia esula* L.), Musk thistle (*Carduus nutans* L.), Oxeye Daisy (*Leucanthemum vulgare* Lam.), Perennial pepperweed (*Lepidium latifolium* L.), Perennial sowthistle (*Sonchus arvensis* L.), Plumeless Thistle (*Carduus acanthoides* L.), Purple Loosestrife (*Lythrum salicaria* L.), Russian Knapweed (*Acroptilon repens* L.), Russian Olive (*Elaeagnus angustifolia* L.), Saltcedar (*Tamarix sp.*), Scotch Thistle (*Onopordum acanthium* L.), Skeletonleaf Bursage (*Ambrosia tomentosa* Nutt.), Spotted Knapweed (*Centaurea stoebe* L. *ssp. micranthos*), Whitetop (*Cardaria draba* L. Desv.), and Yellow Toadflax (*Linaria vulgaris* (P.) Mill.). Cheatgrass (*Bromus tectorum*), another invasive species of concern in wildlife habitats, was not included in this mapping because it has not been designated as a noxious weed species and therefore was not mapped by Weed and Pest Districts. Most of the species commonly occur in both upland and wetland habitat types, but Oxeye Daisy is considered restricted to uplands, and Purple Loosestrife, Russian Olive, and Salt Cedar are invasive only in wetlands (Lichvar 2013, Whitson et al., 2001).

For each raster cell location in Wyoming we calculated the sum of the 23 wetland-affiliated species in locations with riparian or wetland habitat types and the 21 upland-affiliated species in locations with upland habitat types. We used the habitat type map from the 2010 State Wildlife Action Plan (Wyoming Game and Fish Department 2010c), which includes 12 classes that were combined from a more detailed land cover classification (Davidson et al. 2009). Locations above 3048 m (10,000 ft) elevation were excluded from the map to remove some uncertainty due to the coarse scale of the datasets; occurrences are possible at these high elevations but are currently much less likely (Litt and Pearson 2013). The value of each raster cell was normalized to range from 0 to 1, by dividing by either 23 or 21 for wetland or upland cells. Therefore, each cell value represented the percent of the total number of invasive species that may occur in that location (Figure 6d).

Landscape Vulnerability Calculations

Landscape vulnerability was calculated as exposure minus resilience, separately for development and climate change. Exposure is much more certain than resilience, and it might be argued that exposure should therefore be given more weight than resilience in this equation. However, we weighted exposure and resilience equally, because there is no precedence for weighting them differently and choice of weights would have been arbitrary and unsubstantiated (Glick et al. 2011, Klausmeyer et al. 2011, Magness et al. 2011). We also calculated overall vulnerability by combining development vulnerability and climate change vulnerability. The development and climate change vulnerability datasets were each grouped into 10 quantile bins before they were summed and normalized to range in value from 0 to 1.

For each vulnerability dataset, the scores ranging from 0 to 1 were assigned to categories as follows: low (<0.33), moderate (0.34-0.66), and high (>0.67). For each focal landscape, we calculated the percentage of raster cells occurring within each of these categories. Each focal landscape (habitat type or priority area) was then categorized as low, moderate or high vulnerability (overall, development, climate change vulnerability) based on the percent of its land area categorized as "high" as follows: low (<10%), moderate (10-33%), and high (>33%). We used one-third of the habitat area as the cutoff for the high category, because given the large sizes of the habitat areas one-third of the land are could have a significant impact. Additionally, this threshold resulted in a reasonable distribution of categorizations among the habitat types and priority areas. Many of the habitat types cover very large extents of Wyoming, and we were concerned that the percent-area criteria may underestimate vulnerability or exposure. Therefore, we added an additional criterion that if the absolute area occurring in the "high" category exceeded 12,000 km2 (~ 1/20th of Wyoming's land area), the habitat type would be categorized as high vulnerability or high exposure regardless of the percentage. In addition to categorizing vulnerability for each focal landscape, we also categorized development and climate change exposure and resilience, three component datasets of development exposure, and three component datasets of resilience (Figure 1b). The same categories used for vulnerability also applied to these datasets. We did not categorize the component datasets for climate exposure individually, because temperature data were missing across much of the state.

For development exposure specifically, we assessed how much exposure, overall and for oil and gas, wind and residential development individually, occurred within locations categorized as having "high" landscape integrity. We calculated the percentage of high integrity locations having development exposure, across Wyoming and for each focal landscape.

For each habitat type, we calculated the number of associated species and highly vulnerable species (species-based vulnerability), using habitat associations published in Wyoming's 2010 State Wildlife Action Plan (Wyoming Game and Fish Department 2010c). Additionally, we considered how habitat types may be affected by invasive species. For each habitat type, we calculated the mean invasive species diversity across all cells in that habitat type, as well as the percent of each habitat type with at least one invasive species present.

Results

SPECIES VULNERABILITY

Overall Vulnerability

Three species were ranked as very highly vulnerable, the Wyoming Toad, Plains Spadefoot, and Black-footed Ferret (Table 3, Figure 7). Another 48 (37%) of the 131 species had high vulnerability, 33 (25%) had moderate vulnerability, and 47 (36%) had low vulnerability (Table 3 , Figure 7). Amphibians were the most vulnerable of the four taxonomic groups, with 7 of 8 species amphibian species ranked as highly or very highly vulnerable. About 40% of all species were identified as being highly or very highly vulnerable using the species-based approach. Twenty-six of these 51 species (51%) were also identified as highly vulnerable using the landscape-based approach, including 14 birds, two mammals, three amphibians, and seven reptiles (Figure 8). Fifteen of the species with high landscape-based vulnerability had low or moderate species-based vulnerability (Figure 8).

Greater numbers of species were highly vulnerable to development or wildlife disease, as compared with climate change (Table 4). The relative contributions of climate change, development, or disease to overall vulnerability varied considerably among the most highly vulnerable species (Figure 7). However, general patterns emerged among the most highly vulnerable taxa. Climate change had the greatest relative contribution to amphibian vulnerability, and development had the greatest relative contribution to reptile vulnerability (Table 4, Figure 7a). For birds, development and disease contributed the most to vulnerability (Table 4, Figure 7c and d). For mammals, the relative contribution of each component to vulnerability varied greatly among the species (Table 4, Figure 7b).

Table 4. The number of species and the percent of each taxonomic group (shown in parentheses) having high or very high vulnerability, for each vulnerability category.

Taxonomic group (Number of species)	Overall vulnerability	Climate vulnerability	Development vulnerability	Disease vulnerability	Landscape vulnerability
Amphibians (n=8)	7 (88%)	6 (75%)	3 (38%)	1 (13%)	3 (38%)
Birds (n=56)	27 (48%)	0 (0%)	14 (25%)	21(38%)	22 (39%)
Mammals (n=46)	9 (20%)	6 (13%)	6 (13%)	6 (13%)	12 (26%)
Reptiles (n=21)	8 (38%)	5 (24%)	9 (43%)	0 (0%)	11 (52%)
Total (n=131)	51 (39%)	17 (13%)	32 (24%)	28 (21%)	48 (37%)

Across all 131 species, intersecting collective predicted species' habitat with overall vulnerability ranking showed that some areas of the state had greater concentrations of potentially vulnerable species than others (Figure 9a). The cross-species vulnerability index (CSVI) was particularly high in eastern and northeastern Wyoming, the far west and northwest, and in portions of the state's three major river systems, the Bighorn, Upper Green, and North Platte. We identified where the largest concentrations of species are most vulnerable by focusing the CSVI map to include only those locations that were identified as highly vulnerable through the landscape-based assessment (Figure 9b). For example, while many sensitive species occurred in far northwestern Wyoming, this part of the state did not have as many areas of highly vulnerable species' habitat as many locations further east. For each of the four taxonomic groups, the most highly vulnerable habitats occurred more often in eastern Wyoming (Figure 10), especially for reptiles and mammals (Figure 10 d, f). CSVI values were greatest for amphibians and reptiles (Figure 10 e, g).

Development Vulnerability

Thirty-two species were ranked as highly vulnerable to development, and an additional 66 species were ranked as moderately vulnerable (Table 3). Occurrence in the moderate category did not indicate that a species was less sensitive to development than a species in the high category, but rather that they had a higher exposure to development. Residential development resulted in the highest exposure scores, followed by oil and gas development (Figure 11, Table 5). Overall, reptiles were the taxa most exposed to development. The species with the highest total cumulative development exposure indices were the Least Weasel, Great Plains Toad, Pale Milksnake, Great Plains Earless Lizard, Prairie Lizard, Yellow-billed Cuckoo, Western Painted Turtle, Western Spiny Softshell, Prairie Racerunner, and Chestnut-collared Longspur. The Least Weasel, Great Plains Toad, and Black-footed Ferret had the highest cumulative exposures to residential development, oil and gas development, and wind development, respectively (Table 5). Species with the 10 highest cumulative or existing exposure scores for each development type are shown in Table 5.

Some of the species having high cumulative development exposure were currently exposed to high levels of the same development type (Table 5). The Black-footed Ferret had the highest exposure to both existing and cumulative wind development, and its exposure was anticipated to increase by 724% over these 20 years (Figure 12d). Another example is the Pygmy Rabbit, which had high exposure to existing oil and gas development that was anticipated to increase by 103% (Figure 12c). Considerable increases in development exposure were expected for many species, and in many cases these species currently had relatively low exposure (Figure 12). The biggest percent increases in exposure were expected from wind development, from 670 to 5443% for the species shown in Figure 12d. Increases in exposure to oil and gas development were as high as 301%, for the Yellow Pine Chipmunk (Figure 12c), and increases in exposure to residential development were as high as 153%, for the Silky Pocket Mouse (Figure 12b). Detailed development results for all 131 species are provided in Appendix A.

Disease Vulnerability

Twenty-eight species were ranked as highly vulnerable to disease, and an additional 27 species were ranked as moderately vulnerable (Table 3). The species with the highest disease vulnerability scores were the Bighorn Sheep, Northern Pintail, Redhead, Trumpeter Swan, Canvasback, Lesser Scaup, Clark's Grebe, Virginia Rail, Black-footed Ferret, and Burrowing Owl. (Appendix A). Thirteen wildlife diseases were identified that may have broad-scale impacts on or threaten persistence of 76 of the 131 species (Figure 13). Birds were the most vulnerable of the taxonomic groups to disease, with 21 species ranked as highly vulnerable and 37 species potentially affected by disease (Tables 3 and 4). Four diseases affected 19 species

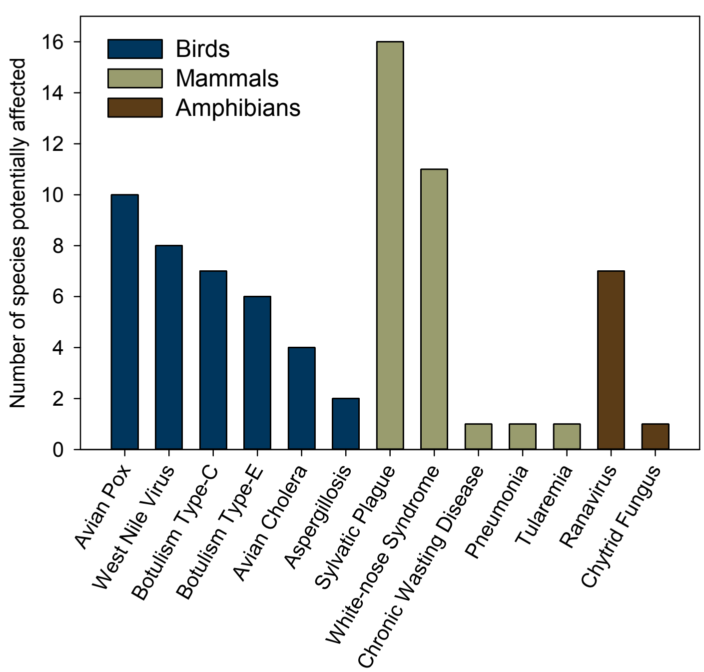


Figure 13. The number of species potentially affected by each of the 13 most highly scored wildlife diseases. Bars are colored based on the taxonomic group each disease affects.

of waterbirds. Aspergillosis affected wading birds, avian cholera affected wading birds, terns and gulls, botulism type-C affected waterfowl, and botulism type-E affected fish-eating birds, terns and gulls (Appendix A). Avian pox and the two types of botulism affected 23 bird species (Figure 13). Avian pox affected raptors, passerines and flycatchers, and West Nile virus affected corvids, passerines, raptors and galliformes (Appendix A). Six species of mammals were highly vulnerable to disease, and 30 species were potentially affected by disease. Sylvatic plague affected the largest number of mammals (16 species including rodents and carnivores), and white-nose syndrome affected 11 species of bats. Three diseases each affected only one mammal species: chronic wasting disease (Moose), pneumonia (Bighorn Sheep), tularemia (Pygmy Rabbit). Amphibians were affected by ranavirus and chytrid fungus, and while ranavirus scored higher in most cases, many of the species had very close scores for chytrid fungus. No reptiles were affected by disease, with exception of the Ornate Box Turtle, which was moderately vulnerable to ranavirus. There were 35 additional bird and mammal species that were not affected by disease.

Climate Change Vulnerability

Four of the species were ranked as "Extremely vulnerable" to climate change: the Canada Lynx, Northern Tree Lizard, Midget Faded Rattlesnake, and Wyoming Toad. Seventeen species were ranked as highly vulnerable to climate change, and an additional 25 species were ranked as moderately vulnerable (Table 3). Six of the eight amphibians were ranked as highly vulnerable to climate change, while no bird species were ranked as highly vulnerable (Tables 3 and 4). There was very high confidence in the CCVI scores for all but three species with low confidence, the Swift Fox, Vagrant Shrew, and Pygmy Shrew.

PHOTOS: TOP CLOCKWISE: Pygmy Rabbit © *Wendy Estes Zumpf;* Wyoming Toad © *Margo Hennet;* Canada Lynx © *Tom Ulrich*; Red Sided Gartersnakes © *Chris Helzer*

Figure 7. The contribution of development, disease and climate change vulnerability to the overall vulnerability for the 51 species ranked as highly or very-highly vulnerable, for amphibians and reptiles (A), mammals (B), and birds (C, D). Categorical rankings for individual vulnerability components were assigned numeric values to illustrate relative contributions, where high =3, moderate = 2, and low =1.

