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A climate-change adaptation framework to reduce continental-scale vulnerability across conservation reserves

Dawn R. Magness,[1,2,]† John M. Morton,[1] Falk Huettmann,[2] F. Stuart Chapin, III,[2] and A. David McGuire[2]

[1]U.S. Fish & Wildlife Service, Kenai National Wildlife Refuge, Soldotna, Alaska 99669 USA
[2]Institute of Arctic Biology, Department of Biology and Wildlife, University of Alaska, Fairbanks, Alaska 99775 USA
[3]U.S. Geological Survey, Alaska Cooperative Fish & Wildlife Research Unit, University of Alaska, Fairbanks, Alaska 99775 USA

Citation: Magness, D. R., J. M. Morton, F. Huettmann, F. S. Chapin, III, and A. D. McGuire. 2011. A climate-change adaptation framework to reduce continental-scale vulnerability across conservation reserves. Ecosphere 2(10):112. doi: 10.1890/ES11-00200.1

Abstract. Rapid climate change, in conjunction with other anthropogenic drivers, has the potential to cause mass species extinction. To minimize this risk, conservation reserves need to be coordinated at multiple spatial scales because the climate envelopes of many species may shift rapidly across large geographic areas. In addition, novel species assemblages and ecological reorganization make future conditions uncertain. We used a GIS analysis to assess the vulnerability of 501 reserve units in the National Wildlife Refuge System as a basis for a nationally coordinated response to climate change adaptation. We used measures of climate change exposure (historic rate of temperature change), sensitivity (biome edge and critical habitat for threatened and endangered species), and adaptive capacity (elevation range, latitude range, watershed road density, and watershed protection) to evaluate refuge vulnerability. The vulnerability of individual refuges varied spatially within and among biomes. We suggest that the spatial variability in vulnerability be used to define suites of management approaches that capitalize on local conditions to facilitate adaptation and spread risk across the reserve network. We conceptually define four divergent management strategies to facilitate adaption: refugia, ecosystem maintenance, "natural" adaptation, and facilitated transitions. Furthermore, we recognize that adaptation approaches can use historic (i.e., retrospective) and future (prospective) condition as temporal reference points to define management goals.

Key words: climate change; conservation reserve; National Wildlife Refuge System; prospective adaptation; resilience; retrospective adaptation; species extinction; U.S. Fish and Wildlife Service; vulnerability.

Received 8 July 2011; revised 25 August 2011; accepted 26 August 2011; final version received 30 September 2011; **published** 18 October 2011. Corresponding Editor: D. P. C. Peters.

† **E-mail:** Dawn_Magness@fws.gov

Introduction

Rapid climate change heightens the need for coordinated reserve networks to accommodate dynamic ecological patterns (Halpin 1997, Hannah 2010). However, to be effective, conservation reserve networks must be coordinated at continental, regional and local scales (Soule and Terborgh 1999). This criterion of planning at multiple spatial scales for multiple resources within a reserve network is problematic because many climate change vulnerability assessments have been based on single species or resources, such as a habitat or ecosystem type (Dawson et al. 2011). A new approach is needed for assessing the vulnerability of reserve units, which are predefined parcels of land in dynamic landscapes, in order to promote a coordinated adaptation response to climate change and other environmental stressors within a conservation network.

Adaptation in a management context is defined as "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC 2007). Traditionally, natural resource managers have used historic condition as a management benchmark (Hunter 1996). Rapid climate change and other anthropogenic change have caused ecologists to reconsider whether historic condition is a viable goal (Millar and Wolfenden 1999, Schroeder et al. 2004). Ecosystems are now seen as complex, adaptive systems with multiple possible trajectories (Chapin et al. 2009). Therefore, adaptation can be retrospective or prospective, which we define here as having different temporal reference points or benchmarks. Prospective adaptation is proactive and works *with* climate change trajectories; retrospective adaptation works *against* climate change, towards historic conditions. The former approach manages the system towards a new climate-change-induced steady state, whereas the latter abates the impact by trying to maintain the current condition despite climate change.

Deciding when to apply retrospective or prospective strategies can be problematic for land managers (GAO 2007). Low-risk and non-intervention strategies have been advocated for facilitating adaptation on conservation reserves; e.g., increasing the redundancy and representation of habitat types and increasing landscape connectivity (Griffith et al. 2009, Heller and Zavaleta 2009, Mawdsley et al. 2009). However, the climate envelopes of many species have been forecast to move rapidly across large geographic areas (for a U.S. example, see Iverson and Prasad 2001). In addition, some large geographic areas have been forecast to experience novel species assemblages in the future due to high species turnover (Lawler et al. 2009). In response to directional change at continental scales, managers may need to engage in high-risk adaptation strategies, such as long-range translocations of species to places they have never occurred before (McLachlan et al. 2007). In these cases, to spread the risk of failure and/or unintended ecological consequences, managers of conservation reserves will need to strategically coordinate strategies for facilitating adaptation at scales larger than the landscape matrix surrounding any individual reserve.