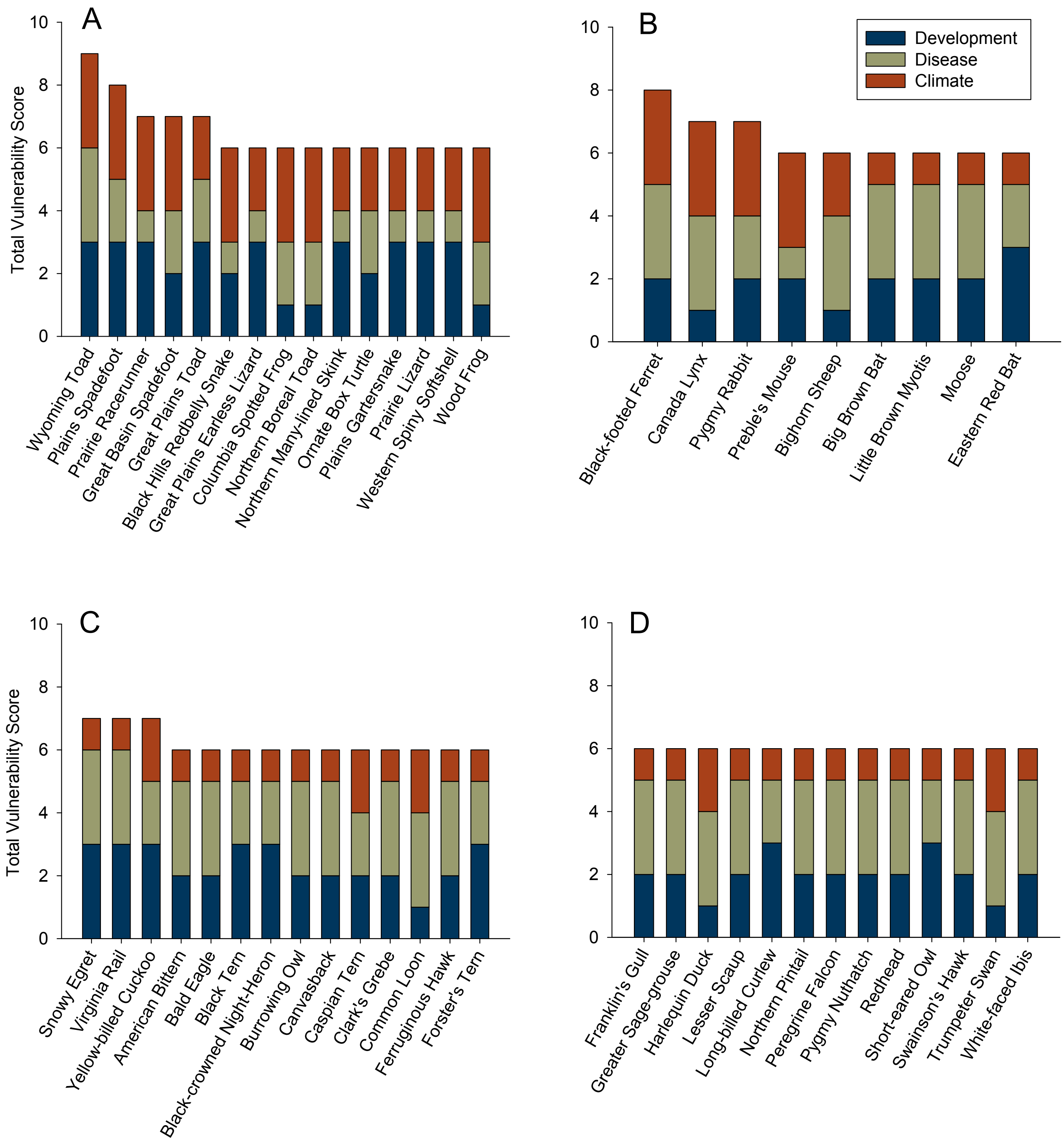


Figure 8. The 48 species ranked as highly vulnerable using the landscape-based approach, separated by birds (A), mammals (B) and amphibians and reptiles (C). The percent of each species' distribution categorized as highly vulnerable is shown on the y-axis and bar shading reflects the rank received for species-based vulnerability.

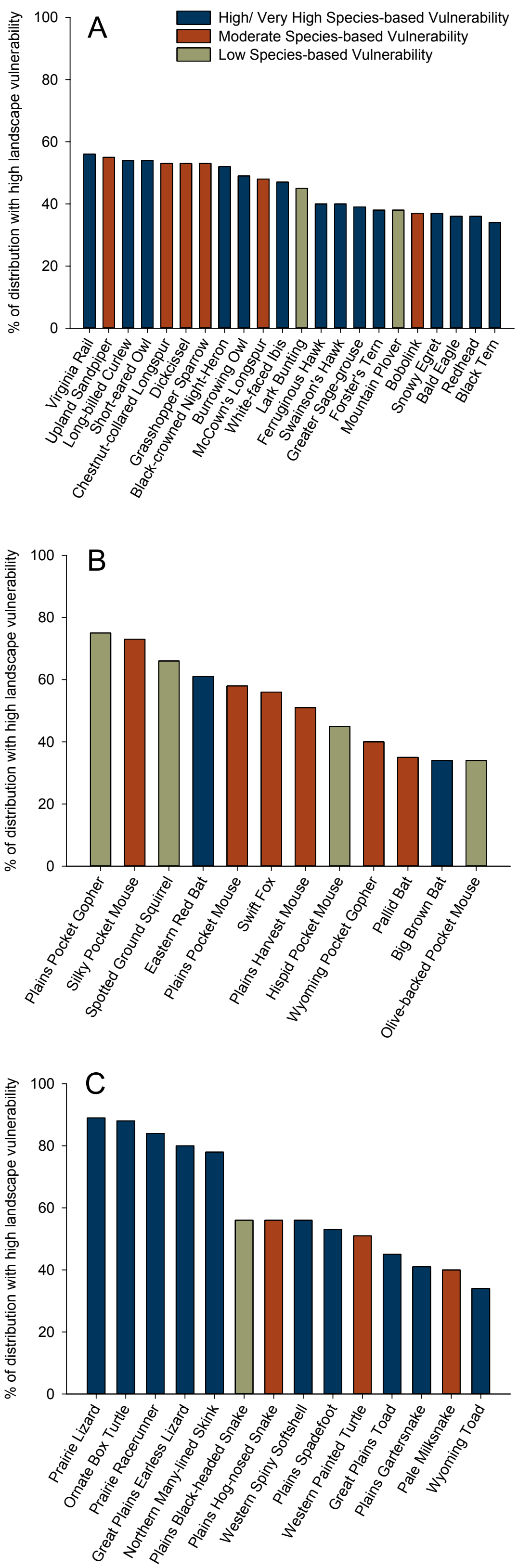


Figure 9. The cross-species vulnerability index (CSVI) was calculated across all 131 species and is displayed in three quantiles (A). High vulnerability habitats for these species were identified as those places where CSVI scores greater than 0.30 overlapped with areas of high overall landscape vulnerability (B).

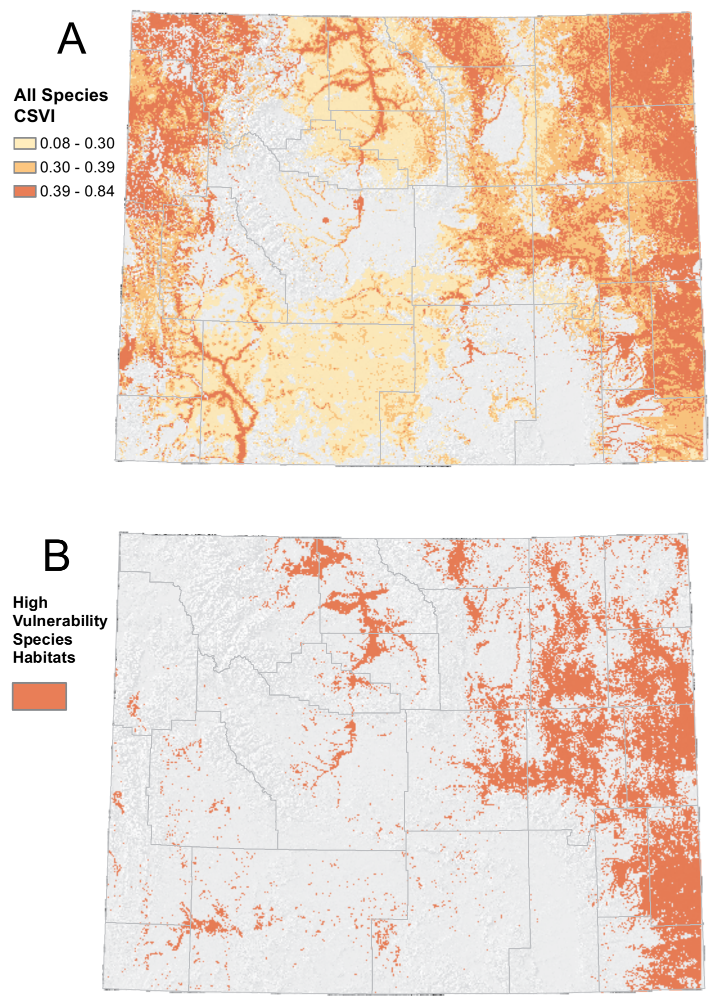


Figure 10. The cross-species vulnerability index (CSVI) was calculated across predicted distributions for (A) birds, (C) mammals, (E) reptiles and (G) amphibians and is displayed in three quantiles. High vulnerability habitats for (B) birds, (D) mammals, (F) reptiles and amphibians (H) were identified as those places where CSVI scores greater than 0.30 overlapped with areas of high overall landscape vulnerability. County boundaries are displayed in gray.

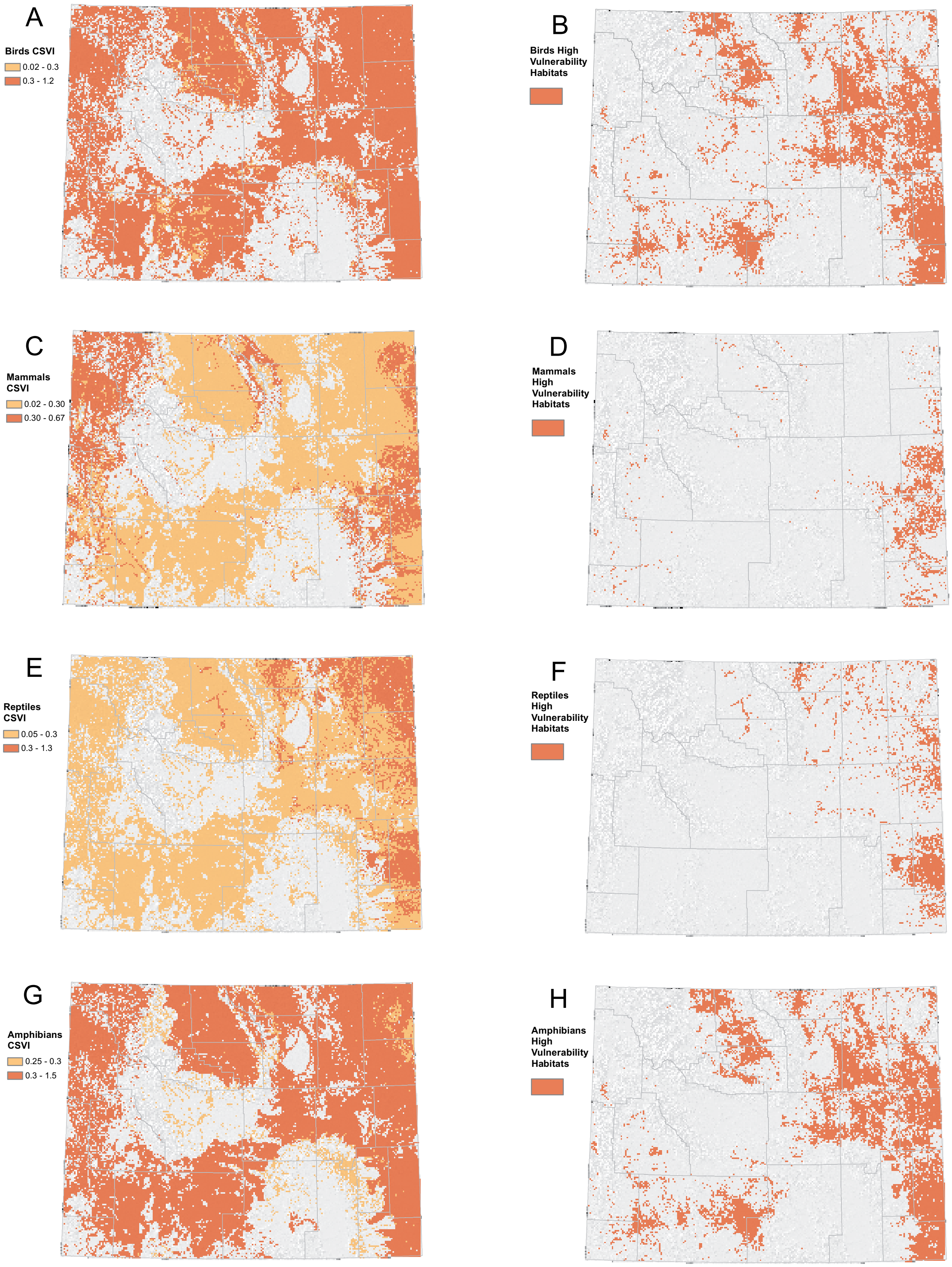


Figure 11. The contribution of residential development, oil and gas development and wind development to cumulative development exposure scores for bird (A), mammal (B), reptile (C), and amphibian (D) species. Only the 15 highest relative exposure scores are shown for birds, mammals, and reptiles. Species with a high development vulnerability rank are denoted with an asterisk.

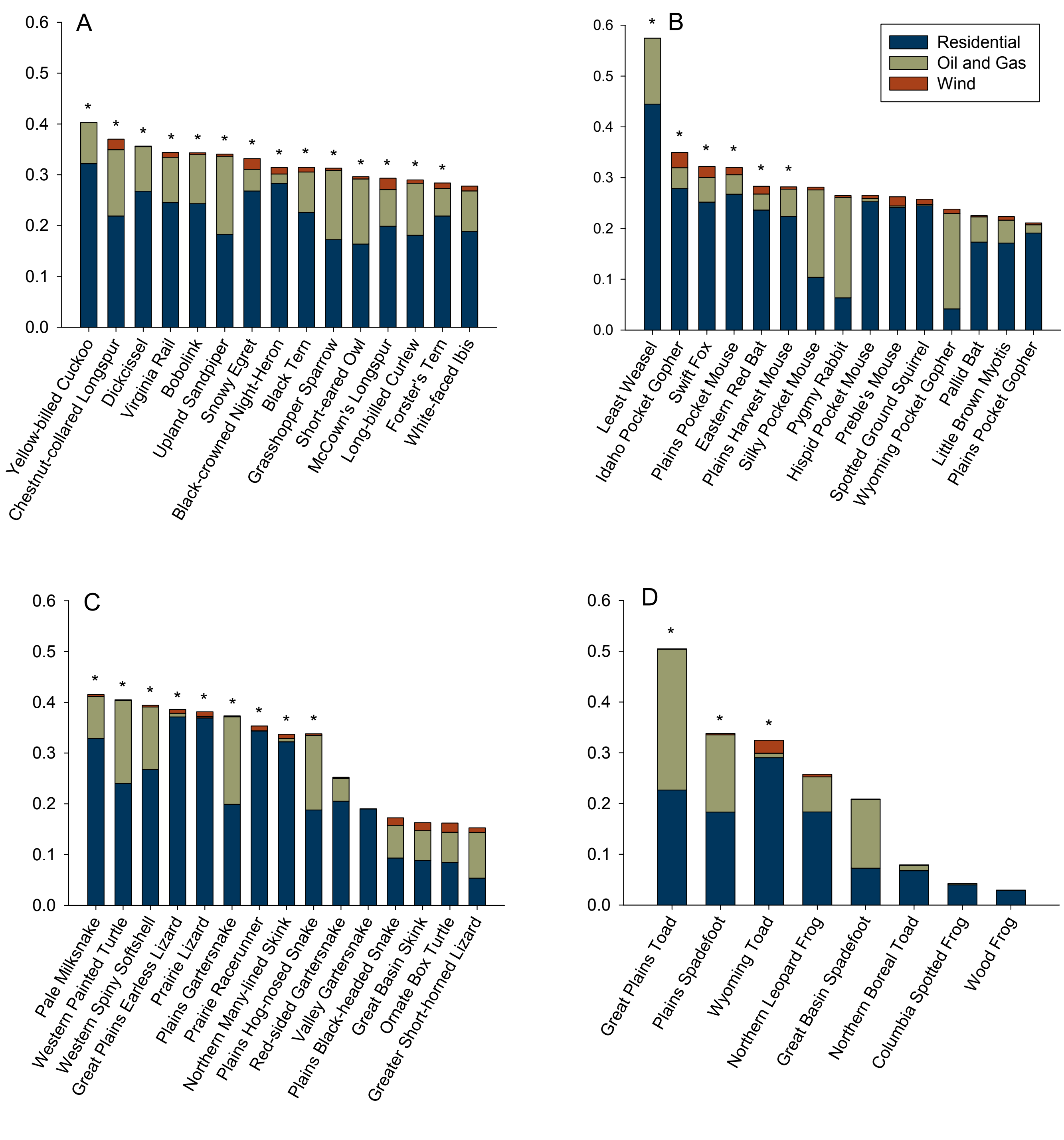


Figure 12. The difference in species' development exposure scores for existing versus cumulative development for all three development types combined (A), residential development (B), oil and gas development (C), and wind development (D). In each group, results are shown for SGCN species having the top 15 greatest percent changes between existing and cumulative exposure, shown in order of decreasing percent change. Species included here had a moderate or high development vulnerability rank and a minimum cumulative exposure index of 0.01 for wind or 0.05 for other development types. Species with a high development vulnerability rank are denoted with an asterisk.

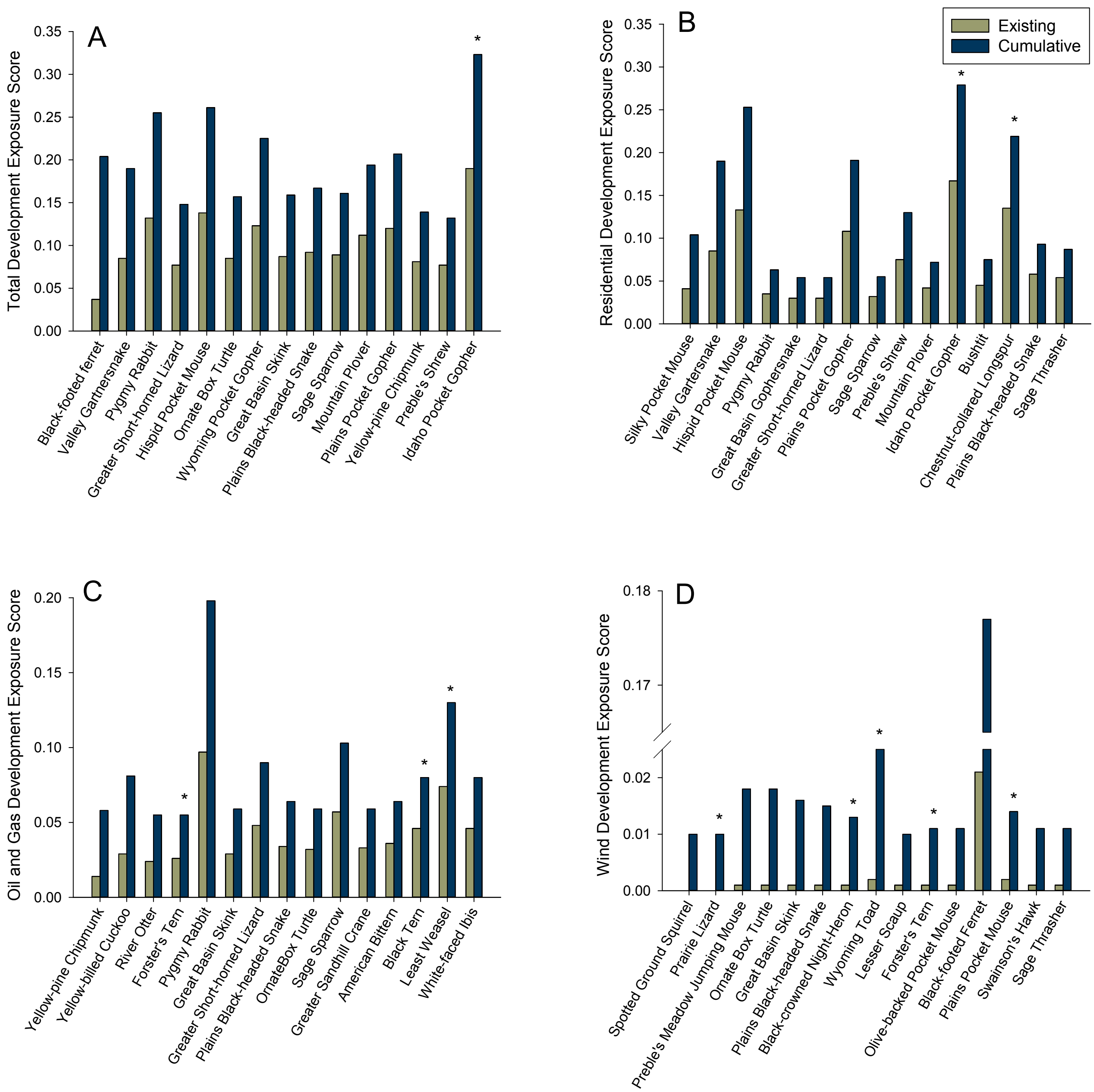


Table 3a. Vulnerability ranking results for bird species, sorted alphabetically within each overall vulnerability category

Name	Overall	Climate Change	Development	Disease	Landscape-based
American Bittern *(Botaurus lentiginosus)*	High	Low	Moderate	High	Moderate
Bald Eagle *(Haliaeetus leucocephalus)*	High	Low	Moderate	High	High
Black Tern *(Chlidonias niger)*	High	Low	High	Moderate	High
Black-crowned Night-Heron *(Nycticorax nycticorax)*	High	Low	High	Moderate	High
Burrowing Owl *(Athene cunicularia)*	High	Low	Moderate	High	High
Canvasback *(Aythya valisineria)*	High	Low	Moderate	High	Moderate
Caspian Tern *(Sterna caspia)*	High	Moderate	Moderate	Moderate	Moderate
Clark's Grebe *(Aechmophorus clarkii)*	High	Low	Moderate	High	Moderate
Common Loon *(Gavia immer)*	High	Moderate	Low	High	Moderate
Ferruginous Hawk *(Buteo regalis)*	High	Low	Moderate	High	High
Forster's Tern *(Sterna forsteri)*	High	Low	High	Moderate	High
Franklin's Gull *(Larus pipixcan)*	High	Low	Moderate	High	Moderate
Greater Sage-grouse *(Centrocercus urophasianus)*	High	Low	Moderate	High	High
Harlequin Duck *(Histrionicus histrionicus)*	High	Moderate	Low	High	Low
Lesser Scaup *(Aythya affinis)*	High	Low	Moderate	High	Moderate
Long-billed Curlew *(Numenius americanus)*	High	Low	High	Moderate	High
Northern Pintail *(Anas acuta)*	High	Low	Moderate	High	Moderate
Peregrine Falcon *(Falco peregrinus)*	High	Low	Moderate	High	Low
Pygmy Nuthatch *(Sitta pygmaea)*	High	Low	Moderate	High	Low
Redhead *(Aythya americana)*	High	Low	Moderate	High	High
Short-eared Owl *(Asio flammeus)*	High	Low	High	Moderate	High
Snowy Egret *(Egretta thula)*	High	Low	High	High	High
Swainson's Hawk *(Buteo swainsoni)*	High	Low	Moderate	High	High
Trumpeter Swan *(Cygnus buccinator)*	High	Moderate	Low	High	Low
Virginia Rail *(Rallus limicola)*	High	Low	High	High	High
White-faced Ibis *(Plegadis chihi)*	High	Low	Moderate	High	High
Yellow-billed Cuckoo *(Coccyzus americanus)*	High	Moderate	High	Moderate	Moderate
Barrow's Goldeneye *(Bucephala islandica)*	Moderate	Low	Low	High	Low
Bobolink *(Dolichonyx oryzivorus)*	Moderate	Low	High	Low	High
Brewer's Sparrow *(Spizella breweri)*	Moderate	Low	Moderate	Moderate	Moderate
Bushtit *(Psaltriparus minimus)*	Moderate	Low	Moderate	Moderate	Moderate
Chestnut-collared Longspur *(Calcarius ornatus)*	Moderate	Low	High	Low	High
Columbian Sharp-tailed Grouse *(Tympanuchus phasianellus columbianus)*	Moderate	Low	Moderate	Moderate	Low
Dickcissel *(Spiza americana)*	Moderate	Low	High	Low	High
Grasshopper Sparrow *(Ammodramus savannarum)*	Moderate	Low	High	Low	High

Table 3a continued.

Name	Overall	Climate Change	Development	Disease	Landscape-based
McCown's Longspur *(Calcarius mccownii)*	Moderate	Low	High	Low	High
Merlin *(Falco columbarius)*	Moderate	Low	Moderate	Moderate	Moderate
Upland Sandpiper *(Bartramia longicauda)*	Moderate	Low	High	Low	High
American Three-toed Woodpecker *(Picoides dorsalis)*	Low	Low	Low	Low	Low
Ash-throated Flycatcher *(Myiarchus cinerascens)*	Low	Low	Moderate	Low	Moderate
Black Rosy-Finch *(Leucosticte atrata)*	Low	Moderate	Low	Low	Low
Black-backed Woodpecker *(Picoides arcticus)*	Low	Low	Low	Low	Low
Boreal Owl *(Aegolius funereus)*	Low	Low	Low	Low	Low
Brown-capped Rosy Finch *(Leucosticte australis)*	Low	Low	Low	Low	Low
Great Gray Owl *(Strix nebulosa)*	Low	Low	Low	Moderate	Low
Greater Sandhill Crane *(Grus canadensis)*	Low	Low	Moderate	Low	Moderate
Juniper Titmouse *(Baeolophus ridgwayi)*	Low	Moderate	Low	Low	Moderate
Lark Bunting *(Calamospiza melanocorys)*	Low	Low	Moderate	Low	High
Lewis' Woodpecker *(Melanerpes lewis)*	Low	Low	Moderate	Low	Moderate
Mountain Plover *(Charadrius montanus)*	Low	Low	Moderate	Low	High
Northern Goshawk *(Accipiter gentilis)*	Low	Low	Low	Moderate	Low
Northern Pygmy-Owl *(Glaucidium gnoma)*	Low	Low	Low	Moderate	Low
Sage Sparrow *(Amphispiza belli)*	Low	Low	Moderate	Low	Moderate
Sage Thrasher *(Oreoscoptes montanus)*	Low	Low	Moderate	Low	Moderate
Western Scrub-Jay *(Aphelocoma californica)*	Low	Low	Low	Moderate	Moderate
Willow Flycatcher *(Empidonax traillii)*	Low	Low	Moderate	Low	Moderate

Table 3b. Vulnerability ranking results for amphibian species, sorted alphabetically within each overall vulnerability category

Name	Overall	Climate Change	Development	Disease	Landscape-based
Plains Spadefoot *(Spea bombifrons)*	Very High	High	High	Moderate	High
Wyoming Toad *(Anaxyrus baxteri)*	Very High	High	High	High	High
Columbia Spotted Frog *(Rana luteiventris)*	High	High	Low	Moderate	Low
Great Basin Spadefoot *(Spea intermontana)*	High	High	Moderate	Moderate	Moderate
Great Plains Toad *(Anaxyrus cognatus)*	High	Moderate	High	Moderate	High
Northern Boreal Toad *(Anaxyrus boreas boreas)*	High	High	Low	Moderate	Low
Wood Frog *(Lithobates sylvatica)*	High	High	Low	Moderate	Low
Northern Leopard Frog *(Lithobates pipiens)*	Moderate	Low	Moderate	Moderate	Moderate

Table 3c. Vulnerability ranking results for reptile species, sorted alphabetically within each overall vulnerability category