In this paper, we use the National Wildlife Refuge System (NWRS) as a case study to demonstrate a new approach to managing reserve networks in a rapidly changing climate. The NWRS is a 600,000 km^2 reserve network managed by the U.S. Fish and Wildlife Service (USFWS). Although individual refuges have management priorities or purposes that originate from legislation outlined when they were established, the NWRS Improvement Act of 1997 (Public Law 105-57) unifies the 540 individual refuges into a coordinated system with an overarching mission to conserve fish, wildlife, and plants and their habitats, and a derivative policy that promotes the maintenance of biological integrity, diversity, and environmental health across the NWRS. This organic legislation makes the NWRS an ideal network to apply a vulnerability approach that focuses on minimizing species extinction at a continental scale.

Vulnerability is defined as "the degree to which a system is susceptible to, and unable to cope with, the adverse effects of climate change" (IPCC 2007). Vulnerability depends on exposure to climate change, the sensitivity of the system, and the adaptive capacity of the system (see Table 1 for definitions). Using these three components, we conduct a spatial analysis of vulnerability across the NWRS. Our final product is an adaptation framework, based on vulnerability that describes how prospective and retrospective approaches can be strategically applied across a continental-scale reserve network to facilitate adaptation while spreading risk.

Methods

We conducted a national-scale vulnerability assessment of NWRS lands in the United States with GIS data from high-quality, public sources. We assessed vulnerability using seven variables representing climate change exposure, sensitivity, and adaptive capacity of refuge lands (Table 1, Fig. 1). We calculated a Pearson correlation matrix for the vulnerability indicators to ensure

Table 1. Variables used in vulnerability assessment. Vulnerability was defined based on Dawson et al. (2011) as the extent to which species or populations within a refuge are threatened due to climate change and has three components: exposure, sensitivity and adaptive capacity.

Component	Definition	Variables
Exposure	extent of climate change experienced by a species or locale.	(1) annual temperature change rate (°C/yr)
Sensitivity	degree to which species survival, persistence, fitness or regeneration may be affected by climate change.	(2) critical habitat for threatened or endangered species in refuge (yes/no); (3) refuge boundary contains biome boundary (yes/no)
Adaptive capacity	capacity of a species to cope with climate change, including adaptation responses such as shifting to more suitable local microhabitat or migrating to more suitable regions	(4) latitude range within refuge boundary (decimal degrees); (5) elevation range within refuge boundary (m); (6) road density of watershed(s) in which refuge is embedded (m/ha); (7) percentage of watershed(s) with permanent conservation protection (%)

that the continuous variables provide relatively independent measures ($r < 0.7$).

We used the legislative boundaries to delineate NWRS lands (USFWS 2010). These boundaries include lands owned, lands with established management agreements or easements, and lands that have been authorized by Congress for future acquisition. Therefore, the legislative boundaries represent the planned future spatial distribution of refuge lands.

Climate change exposure

We used annual temperature change rate (°C/yr) to summarize the historic (1950–2006) climate change exposure on refuge lands. We chose to use historic temperature change instead of future forecasts because we wanted the analysis to focus on areas already experiencing change. Temperature change has been linked with very high confidence to changes in natural systems (IPCC 2007). The gridded data, along with gridded statistical confidence estimates for the trend (p-value), were distributed by Climate Wizard (www.climatewizard.org). We only used the rate estimates from grid cells with a p-value ≤ 0.10 associated with the trend. We conservatively assumed that pixels with a p-value > 0.10 had no trend. To generate an annual temperature change rate for each refuge, we averaged the pixels within the refuge.

For the contiguous U.S., Climate Wizard uses the 4-km resolution PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system (www.prism.oregonstate.edu). The PRISM algorithm interpolates spatial climate data through a process in which individual station data were weighted using expert knowledge to reduce bias caused by sparse or unrepresentative stations and factors that affect climate at finer spatial scales (Daly et al. 2002, Daly 2006). In Alaska and Hawaii, where climate station data are sparse, yearly PRISM data were not available and we used Climate Wizard's 50-km resolution global data generated from Climate Research Unit (CRU) Time Series ver2.10 (Mitchell and Jones 2005). Data were not available for oceans or large water bodies and 18 island refuges had no temperature data and were excluded from the analysis: Block Island, Brenton, Cross Island, Egmont Key, Farallon, Fisherman Island, Great White Heron, Huron, Key West, Martin, Michigan Islands, National Key Deer, Nomans Land Island, Passage Key, Seal Island, Shell Keys, and West Sister Island NWRs.

The IPCC (2007) estimates that 1.2–2°C increase from pre-industrial temperature in the next 50 years would place 9–31% of species at high risk for extinction. Therefore, we used a 1.2°C increase over 50 years to delineate an annual temperature change rate of 0.024°C/yr as a vulnerability threshold. Refuges experiencing temperature change >0.024°C/yr were categorized as having high exposure vulnerability (Fig. 1). We considered areas experiencing 0.005°C/yr (0.25°C increase over 50 years) to have low exposure vulnerability because a 0.5°C increase from pre-industrial temperature was not linked with ecosystem or biodiversity change (IPCC 2007).