Name	Overall	Climate Change	Development	Disease	Landscape-based
Prairie Racerunner *(Aspidoscelis sexlineatus viridis)*	High	High	High	Low	High
Black Hills Redbelly Snake *(Storeria occipitomaculata pahasapae)*	High	High	Moderate	Low	Moderate
Great Plains Earless Lizard *(Holbrookia maculata)*	High	Moderate	High	Low	High
Northern Many-lined Skink *(Eumeces multivirgatus)*	High	Moderate	High	Low	High
Plains Gartersnake *(Thamnophis radix)*	High	Moderate	High	Low	High
Prairie Lizard *(Sceloporus consobrinus)*	High	Moderate	High	Low	High
Western Spiny Softshell *(Apalone spinifera hartwegi)*	High	Moderate	High	Low	High
Great Basin Skink *(Plestiodon multivirgatus ultivirgatus)*	Moderate	Moderate	Moderate	Low	Low
Midget Faded Rattlesnake *(Crotalus oreganus concolor)*	Moderate	High	Low	Low	Moderate
Northern Tree Lizard *(Urosaurus ornatus wrighti)*	Moderate	High	Low	Low	Moderate
Ornate Box Turtle *(Terrapene ornata ornata)*	Moderate	Moderate	Moderate	Moderate	High
Pale Milksnake *(Lampropeltis triangulum multistriata)*	Moderate	Low	High	Low	High
Plains Hog-nosed Snake *(Heterodon nasicus)*	Moderate	Low	High	Low	High
Rubber Boa *(Charina bottae)*	Moderate	High	Low	Low	Low
Smooth Green Snake *(Opheodrys vernalis)*	Moderate	Moderate	Moderate	Low	Low
Valley Gartersnake *(Thamnophis sirtalis fitchi)*	Moderate	Moderate	Moderate	Low	Moderate
Western Painted Turtle *(Chrysemys picta bellii)*	Moderate	Low	High	Low	High
Great Basin Gophersnake *(Pituophis catenifer deserticola)*	Low	Low	Moderate	Low	Moderate
Greater Short-horned Lizard *(Phrynosoma hernandesi)*	Low	Low	Moderate	Low	Moderate
Plains Black-headed Snake *(Tantilla nigriceps)*	Low	Low	Moderate	Low	High
Red-sided Gartersnake *(Thamnophis sirtalis parietalis)*	Low	Low	Moderate	Low	Moderate

Table 3d. Vulnerability ranking results for mammal species, sorted alphabetically within each overall vulnerability category

Name	Overall	Climate Change	Development	Disease	Landscape-based
Black-footed Ferret *(Mustela nigripes)*	Very High	High	Moderate	High	Moderate
Big Brown Bat *(Eptesicus fuscus)*	High	Low	Moderate	High	High
Bighorn Sheep *(Ovis canadensis)*	High	Moderate	Low	High	Low
Canada Lynx *(Lynx canadensis)*	High	High	Low	High	Low
Eastern Red Bat *(Lasiurus borealis)*	High	Low	High	Moderate	High
Little Brown Myotis *(Myotis lucifugus)*	High	Low	Moderate	High	Moderate
Moose *(Alces alces)*	High	Low	Moderate	High	Low
Preble's Meadow Jumping Mouse *(Zapus hudsonius preblei)*	High	High	Moderate	Low	Moderate
Pygmy Rabbit *(Brachylagus idahoensis)*	High	High	Moderate	Moderate	Moderate
Great Basin Pocket Mouse *(Perognathus parvus)*	Moderate	Moderate	Moderate	Low	Moderate
Idaho Pocket Gopher *(Thomomys idahoensis)*	Moderate	Low	High	Low	Moderate
Least Weasel *(Mustela nivalis)*	Moderate	Low	High	Low	Moderate
Northern Myotis *(Myotis septentrionalis)*	Moderate	Low	Moderate	Moderate	Low
Pallid Bat *(Antrozous pallidus)*	Moderate	Low	Moderate	Moderate	High
Piñon Mouse *(Peromyscus truei)*	Moderate	High	Low	Low	Low
Plains Harvest Mouse *(Reithrodontomys montanus)*	Moderate	Low	High	Low	High
Plains Pocket Mouse *(Perognathus flavescens)*	Moderate	Low	High	Low	High
Silky Pocket Mouse *(Perognathus flavus)*	Moderate	Moderate	Moderate	Low	High
Swift Fox *(Vulpes velox)*	Moderate	Low	High	Low	High
Wolverine *(Gulo gulo)*	Moderate	High	Low	Low	Low
Wyoming Pocket Gopher *(Thomomys clusius)*	Moderate	Moderate	Moderate	Low	High
American Pika *(Ochotona princeps)*	Low	Moderate	Low	Low	Low
Canyon Mouse *(Peromyscus crinitus)*	Low	Moderate	Low	Low	Low
Cliff Chipmunk *(Neotamias dorsalis)*	Low	Low	Moderate	Low	Moderate
Dwarf Shrew *(Sorex nanus)*	Low	Low	Moderate	Low	Low
Fisher *(Martes pennanti)*	Low	Low	Low	Low	Low
Fringed Myotis *(Myotis thysanodes)*	Low	Low	Moderate	Low	Moderate
Hayden's Shrew *(Sorex haydeni)*	Low	Low	Low	Low	Low
Hispid Pocket Mouse *(Chaetodipus hispidus)*	Low	Low	Moderate	Low	High
Long-eared Myotis *(Myotis evotis)*	Low	Low	Moderate	Low	Moderate
Long-legged Myotis *(Myotis volans)*	Low	Low	Moderate	Low	Moderate
Marten *(Martes americana)*	Low	Low	Low	Low	Low
Northern Flying Squirrel *(Glaucomys sabrinus)*	Low	Low	Low	Low	Low
Olive-backed Pocket Mouse *(Perognathus fasciatus)*	Low	Low	Moderate	Low	High

Table 3d continued.

Name	Overall	Climate Change	Development	Disease	Landscape-based
Plains Pocket Gopher *(Geomys bursarius)*	Low	Low	Moderate	Low	High
Preble's Shrew *(Sorex preblei)*	Low	Low	Moderate	Low	Low
Pygmy Shrew *(Sorex hoyi)*	Low	Moderate	Low	Low	Low
River Otter *(Lontra canadensis)*	Low	Low	Moderate	Low	Moderate
Spotted Bat *(Euderma maculatum)*	Low	Low	Moderate	Low	Moderate
Spotted Ground Squirrel *(Spermophilus spilosoma)*	Low	Low	Moderate	Low	High
Townsend's Big-eared Bat *(Corynorhinus townsendii)*	Low	Low	Moderate	Low	Moderate
Uinta Chipmunk *(Neotamias umbrinus)*	Low	Low	Low	Low	Low
Vagrant Shrew *(Sorex vagrans)*	Low	Low	Moderate	Low	Low
Water Vole *(Microtus richardsoni)*	Low	Moderate	Low	Low	Low
Western Small-footed Myotis *(Myotis ciliolabrum)*	Low	Low	Moderate	Low	Moderate
Yellow-pine Chipmunk *(Neotamias amoenus)*	Low	Low	Moderate	Low	Low

Table 5. Species with the 10 highest cumulative or existing development exposure scores for each development type. Scores are shown in parentheses.

Exposure Ranking	Residential Existing	Residential Cumulative	Oil & Gas Existing	Oil & Gas Cumulative	Wind Exising	Wind Cumulative
1	Least Weasel (0.394)	Least Weasel (0.445)	Great Plains Toad (0.182)	Great Plains Toad (0.277)	Black-footed Ferret (0.021)	Black-footed Ferret (0.177)
2	Prairie Lizard (0.300)	Great Plains Earless Lizard (0.371)	Silky Pocket Mouse (0.124)	Pygmy Rabbit (0.198)	Idaho Pocket Gopher (0.012)	Idaho Pocket Gopher (0.030)
3	Pale Milksnake (0.273)	Prairie Lizard (0.369)	Plains Garter-snake (0.119)	Wyoming Pocket Gopher (0.188)	Chestnut-collared Longspur (0.004)	Wyoming Toad (0.026)
4	Yellow-billed Cuckoo (0.254)	Prairie Racerunner (0.343)	Wyoming Pocket Gopher (0.112)	Plains Garter Snake (0.173)	McCown's Longspur (0.004)	McCown's Longspur (0.022)
5	Great Plains Earless Lizard (0.250)	Pale Milksnake (0.329)	Western Painted Turtle (0.112)	Silky Pocket Mouse (0.172)	Swift Fox (0.004)	Swift Fox (0.022)
6	Wyoming Toad (0.247)	Northern Many-lined Skink (0.322)	Upland Sandpiper (0.105)	Western Painted Turtle (0.163)	Silky Pocket Mouse (0.003)	Snowy Egret (0.021)
7	Black-crowned Night-Heron (0.234)	Yellow-billed Cuckoo (0.322)	Plains Spadefoot (0.102)	Upland Sandpiper (0.154)	Snowy Egret (0.003)	Chestnut-collared Longspur (0.021)
8	Northern Many-lined Skink (0.221)	Wyoming Toad (0.290)	Plains Hog-nosed Snake (0.099)	Plains Spadefoot (0.152)	Eastern Red Bat (0.003)	Ornate Box Turtle (0.018)
9	Western Spiny Softshell (0.214)	Black-crowned Night-Heron (0.283)	Pygmy Rabbit (0.097)	Plains Hog-nosed Snake (0.147)	Wyoming Toad (0.002)	Preble's Meadow Jumping Mouse (0.018)
10	Snowy Egret (0.203)	Idaho Pocket Gopher (0.279)	Chestnut-collared Longspur (0.091)	Grasshopper Sparrow (0.136)	Mountain Plover (0.002)	Great Basin Skink (0.016)

LANDSCAPE VULNERABILITY

Overall Vulnerability

Landscape-based overall vulnerability was high in 30% of Wyoming and low in 27% (Figure 14). Overall vulnerability was high for prairie grasslands, sagebrush shrublands, desert shrublands, riparian areas and wetlands and low for the other habitat types (Table 6a). Some of the same habitats with high vulnerability were also associated with highly vulnerable species. The greatest numbers of highly vulnerable species were associated with wetlands, riparian areas and prairie grasslands, which each had greater than a third of their SGCN categorized as highly or very highly vulnerable (Table 8, Appendix A). More than half of the highly vulnerable species use only one habitat type (Appendix A). Eleven of the priority areas had high overall vulnerability (Table 7a). One of these areas, number 11, had 100% of its area in a high vulnerability location (Table 7a). The majority of these highly vulnerable priority areas were located in eastern Wyoming (Figure 3), and high vulnerability was attributed to climate change more often than development; only three priority areas had high vulnerability to development as compared to 18 areas that had high vulnerability to climate change (Table 7a).

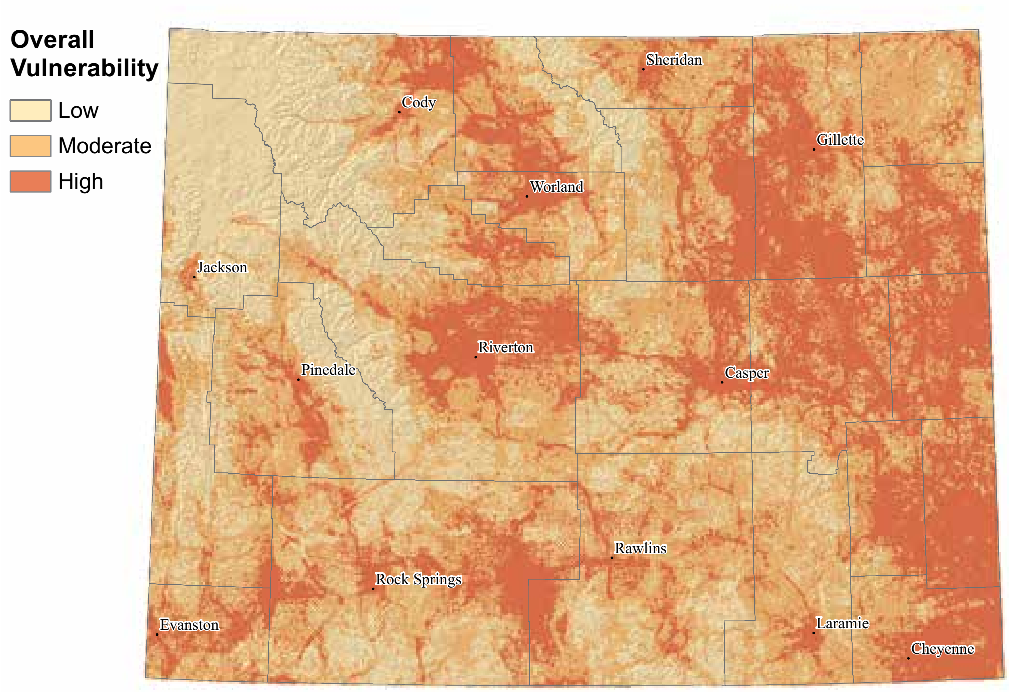


Figure 14. Overall landscape-based vulnerability across Wyoming. County boundaries are displayed in gray.

Development

Development vulnerability was high in 17% and low in 47% of Wyoming (Figure 15a). Sagebrush shrublands and wetlands had high vulnerability to development, and vulnerability was moderate for prairie grasslands, desert shrubland, and riparian areas (Table 6a). All but three of the priority areas had low development vulnerability (Table 8). Exposure to oil and gas and wind development individually was categorized as low for all habitat types and priority areas (results not shown in tables). One exception was moderate exposure to oil and gas development for priority area 41 (18% high). Residential development contributed the most to exposure, followed by oil and gas development (Figure 16). Exposure to residential development was high for wetlands (42% high) and moderate for prairie grassland (19%), riparian areas (19%), aspen/deciduous forest (12%), xeric forest (12%) and foothills shrubland (10%).

Statewide, locations categorized as having high landscape integrity had 5% of their area overlap with high development exposure (Figure 17) and 6% overlap with moderate development exposure. Residential development contributed the most to the high exposure (4%), followed by oil and gas development (1%) and wind development (0.5%). Percentages of high exposure in high integrity locations were small relative to the large extents of the habitat types, but even these small percentages represented considerable land areas. Five percent of Wyoming's high integrity land area corresponds with 4532 km² (1750 mi²), which is slightly smaller than the size of Hot Springs County, for example. Within high integrity locations for each habitat type, high development exposure was greatest in prairie grasslands, overlapping with 11% of high integrity grasslands, and was driven by residential development. Riparian areas had 7% overlap of high integrity areas with high development exposure, and there was 6% overlap for sagebrush shrublands and xeric forest.

For priority areas, overlap between high integrity areas and high development exposure was moderate in six areas: area 3 (37%), area 41 (27%), area 4 (20%), area 39 (13%), area 2 (11%), and area 24 (10%) (Figure 17). One priority area had moderate exposure to oil and gas development within high integrity locations, area 41 (12%), and one area had moderate exposure to wind development, area 3 (29%). Residential development exposure had greater overlap with high integrity areas within priority areas, with moderate exposure in 10 areas: area 4 (31%), area 3 (22%), area 39 (21%), area 41 (15%), area 37 (14%), area 2 (13%), area 43 (13%), area 19 (12%), area 25 (11%), and area 27 (10%).

Climate Change and Resilience

Climate change vulnerability was high in 31% and low in 34% of Wyoming (Figure 18a). Overall spatial patterns in climate change vulnerability (Figure 18a) were remarkably similar to those observed for development vulnerability (Figure 15a). Prairie grasslands, sagebrush shrubland, desert shrubland, riparian areas and wetlands had high vulnerability to climate change (Table 6a). Climate exposure was also high for each of these habitats, while resilience was moderate (Table 6c). Eighteen of the 44 priority areas (41%) had high climate change vulnerability and fourteen had low vulnerability (Table 7a).

Three habitat types had high resilience to both development and climate change: mountain grassland, montane/subalpine forest and cliff/canyon/rock outcrops (Table 6b, c), which each typically occur at high elevations or in remote areas. These three habitats had high or moderate topographic diversity, high landscape integrity, and they were the only three habitat types with high land management status – they had the highest percentages of their habitats in GAP status 1 or 2 (Table 6d). Three additional habitats had high climate change resilience: foothills shrubland, aspen/deciduous forest, and xeric forest (Table 6c). Overall, the least resilient habitat types were prairie grassland, riparian areas and wetlands (Table 6b, c). These three habitats had the lowest landscape integrity (no habitats had "low" integrity); for prairie grasslands and riparian areas land management status was also low (Table 6d). Topographic diversity and water availability was ranked as low for only prairie grassland and desert shrubland, meaning that most habitat types had at least 10% of their area that offered buffering capacity against climate change. This capacity was greatest for the three forested habitat types (Table 6d). Landscape integrity was high or moderate for all 11 habitat types, with the highest values for mountain grasslands and lowest for wetlands (Table 6d). Land management status was low for prairie grasslands, sagebrush shrubland, and desert shrubland, xeric forest and riparian areas, but most notable were prairie grasslands and wetlands, which had 70-74% of their extent in GAP status 4, which lacks any management status or legal protection (Table 6d). Half of priority areas had high climate change resilience, and only 11% had high development resilience (Table 7b, c). Landscape integrity was high in most of the areas, and land management status was low (Table 7d). Only four areas had high land management status, the highest of which were area 42, which overlaps with Yellowstone National Park, and area 26, which corresponds with Ocean Lake Wildlife Habitat Management Area (Figure 3, Table 7d).

One component of landscape integrity was invasive plant species. Wetlands had the highest diversity of invasive species, followed by foothills shrubland and aspen/deciduous forest (Table 9). Due in part to the coarse-scale nature of the available invasive species data, all habitat types had some invasive species records; however, the relative percentage of each habitat having at least one invasive species present was variable. The habitat types having the greatest percentage of overlap with at least one invasive species were wetlands, aspen/deciduous forest, and foothills shrubland. Habitat types with the lowest overlap with invasive species were mountain grassland and cliff/canyon/rock outcrop (Table 9). Invasive species diversity was particularly concentrated in parts of northwest and southeast Wyoming (Figure 6d).

Figure 15. Development vulnerability across Wyoming (A) was calculated as development exposure (B) minus development resilience (C).

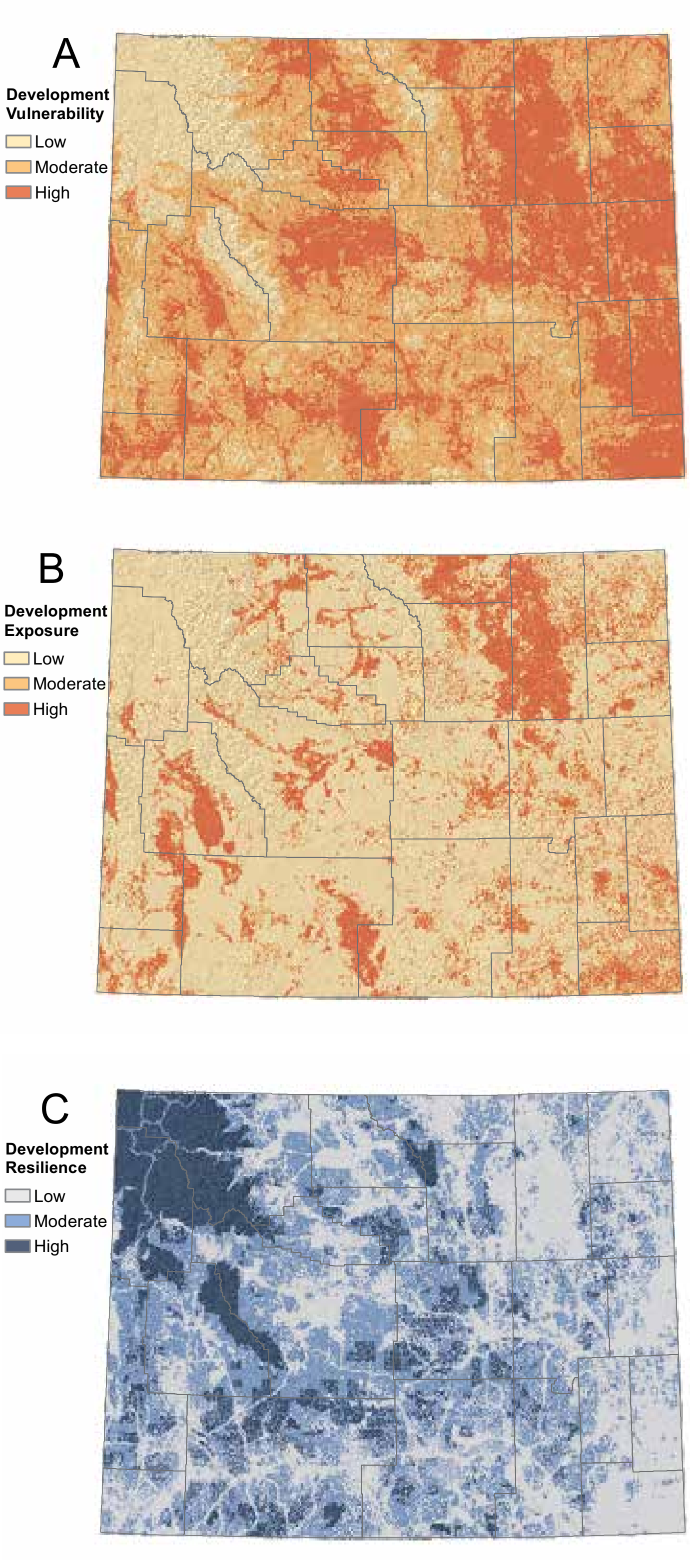


Figure 16. Exposure to oil and gas development (A), wind development (B) and residential development (C) included both existing and projected (2030) development locations.

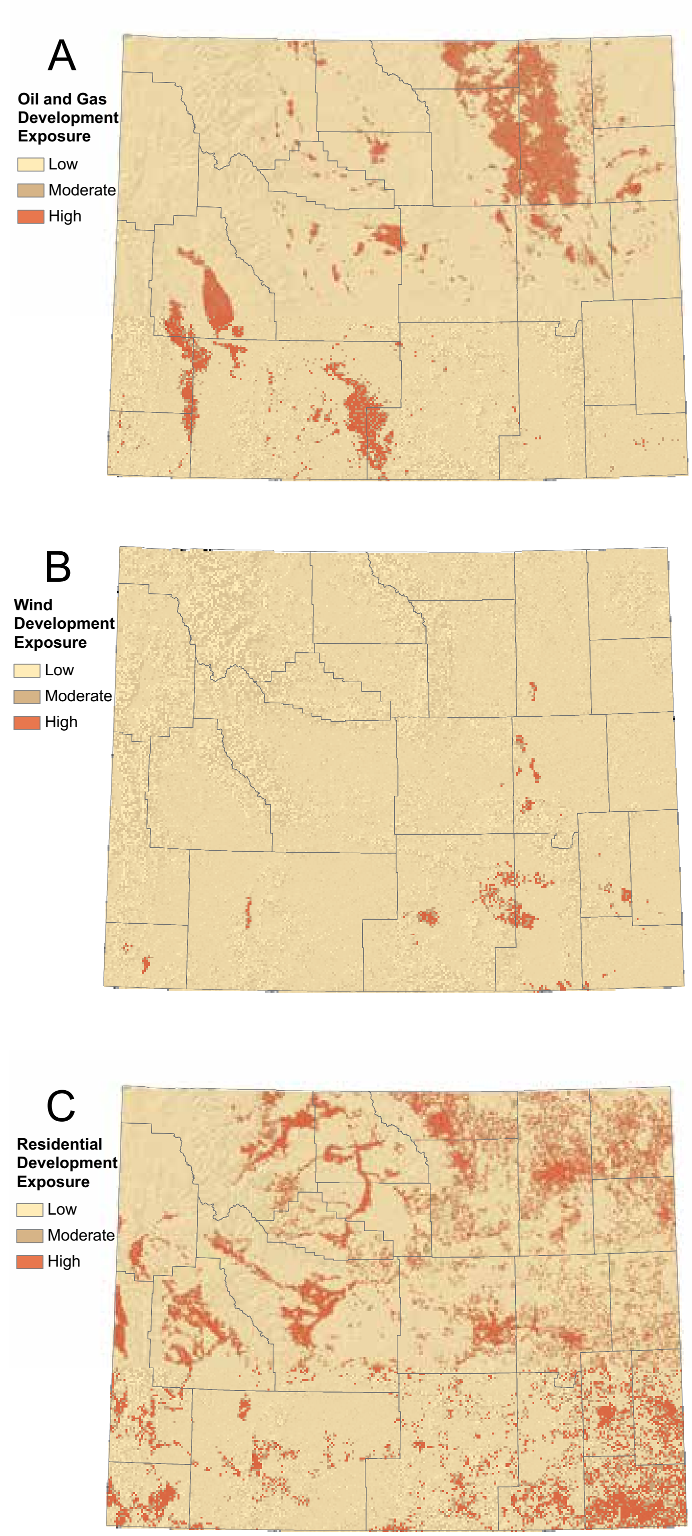


Figure 17. Development exposure within areas categorized as high landscape integrity. Terrestrial priority areas are shown for reference.

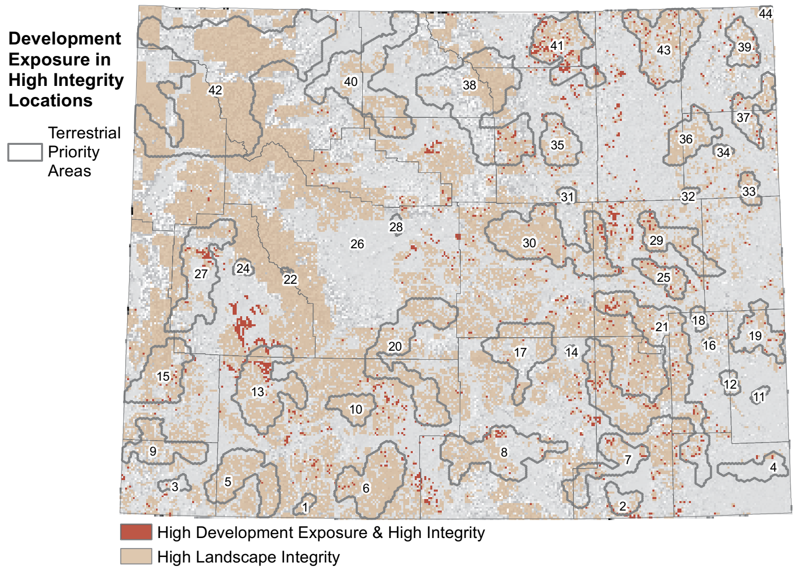


Figure 18. Climate change vulnerability across Wyoming (A) was calculated as climate change exposure (B) minus climate change resilience (C).

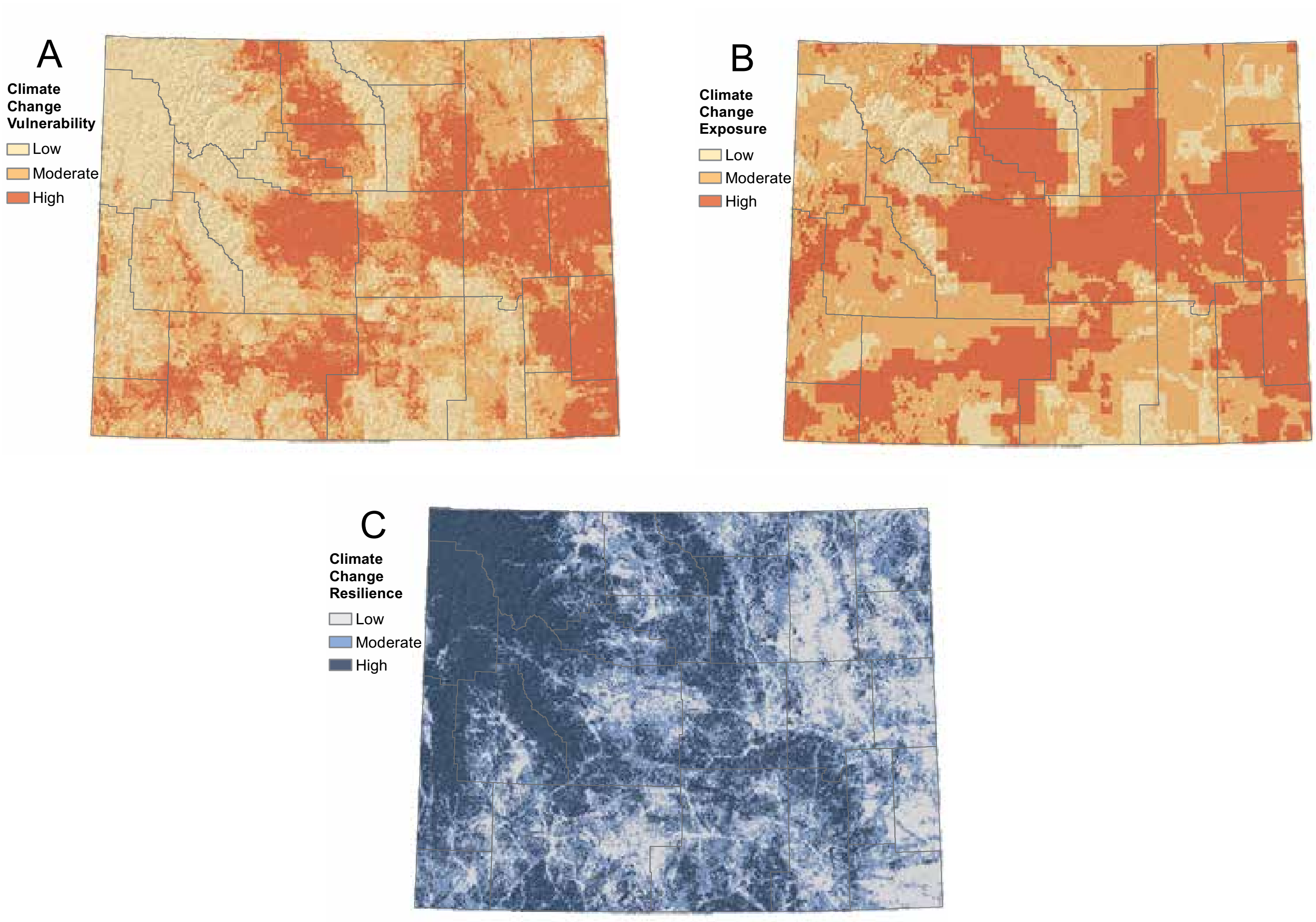


Table 6a. Vulnerability ranks for the 11 habitat types, including overall vulnerability, development vulnerability and climate change vulnerability. Categories of low moderate or high were based on the percent of habitat having high vulnerability (H=high). Percentages for moderate (M) and low (L) vulnerability are also presented.

	Overall Vulnerability				Development Vulnerability				Climate Vulnerability			
Habitat Type	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**
Mountain Grassland	Low	1	15	84	Low	1	9	90	Low	1	9	90
Prairie Grassland	High	50	44	6	Moderate	25	54	21	High	47	40	13
Sagebrush Shrubland	High*	32	52	17	High*	17	37	46	High	36	44	20
Desert Shrubland	High	35	51	14	Moderate	14	38	49	High	46	42	12
Foothills Shrubland	Low	4	46	50	Low	6	33	61	Low	3	25	73
Montane/Subalpine Forest	Low	1	21	78	Low	1	14	85	Low	0	10	90
Aspen/Deciduous Forest	Low	4	51	45	Low	8	37	56	Low	2	25	73
Xeric Forest	Low	9	54	37	Low	9	43	48	Low	7	33	59
Riparian Areas	High	39	45	15	Moderate	26	43	31	High	34	42	24
Wetlands	High	61	27	12	High	47	35	17	High	48	34	18
Cliff/Canyon/Rock Outcrop	Low	4	23	73	Low	3	13	84	Low	4	18	77

*Percent was below 34 but absolute land area exceeded 12,000 km^2

Table 6b. Development ranks for the 11 habitat types, including development exposure and resilience. Categories of low moderate or high were based on the percent of habitat having high exposure or resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented. (H=high). Percentages for moderate (M) and low (L) vulnerability are also presented.

	Development Exposure				Development Resilience			
Habitat Type	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**
Mountain Grassland	Low	1	2	97	High	64	28	9
Prairie Grassland	Moderate	22	21	57	Low	2	27	71
Sagebrush Shrubland	High*	17	12	70	Moderate	10	45	46
Desert Shrubland	Moderate	14	9	76	Moderate	10	44	46
Foothills Shrubland	Low	8	10	82	Moderate	21	48	31
Montane/Subalpine Forest	Low	2	2	96	High	48	39	13
Aspen/Deciduous Forest	Low	9	11	80	Moderate	15	49	37
Xeric Forest	Moderate	10	15	75	Low	6	52	42
Riparian Areas	Moderate	24	17	60	Low	8	30	62
Wetlands	High	36	24	40	Low	8	14	78
Cliff/Canyon/Rock Outcrop	Low	4	4	92	High	58	28	13

*Percent was below 34 but absolute land area exceeded 12,000 km^2

Table 6c. Climate change ranks for the 11 habitat types, including climate change exposure and resilience. Categories of low moderate or high were based on the percent of habitat having high exposure or resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented.

	Climate Exposure				Climate Resilience			
Habitat Type	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**
Mountain Grassland	Moderate	13	56	32	High	91	8	1
Prairie Grassland	High	48	44	7	Moderate	14	45	41
Sagebrush Shrubland	High	49	44	8	Moderate	31	46	23
Desert Shrubland	High	64	31	6	Moderate	26	49	25
Foothills Shrubland	Moderate	15	54	31	High	69	28	2
Montane/Subalpine Forest	Moderate	12	52	37	High	89	10	1
Aspen/Deciduous Forest	Moderate	18	50	32	High	68	30	2
Xeric Forest	Moderate	21	53	26	High	60	36	4
Riparian Areas	High	44	47	9	Moderate	29	49	22
Wetlands	High	45	46	9	Moderate	19	35	47
Cliff/Canyon/Rock Outcrop	Moderate	18	54	29	High	86	13	1

Table 6d. Resilience ranks for the 11 habitat types, including topographic diversity/water availability, landscape integrity, and land management status. Categories of low, moderate, or high were based on the percent of the habitat having high resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented. For land management status, high (H) corresponds to the percent of the habitat occurring in GAP status 1 or 2, medium (M) to the percent occurring in GAP status 2b or 3, and low (L) to the percent occurring in GAP status 4. GAP status is defined in Table 1.

	Topographic Diversity/Water Availability				Landscape Integrity				Land Management Status			
Habitat Type	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**	**Rank**	**H**	**M**	**L**
Mountain Grassland	High	35	62	3	High	80	16	5	High	57	33	10
Prairie Grassland	Low	9	45	46	Moderate	22	30	47	Low	2	25	74
Sagebrush Shrubland	Moderate	11	49	40	Moderate	33	34	33	Low	2	60	38
Desert Shrubland	Low	7	44	49	High	39	32	29	Low	1	69	29
Foothills Shrubland	High	41	54	6	High	43	40	17	Moderate	19	54	27
Montane/Subalpine Forest	High	49	48	2	High	62	30	8	High	44	48	7
Aspen/Deciduous Forest	High	47	51	2	High	42	37	21	Moderate	13	60	27
Xeric Forest	High	43	52	5	High	43	37	20	Low	3	52	45
Riparian Areas	Moderate	24	51	25	Moderate	24	29	47	Low	6	38	56
Wetlands	Moderate	17	53	30	Moderate	11	11	78	Moderate	12	18	71
Cliff/Canyon/Rock Outcrop	Moderate	29	67	4	High	76	17	7	High	49	38	13

Table 7a. Vulnerability ranks for the 44 terrestrial priority areas, including overall vulnerability, development vulnerability and climate change vulnerability. Categories of low, moderate, or high were based on the percent of the habitat having high vulnerability (H=high). Percentages for moderate (M) and low (L) vulnerability are also presented.

	Overall Vulnerability				Development Vulnerability				Climate Vulnerability			
Area	Rank	H	M	L	Rank	H	M	L	Rank	H	M	L
1	Low	0	13	87	Low	0	2	98	Low	0	6	94
2	Moderate	10	80	9	Moderate	14	61	25	Low	1	69	30
3	High	58	42	0	High	60	37	3	Moderate	11	88	1
4	High	86	13	1	High	44	52	4	High	78	21	1
5	Moderate	12	56	32	Low	0	18	81	Moderate	27	47	26
6	Low	7	51	42	Low	3	23	74	Moderate	12	43	45
7	Moderate	10	63	27	Low	9	54	38	Low	2	51	47
8	Moderate	15	57	28	Low	6	38	56	Moderate	17	44	39
9	Moderate	20	56	24	Low	3	39	58	Moderate	25	49	26
10	Moderate	17	65	17	Low	0	14	85	High	53	43	4
11	High	100	0	0	High	47	53	0	High	100	0	0
12	High	79	21	0	Moderate	11	73	16	High	86	14	0
13	Moderate	12	58	30	Low	4	20	76	Moderate	26	66	9
14	Low	4	85	11	Low	0	22	78	Low	8	85	8
15	Low	2	43	55	Low	7	27	67	Low	0	24	76
16	Low	7	73	19	Low	1	44	55	Low	6	65	29
17	Moderate	10	64	26	Low	2	22	76	Moderate	17	65	19
18	Moderate	31	65	4	Moderate	12	65	23	Moderate	23	65	12
19	High	68	32	0	Low	9	70	22	High	81	19	0
20	Moderate	13	59	29	Low	2	13	84	High	35	55	10
21	Moderate	19	66	15	Low	8	48	44	Moderate	19	57	24
22	Low	0	0	100	Low	0	0	100	Low	0	0	100
23	Low	0	0	100	Low	0	0	100	Low	0	0	100
24	Moderate	11	63	26	Moderate	12	30	58	Low	3	52	45
25	High	54	44	2	Low	6	43	50	High	88	11	1
26	Moderate	23	77	0	Moderate	10	25	65	High	61	39	0
27	Moderate	12	61	27	Moderate	14	31	55	Low	3	54	43
28	High	84	16	0	Low	1	86	14	High	97	3	0
29	High	63	37	0	Low	6	44	49	High	90	10	0
30	Moderate	24	63	13	Low	4	22	74	High	54	43	2
31	High	67	33	0	Low	0	75	25	High	98	2	0
32	Moderate	14	71	15	Low	0	7	93	High	67	33	0
33	High	51	49	0	Low	1	39	60	High	97	3	0
34	High	54	45	1	Low	4	38	58	High	91	9	0
35	Moderate	29	64	8	Low	4	25	71	High	61	38	1
36	Moderate	18	61	21	Low	4	35	61	Moderate	24	50	26
37	Moderate	15	62	23	Moderate	10	57	34	Moderate	11	43	46
38	Low	7	43	50	Low	5	35	59	Moderate	10	16	74
39	Low	1	73	26	Moderate	12	63	25	Low	0	19	81
40	Moderate	20	65	14	Low	5	30	65	High	36	44	20
41	Moderate	15	74	10	Moderate	21	50	29	Low	6	57	36
42	Low	3	10	87	Low	2	8	90	Low	3	6	91
43	Moderate	10	74	15	Moderate	12	53	35	Low	2	65	33
44	Moderate	8	92	0	Low	0	10	90	High	41	59	0

	Development Exposure				Development Resilience			
Area	Rank	H	M	L	Rank	H	M	L
1	Low	0	0	100	High	54	44	2
2	Moderate	15	23	62	Low	1	39	60
3	High	49	32	18	Low	0	11	89
4	Moderate	27	40	32	Low	0	7	93
5	Low	0	1	99	Moderate	15	66	19
6	Low	5	5	90	Moderate	23	56	21
7	Low	9	13	78	Low	4	41	56
8	Low	8	11	81	Low	9	56	35
9	Low	2	5	93	Low	7	54	39
10	Low	0	1	98	Moderate	26	60	14
11	Moderate	23	35	41	Low	0	0	100
12	Low	8	18	74	Low	0	19	81
13	Moderate	11	5	85	High	34	53	12
14	Low	0	0	100	Low	6	72	22
15	Moderate	11	12	77	Moderate	21	58	21
16	Low	3	8	89	Low	4	60	37
17	Low	4	6	90	Moderate	12	70	18
18	Moderate	10	15	74	Low	0	29	71
19	Low	8	19	73	Low	0	31	69
20	Low	4	5	92	Moderate	33	56	11
21	Moderate	10	17	73	Low	5	51	44
22	Low	0	0	100	High	35	65	0
23	Low	0	0	100	High	51	49	0
24	Moderate	18	13	69	Low	5	68	26
25	Moderate	11	20	69	Moderate	11	59	30
26	Moderate	16	20	64	Low	0	90	10
27	Moderate	18	15	66	Low	7	65	28
28	Low	1	2	97	Low	0	14	86
29	Low	9	15	75	Low	5	59	36
30	Low	7	10	83	Moderate	25	57	17
31	Low	0	1	99	Low	0	26	74
32	Low	0	1	98	High	44	50	6
33	Low	2	7	91	Low	2	65	33
34	Low	5	13	82	Moderate	20	46	34
35	Low	9	11	80	Moderate	19	66	15
36	Low	6	11	84	Moderate	16	51	33
37	Moderate	11	21	69	Low	0	48	52
38	Low	6	10	83	Moderate	19	47	34
39	Moderate	13	26	61	Low	0	43	57
40	Low	4	5	90	Low	2	66	33
41	High	34	24	42	Low	3	59	38
42	Low	2	3	95	High	79	13	8
43	Moderate	14	24	62	Low	3	47	50
44	Low	1	1	98	Low	0	91	9

Table 7b. Development ranks for the 44 terrestrial priority areas, including development exposure and resilience. Categories of low, moderate, or high were based on the percent of the area having high exposure or resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented.

Site	Climate Exposure				Climate Resilience			
	Rank	H	M	L	Rank	H	M	L
1	Low	0	100	0	High	88	12	0
2	Low	0	72	28	Moderate	10	66	24
3	Moderate	25	75	0	Low	6	53	41
4	High	45	55	0	Low	3	7	90
5	High	69	31	0	High	53	38	8
6	Moderate	16	26	58	Moderate	28	46	26
7	Low	0	58	42	Moderate	27	50	23
8	Moderate	23	51	26	High	34	56	10
9	High	53	44	3	High	43	50	7
10	High	79	21	0	Moderate	18	58	24
11	High	84	16	0	Low	0	0	100
12	High	100	0	0	Low	9	35	56
13	Moderate	25	73	2	Moderate	28	57	15
14	Low	0	94	6	Low	4	60	36
15	Low	5	89	6	High	76	23	1
16	High	95	5	0	High	72	28	0
17	High	66	33	1	High	58	38	3
18	Low	4	96	0	Moderate	23	50	27
19	High	84	16	0	Low	4	47	49
20	High	67	33	0	High	39	48	13
21	High	37	59	4	High	38	51	12
22	Low	0	96	4	High	100	0	0
23	Low	0	100	0	High	100	0	0
24	High	43	57	0	High	80	17	3
25	High	93	7	0	Low	7	50	43
26	High	100	0	0	High	39	58	2
27	Moderate	33	67	1	High	65	30	5
28	High	100	0	0	Moderate	11	79	10
29	High	95	5	0	Low	5	43	52
30	High	96	4	0	High	41	44	15
31	High	100	0	0	Moderate	24	74	2
32	High	100	0	0	High	46	48	6
33	High	100	0	0	Low	8	61	31
34	High	100	0	0	Moderate	11	42	48
35	High	89	11	0	Moderate	26	51	22
36	Moderate	27	62	11	Moderate	22	51	28
37	Moderate	15	68	17	High	38	54	8
38	Moderate	17	34	49	High	67	30	3
39	Low	0	55	45	High	52	47	1
40	High	60	33	7	High	40	48	12
41	Moderate	17	83	0	High	40	52	8
42	Low	8	62	30	High	93	5	1
43	Low	1	90	9	Moderate	21	54	25
44	High	100	0	0	Low	2	69	29

Table 7c. Climate change ranks for the 44 terrestrial priority areas, including climate change exposure and resilience. Categories of low, moderate, or high were based on the percent of the area having high exposure or resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented.

	Topographic Diversity & Water Availability				Landscape Integrity				Land Management Status			
Site	Rank	H	M	L	Rank	H	M	L	Rank	H	M	L
1	High	38	53	9	High	73	19	8	Low	0	99	1
2	Low	1	62	37	High	36	38	26	Low	2	15	83
3	Low	8	73	19	Moderate	10	19	72	Low	0	14	85
4	Low	0	7	92	Low	4	16	80	Low	3	7	89
5	Moderate	17	46	37	High	69	24	7	Low	0	73	27
6	Low	0	22	78	High	72	22	6	Low	0	72	28
7	Low	9	53	37	High	36	42	23	Low	2	46	52
8	Low	7	63	30	High	38	38	24	Low	6	53	41
9	Moderate	14	72	14	High	47	32	21	Low	0	53	47
10	Low	0	8	92	High	79	19	3	Low	0	61	39
11	Low	0	4	96	Low	0	0	100	Low	0	5	94
12	Low	3	42	56	Moderate	17	34	49	Low	1	9	91
13	Low	0	26	73	High	57	29	14	Low	2	87	11
14	Low	0	3	97	High	43	50	7	Low	0	98	2
15	High	39	58	2	High	54	29	18	Low	4	82	14
16	High	63	37	0	High	50	37	13	Low	0	66	34
17	Moderate	19	60	21	High	46	40	14	Low	3	81	16
18	Moderate	14	65	21	Moderate	24	31	45	Low	0	43	57
19	Low	3	34	64	Moderate	31	35	34	Low	0	7	93
20	Low	2	33	65	High	57	30	12	Low	6	86	8
21	Moderate	21	52	27	High	51	33	16	Low	2	28	71
22	High	49	51	0	High	100	0	0	High	35	0	65
23	High	44	56	0	High	98	2	0	High	51	0	49
24	High	48	52	0	High	44	37	19	Moderate	13	72	15
25	Low	0	9	91	High	65	25	10	Low	0	23	77
26	Low	0	57	43	Low	0	51	49	High	90	9	1
27	Moderate	29	65	6	High	34	41	26	Low	8	71	21
28	Moderate	10	76	14	Low	0	66	34	Moderate	11	30	59
29	Low	0	12	88	High	57	29	14	Low	0	28	72
30	Low	3	41	56	High	65	23	12	Low	0	73	27
31	Moderate	23	74	3	Moderate	19	70	11	Low	0	14	86
32	Low	0	33	67	High	59	32	9	Low	5	92	3
33	Low	0	24	76	High	66	23	11	Low	0	19	81
34	Low	0	2	98	High	49	35	17	Low	0	46	54
35	Low	1	30	69	High	44	39	17	Low	1	82	17
36	Low	0	29	71	High	53	34	13	Low	0	48	52
37	Moderate	20	69	11	High	44	34	22	Low	0	34	66
38	High	36	57	8	High	40	43	16	Moderate	19	57	24
39	High	56	44	0	High	40	31	29	Low	0	30	70
40	Moderate	14	54	32	Moderate	33	44	23	Low	2	89	9
41	Moderate	17	65	19	High	54	27	19	Low	1	26	73
42	High	47	49	4	High	68	25	7	High	81	15	4
43	Low	2	57	42	High	43	34	23	Low	0	33	67
44	Low	0	6	94	High	91	9	0	Low	0	19	81

Table 7d. Resilience ranks for the 44 terrestrial priority areas, including topographic diversity and water availability, landscape integrity, and land management status. Categories of low, moderate, or high were based on the percent of the area having high resilience (H=high). Percentages for moderate (M) and low (L) exposure or resilience are also presented. For land management status, high (H) corresponds to the percent of the habitat occurring in GAP status 1 or 2, medium (M) to the percent occurring in GAP status 2b or 3, and low (L) to the percent occurring in GAP status 4. GAP status is defined in Table 1.

Table 8. Numbers of highly vulnerable species associated with each habitat type.

Habitat Type	Number of species	Number of highly-vulnerable species	Percent of species that are highly vulnerable
Mountain Grassland	17	4	24
Prairie Grassland	33	12	36
Sagebrush Shrubland	25	7	28
Desert Shrubland	11	2	18
Foothills Shrubland	17	2	12
Montane/Subalpine Forest	35	10	29
Aspen/Deciduous Forest	32	10	31
Xeric Forest	26	4	15
Riparian Areas	40	19	48
Wetlands	46	27	59
Cliff/Canyon/Rock Outcrop	27	5	19

Table 9. Relative invasive species diversity or presence by habitat type.

Habitat Type	Invasive Species Mean %	Invasive Species Mean Count	% Habitat with at least one species present
Mountain Grassland	8	3	41
Prairie Grassland	12	2.5	69
Sagebrush Shrubland	14	3	67
Desert Shrubland	12	2.5	60
Foothills Shrubland	19	4	78
Montane/Subalpine Forest	17	3.5	70
Aspen/Deciduous Forest	19	4	82
Xeric Forest	15	3	73
Riparian Areas	15	3.5	73
Wetlands	24	5.5	86
Cliff/Canyon/Rock Outcrop	7	1.5	34

Discussion

KEY FINDINGS

This assessment prioritized which of Wyoming's 131 terrestrial SGCN may need the most attention based on estimated future vulnerability, narrowing that list to 51 or fewer species. The factors contributing to species vulnerability varied among the taxonomic groups, and this information can be used to further focus conservation strategies. Amphibians were the most vulnerable taxonomic group (88% highly vulnerable), and most amphibians were highly vulnerable to climate change. No bird species were highly vulnerable to climate change, but birds were the most vulnerable taxonomic group to disease, by number and proportion. Reptiles were the taxa most exposed to development, with nearly half of the species highly vulnerable. Mammals were the least vulnerable taxonomic group, with only one-fifth of mammal species ranked as highly vulnerable, and vulnerability to development, disease, and climate change varied greatly among individual mammal species.

Overall landscape vulnerability was highest for wetlands and prairie grasslands. These habitat types had high or moderate vulnerability to both climate change and development, low resilience to development, very limited legal protections and some of the greatest numbers of associated highly vulnerable species. Sagebrush shrublands, desert shrublands, and riparian areas also had high vulnerability, and riparian areas had the second highest number and percentage of associated highly vulnerable species. Spatial patterns in climate and development vulnerability were similar, suggesting that interactions between these two factors will be important. Greater numbers of habitats and terrestrial priority areas were ranked highly vulnerable to climate change compared with development. Of the three types of development considered, residential development contributed the most to species and habitat vulnerability, followed by oil and gas development. However, the greatest percent increases in development exposure to species are expected from wind development.

RECOMMENDATIONS AND IMPLICATIONS

Our assessment provides new information about which of three major stressors, climate change, development, and disease, are expected to have the greatest impacts on terrestrial species, habitats, and priority areas in the fuure. We hope these results inform the development of conservation strategies aimed at mitigating threats we have identified. These findings can guide activities of the Wyoming Game and Fish Department, public land management agencies, and conservation organizations by highlighting which species and habitats have the greatest conservation needs and where additional information may be needed. Additionally, our results could be used to inform the next revision of the State Wildlife Action Plan.

Our results may be useful to refine a current species prioritization used by the Wyoming Game and Fish Department. In the 2010 plan, each species was assigned to one of three tiers, reflecting their conservation priority (Wyoming Game and Fish Department 2010c). Tier 1 is the highest priority, Tier II is moderate priority and Tier III is the lowest priority. The tiers were based on six criteria, including WGFD Native Species Status (NSS) rank, Wyoming's contribution to the species' overall conservation, regulatory or monetary impacts of the species' Endangered Species Act (ESA) listing, urgency of conservation action, ability to implement effective conservation actions, and the species' role as a keystone, indicator or umbrella species (Wyoming Game and Fish Department 2010c). Generally, we found high agreement between those species we determined to be very highly and highly vulnerable and species ranked as Tier I (11 species) and Tier II (34 species) (Appendix A). Two of the species ranked as very highly vulnerable, the Wyoming Toad and the Black-footed Ferret, are listed as endangered under the ESA and special attention is being paid to their recovery. However, six of the species we identified in the high and very high vulnerability categories were classified as Tier III, including one bird (Yellow-billed Cuckoo), two amphibians (Great Plains Toad, Plains Spadefoot), and three reptiles (Great Plains Earless Lizard, Northern Many-Lined Skink, Western Spiny Softshell). We suggest that these six species be evaluated closely during the revision process as our results indicate that they may be more vulnerable than previously believed and may warrant additional management attention in the future. Five of these six species (all except the Western Spiny Softshell) had a Native Species Status of U indicating that threats and status of the species were not completely known (Wyoming Game and Fish Department 2010c). For the Plains Spadefoot, baseline surveys have been underway since 2011 and are continuing (Walker and Snoberger 2014). Only 45 of the 108 species identified as Tier I and II species in the SWAP ranked as very highly or highly vulnerable in our analysis. This suggests that there is potential to refine the rankings based on improved understanding of threats and vulnerability identified in this project.

The species vulnerability rankings may be most useful in combination with other available information. For example, the Wolverine was ranked as having moderate vulnerability; however, it has been petitioned for listing under the Endangered Species Act and may warrant special attention. Another example is the Northern Boreal Toad, for which a listing petition has been submitted for the eastern clade that includes only some populations occurring in Wyoming, while this assessment did not analyze clades separately. It is also important to consider the specific details for each species, in addition to the overall vulnerability ranking. In particular, species with moderate rankings should be considered closely, as some moderately vulnerable species may still be highly vulnerable to disease, development or climate change individually. For example, six of 10 reptile species with overall moderate vulnerability had high vulnerability to either climate change or development.

Prioritization of habitats and terrestrial priority areas were lacking in the 2010 SWAP. We suggest that our results be used as a foundation for developing priority tiers for habitats and terrestrial priority areas, similar to the tier system used by WGFD for species. Our results indicate that wetlands, prairie grasslands, and some priority areas are warranted for additional management and conservation concern.

Grasslands in Wyoming and across the Great Plains have repeatedly risen to the top of the list of least protected and vulnerable habitats (Noss et al. 1995, Hoekstra et al. 2004, Pocewicz et al. 2009), as shown again through this assessment. Consequently, prairie grasslands have been receiving attention through targeted planning efforts led by the Wyoming Game and Fish Department and others (Wyoming Game and Fish Department 2010c), including a plan for grassland bird and mammal SGCN (Wyoming Game and Fish Department 2006). Additionally, recent funding to the Wyoming Game and Fish Department Nongame Program from the Wyoming Governor's Endangered Species Account has spearheaded development of a monitoring program for Mountain Plover, Upland Sandpiper, Long-billed Curlew, and Burrowing Owl in eastern Wyoming (Orabona and Coyle 2014). Some efforts are underway, but conservation focused on grasslands has been challenging, due in part to primarily private ownership and funding constraints.

The importance of wetlands as critical wildlife habitat has long been recognized, and many groups are working on wetland issues in Wyoming. The Wyoming Bird Habitat Conservation Partnership (WBHCP) has developed a Wyoming Wetlands Conservation Strategy that identified nine of the state's 221 wetland complexes as priorities for conservation work (Wyoming Joint Venture Steering Committee 2010), based on an assessment of threats and wildlife values for each wetland complex (Copeland et al. 2010). The WBHCP is a stakeholder group with representation from WGFD, Wyoming Department of Environmental Quality, Natural Resources Conservation Service, and several NGOs. Building off this work, basin-specific step down plans have been completed for seven wetland complexes. The Intermountain West Joint Venture recently completed an implementation plan that covers much of Wyoming and prioritizes conservation needs for wetlands and grassland and shrubland bird species (Intermountain West Joint Venture 2013). A basin-wide condition and assessment monitoring is underway in three priority wetland complexes identified by the WBHCP, led by the WGFD and The Nature Conservancy. When completed, condition studies will provide field-level insights into baseline condition and identify actual causes of degradation in condition that can inform targeted strategies and restoration needs. The WBHCP has also identified the need for a statewide wetlands coordinator to help leverage available funding for wetlands restoration and protection.

Terrestrial priority areas were identified in the 2010 SWAP as the places that best meet conservation goals in the smallest areas of land for the most terrestrial SGCN and their habitats. By definition all of the 44 areas are priorities, but they could be ranked further in order to focus limited resources. This prioritization could be informed by vulnerability to development and climate change, but other factors could also be considered, as done through the species tier system, such as urgency and ability to implement effective conservation actions. There are several available examples of how land managers and conservationists have balanced cost, threat, and opportunity when prioritizing lands for conservation actions (Copeland et al. 2007, Bottrill et al. 2008, Withey et al. 2012). These decisions are not simple, but when they are informed by analyses such as this assessment, decision-makers can weigh the various benefits and risks to make good conservation decisions. For example, in some cases it may be less costly to focus conservation actions in locations having moderate as opposed to high vulnerability (Copeland et al. 2007). An alternative method to further prioritization would be to re-run the original spatial analysis in which priority areas were identified, but with the new development and climate change vulnerability datasets incorporated. Through that analysis it may be possible to identify where conservation goals could met while avoiding those places with the highest climate change and development vulnerability. The methods used to identify the priority areas intentionally selected locations with the least existing fragmentation and disturbance (Wyoming Game and Fish Department 2010c), so most of the areas had low development vulnerability and high landscape integrity. This presents an opportunity to focus on maintaining those high integrity conditions, which will be less costly than later attempting to recreate or restore these areas if their condition is degraded. Climate change vulnerability was high for many of the priority areas, and these would be appropriate places to focus on the climate adaptation strategies outlined below.

Climate Change

Wyoming's basin areas that are dominated by grasslands and shrublands are most vulnerable to climate change. These lower elevation areas are expected to experience decreases in available moisture, which may also dry basin wetlands (Copeland et al. 2010). Additionally, climate changes are likely to occur faster in these lower elevation areas than in higher elevation montane systems, due to the buffering effects of complex topography in the mountains (Peterson 2003, Loarie et al. 2009, Ackerly et al. 2010). The major basin habitat types – prairie grasslands, sagebrush shrublands, desert shrublands, and the wetlands and riparian areas associated with these systems, should be the focus of efforts to manage for and adapt to climate change.

Multiple approaches can be used to manage for climate change. Because we cannot affect changing climate conditions directly, these strategies are focused on reducing other stressors that we have greater ability to control, such as habitat fragmentation and invasive species (Heller and Zavaleta 2008, West et al. 2009). One strategy is to maintain large areas of high quality habitat that include a variety of bioclimatic conditions (i.e. topographic diversity) and maintain and enhance connectivity among these areas and their wildlife populations (Heller and Zavaleta 2008, Mawdsley et al. 2009, Hunter et al. 2010). Large, connected habitats can be maintained through a variety of tools, including Wyoming's Sage-Grouse Core Area Policy that limits development on public lands in important sagebrush habitats (Wyoming Governor's Sage-Grouse Implementation Team 2010), incentive and cooperative programs through agencies such as the BLM, FWS, Forest Service, and Natural Resources Conservation Service (NRCS) that assist private landowners with conservation actions (Wyoming Game and Fish Department 2006), and conservation easements. Conservation easements are voluntary agreements that can be used to limit new residential development and wind development on privately-owned lands (Kiesecker et al. 2007, Fishburn et al. 2009, Pocewicz et al. 2011). Important areas for connectivity have been identified for some Wyoming species, including migrating ungulates and sage-grouse (Sawyer et al. 2005, Wyoming Governor's Sage-Grouse Implementation Team 2010). Identifying additional key geographic areas to manage for habitat connectivity or linkages for other suites of species would be valuable (Lacher and Wilkerson 2014). Other strategies are focused on adaptation to changing conditions that are specific to habitat types and climate conditions. Adaptation-focused projects might include restoring riparian areas with native vegetation, conducting prescribed fires to reduce risk of large wildfires, restoring beavers to streams to enhance wetlands, preventing and controlling invasive species, and managing for drought-tolerant plant species (Mawdsley et al. 2009, West et al. 2009, Cross et al. 2013).

Additional examples are vegetation restoration to improve habitat for specific species, modifying grazing management, and restoring disturbed areas with locally-adapted seed. Efforts such as these increase the resilience of habitats, allowing them to better withstand greater disturbances and fluctuations in climate, or new, often drier conditions.

Amphibians and reptiles were identified as most vulnerable to climate change, and birds as least vulnerable. Amphibians are known to be highly sensitive to changes in temperature and moisture, and global declines in amphibians have been associated with both climate change and disease (Pounds et al. 2006, Rohr and Raffel 2010, Hof et al. 2011). Reptiles have been less studied than amphibians but are also susceptible to climate change (Gibbon et al. 2000). Neither amphibians nor reptiles are highly mobile, which contributes to their vulnerability. In contrast, birds are typically highly mobile, and while some birds use specific habitats, they might more easily move to find those specific habitats in other locations. While we found that no birds were highly vulnerable to climate change, birds are expected to be sensitive to climate change due to changes in phenology, such as the timing of migration and nesting (Walther et al. 2002, Crick 2004). Migratory status or factors related to migration were not included in the CCVI (Small-Lorenz et al. 2013), and because it is not specific to any one taxonomic group, the CCVI may have overlooked other important criteria specific to birds or another taxa (Gardali et al. 2012). The CCVI also did not account for interactions between climate change and disease. Birds were highly vulnerable to disease, and climate change may lead to increases in some avian diseases, including West Nile Virus (Schrag et al. 2011) and botulism (Moraska Lafrancois et al. 2011).

We used Nature Serve's CCVI to assess climate vulnerability, because it allowed for numerous species to be rapidly assessed (Hameed et al. 2013), and it had been applied in many other statewide assessments. One of the CCVI's limitations is that it does not show which portions of a species' habitat may be most affected by climate change (Rowland et al. 2011), which we partially addressed by assessing climate change vulnerability across habitat types and priority areas. Other tools exist to assess species' climate change vulnerability and results compared among the CCVI and other tools have been inconsistent; however the CCVI relies upon more detailed data than the other available tools (Lankford et al. 2014).

To manage for species vulnerable to climate change, maintaining large areas of quality habitat having strong linkages between them is a strong strategy (Heller and Zavaleta 2008, Mawdsley et al. 2009). For individual species, it will also be important to increase and maintain basic monitoring programs, study responses to climate change, better understand genetic variation, and reduce pressures from other sources such as noise, pollution or disease (Heller and Zavaleta 2008, Mawdsley et al. 2009).

Development

Development vulnerability was high in nearly one-fifth of the state, with the greatest vulnerability in sagebrush shrublands and wetlands, and 32 species were ranked as highly vulnerable to development. Residential development contributed the most to species and habitat vulnerability, followed by oil and gas development. However, the greatest percent increases in development exposure to species are expected from wind development.

The amount of vulnerability attributable to residential development was surprising. This may have occurred because residential development is the most widespread of the three development types. There were 224,164 houses in Wyoming in 2010, as compared with 40,953 oil and gas wells and 959 wind turbines (Copeland et al. 2013). New rural housing is expected to increase 10% (24,491) by 2030 (Wyoming Housing Database Partnership 2010, Copeland et al. 2013). The numbers of oil and gas wells and wind turbines may be smaller than the numbers of houses in Wyoming, but both are expected to experience proportionately larger increases than residential development. New oil and gas wells are expected to more than double between 2010 and 2030 (52,626 new wells), and wind development is expected to increase by nearly five times (4,569 new turbines) (Copeland et al. 2013). The 250,000 homes resulted in greater exposures from residential development than from energy development. The methods used to simulate new houses on the landscape were not as precise as those applied for oil and gas and wind development, so it is possible that residential development exposure may be overestimated, though this limitation did not affect the existing homes (Copeland et al. 2013). Even if estimates are high, exposure from residential development was highlighted as being more widespread than anticipated and there is a need to better understand potential impacts. There are many uncertainties regarding effects of development on wildlife. This analysis highlights those species that may be most exposed to development; however, it does not describe those species' actual sensitivity to development.

There is a widely recognized need to understand and minimize the trade-offs between development and wildlife conservation in Wyoming (Wyoming Governor's Office 2012). Our analysis provides specific guidance as to which species, habitats and terrestrial priority areas warrant additional focus for conservation. We recommend that conservation efforts related to limiting habitat fragmentation and other impacts from development be focused on the moderately or highly vulnerable priority terrestrial areas that have high landscape integrity. On publicly- managed land, ACECs, WSAs and no surface occupancy designations are mechanisms that limit habitat fragmentation and can be implemented through the public land management planning process. Enforcing and maintaining Wyoming's Sage-Grouse Core Area Policy will minimize disturbance from development in sagebrush shrublands, primarily on public lands. This policy likely also benefits other sagebrush species in addition to the sage-grouse (Hanser and Knick 2011, Gamo et al. 2013), but grassland species and their habitats are not likely to benefit. For vulnerable grassland and wetland habitats, conservation easements can limit development in critical habitats. Where development does occur, the mitigation hierarchy should be applied to avoid impacts in the most critical habitats, minimize impacts that cannot be avoided, ensure that adequate resources are available for restoration, and use offsite mitigation to compensate for impacts and improve similar habitat elsewhere (Kiesecker et al. 2009). Established best management practices should be applied to minimize impacts from development and ensure successful restoration outcomes (Wyoming Game and Fish Department 2010b, a, U.S. Fish and Wildlife Service 2012). Another strategy related to development might focus on reducing other stressors to habitats by working with private landowners on conservation actions such as invasive species control or grazing management, as discussed in the previous section on climate change strategies. Finally, it is important to continue to demonstrate the value of high integrity wildlife habitats to Wyoming's residents and economy through education and outreach, such as hands-on educational opportunities and promotion of terrestrial priority areas for wildlife-related tourism.

Disease

Thirteen wildlife diseases were identified that could potentially impact 76 of the 131 (58%) wildlife species we considered in our analysis. Notably, 55 (41%) of the species were not affected by any diseases, including many reptiles. The true impacts of diseases are difficult to characterize, as epizootics are stochastic events that are difficult to predict. Unlike other threats, we hypothesize that the actual vulnerability to diseases may have been over-represented in our analysis. This may be especially true for birds. Outbreaks of avian botulism and cholera, which affected the vast majority of species in our analysis, have occurred infrequently in Wyoming. Species may go years or decades without being exposed to outbreaks of diseases. However, when outbreaks occur they can quickly devastate local populations. Capturing and characterizing the range of variability is difficult without complex modeling. Unfortunately, many of the parameters that would be necessary to elucidate this phenomenon correctly are currently lacking or poorly understood for many diseases and wildlife species. We considered weighting the results of diseases differently than other threats, however we had no prior information that would support such an approach. Notably, this is the first statewide vulnerability assessment that includes a disease component. As such, we believe our results, in spite of their limitations, highlight general patterns with diseases that should be considered by managers in the future. It is also worth noting that diseases could potentially confound the impacts of other threats such as climate change or urban development. While this assessment considered climate change, development and disease separately, the potential interactions among these threats should also be considered when developing strategies.

ADDITIONAL CONSERVATION CHALLENGES

This assessment focused on three challenges to wildlife conservation in Wyoming: development, climate change, and disease. There are many additional challenges which were not addressed, including disruption of historic disturbance regimes, which was identified as one of five leading challenges in the 2010 SWAP. Disruption of historic disturbance regimes was not included because data representing fire and grazing regimes and how they may affect wildlife habitats in the future were not available statewide. We included the current 131 terrestrial Species of Greatest Conservation Need, but there may be emerging species of concern that were not included, such as the Golden Eagle or Abert's Squirrel. In addition to the 131 terrestrial species, the 2010 SWAP also identified 30 fish species and 19 crustacean and mollusk species or taxonomic groups. We recommend expanding this type of assessment to include these aquatic species and their habitats.

Invasive species were identified in the 2010 SWAP as one of five leading challenges. We included invasive species in the assessment but not to the desired degree because spatial data currently available to represent invasive species are limited, constraining our analyses. We suggest that because of this, the results for invasive species should be interpreted cautiously. Only coarse-scale spatial datasets representing invasive species were publicly-available across Wyoming when we initiated this project. Some Weed and Pest Districts were willing to share finer-scale GIS data, but similar datasets were not available statewide. We also encountered considerable differences in mapping efforts among counties, which affected the resolution of the data at all scales. Some county Weed and Pest Districts, including Fremont, Park and Teton counties have well-developed mapping programs, while others have only recently begun mapping invasive species. A few counties, including Sweetwater, had no formal mapping programs. Consistent mapping efforts are needed across all counties, along with guidelines informing spatial data management. We also recommend focusing attention on invasive plant species that are not currently listed as noxious weeds. The most obvious is cheatgrass, which was missing from our analysis because it was not listed as a noxious weed in Wyoming and therefore was not tracked by Weed and Pest Districts. Notably, an effort is currently underway to develop a statewide map that will identify the probability of cheatgrass occurrence and help to prioritize treatment efforts (Noseworthy and Mealor 2013).

We considered oil and gas, wind and residential development, but other types of development and native habitat conversion are also occurring in Wyoming. Mining of coal, uranium, trona, and rare earth minerals is prevalent in Wyoming. We did not include mining in this analysis, because models of the anticipated distribution of new mines are not currently available. Many mining operations are primarily underground, use in-situ technologies or have discrete surface impacts, and overall mining may not impact habitats as extensively as oil and gas or wind energy development. However, because mining is missing, this assessment likely underestimates development-related impacts that may occur to species or their habitats. Across the Great Plains, native grasslands are rapidly being tilled to grow agricultural crops (Wright and Wimberly 2013). This type of land conversion is affecting grasslands in some areas of eastern Wyoming. Two different models representing the risk of conversion of grasslands to crops have been developed recently by researchers at the University of Wyoming (Rashford et al. 2012, Rashford et al. 2013) and The Nature Conservancy's North America Program that might be considered when revising the SWAP.

PHOTO: Cheatgrass © *Cara Noseworthy*

CONCLUSIONS

Overall, this vulnerability assessment should inform and improve the next version of the SWAP and highlight additional focus areas for planning and implementation. There are several ways that this assessment may inform the next SWAP:

- Help to reevaluate and prioritize Wyoming's list of SGCN
- Prioritize terrestrial habitat types and priority areas for conservation action
- Provide additional information about disease, which was only minimally addressed in the 2010 SWAP
- Strengthen the "Leading Challenges" section of the SWAP by further describing development, climate change and their potential interactions

We hope that by drawing special attention to wildlife species and habitats that appear to be particularly vulnerable to projected future changes, we have identified opportunities to avoid potential declines and that this information will facilitate enhanced conservation in Wyoming. For example, although grassland conservation is highlighted in the 2010 SWAP and has been WGFD's conservation focus throughout the years, effective and focused conservation measures have only begun to be implemented on the ground. As resources become increasingly scarce and conservation becomes more complex in the future, this analysis and the results we provide justify expending resources on certain species and habitats based on their anticipated vulnerability and associated conservation needs.

These data, analyses, and results provide a benchmark for terrestrial species, habitats, and priority areas in Wyoming. This vulnerability assessment was unique, because we considered multiple stressors (i.e., climate change, development, and disease) and because we used both species-based and landscape-based approaches. By considering both species and habitats, we were able to capture species-specific traits as well as landscape patterns that affect many species and habitats. This approach allowed us to refine conservation priorities by identifying places where many vulnerable species occur in vulnerable habitats, which included grasslands and wetlands. We hope that future analyses will benefit from our approach and results. In spite of the limitations of some components of our analyses, we believe our results are robust and will be valuable for improving conservation efforts in Wyoming. Undoubtedly, conservation is complex and existing conditions will likely change in the future. This project provides a template for completing similar analyses and a baseline for interpreting those results when these issues are revisited, as new data becomes available or as conditions change in Wyoming.

PHOTO: LEFT TO RIGHT Grasslands in northeast Wyoming © *Michael Wickens;* Riparian area along the Shoshone River © *Sara Caudle*

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