Sensitivity

We defined sensitivity based on whether the

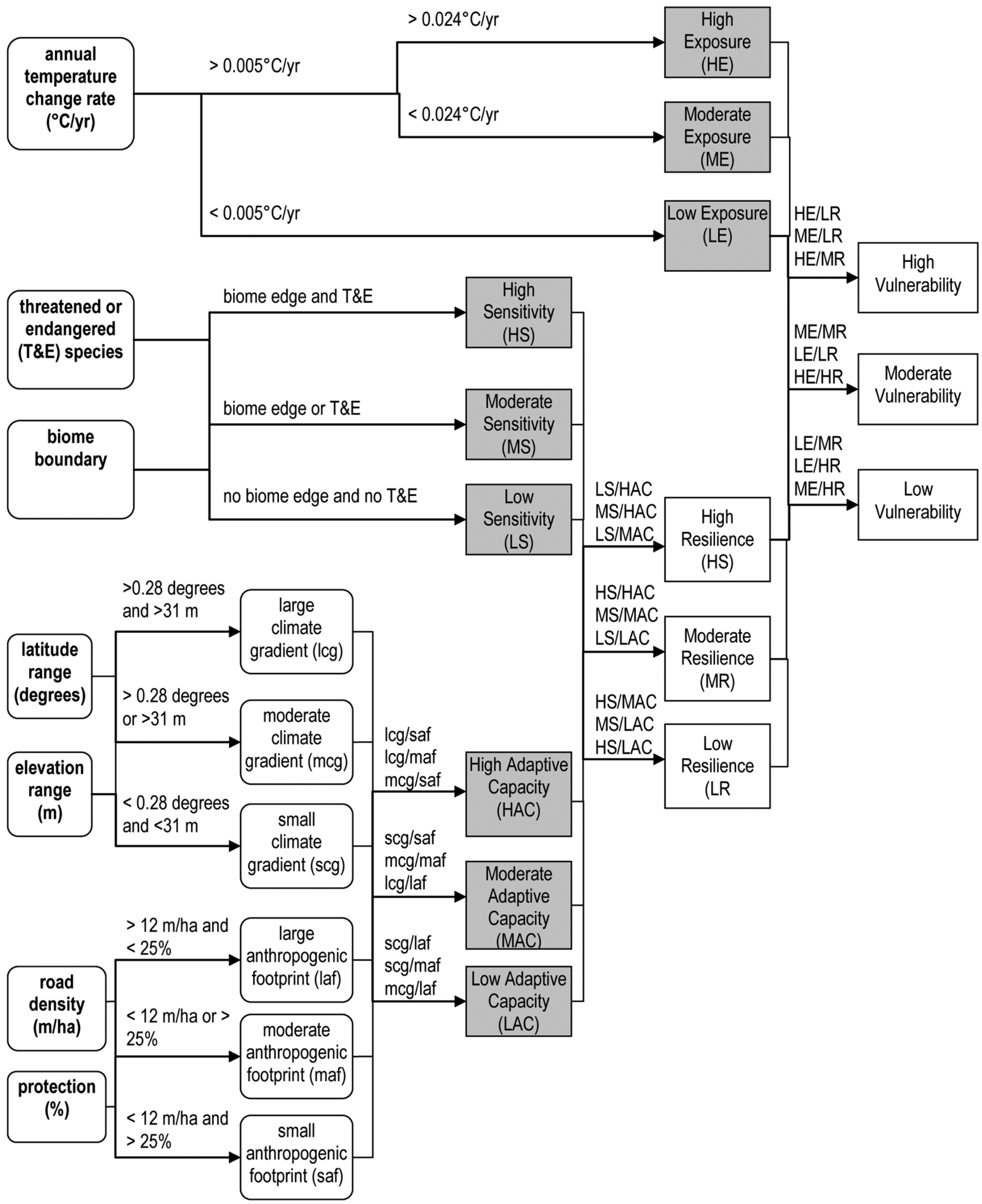

Fig. 1. Flowchart of variables with thresholds that define vulnerability categories.

refuge contained critical habitat for threatened and endangered species, and whether a refuge was located at a biome edge. The USFWS maintains a geodatabase of critical habitats (USFWS 2011). Critical habitats are lands designated under the Endangered Species Act to be occupied by an endangered species or to contain essential physical or biological features for a listed species. Threatened and endangered species are more likely to be sensitive to climate change because of their restricted ranges, weak dispersal abilities, or small population sizes

(Wilcove et al. 1998) and therefore are sensitive to environmental change.

Olson et al. (2001) delineated 14 global biomes based on flora and fauna. Biomes have been forecast to undergo large-scale shifts under future climate change scenarios (Gonzalez et al. 2010, Murphy et al. 2010). Species responses to climate change are influenced by population changes at range margins which are often associated with biome boundaries (Hampe and Petit 2005). Therefore, biome edges are expected to be more sensitive to climate change. We used the presence of critical habitat and biome edge within the refuge boundary to define high, moderate, and low sensitivity (Fig. 1).

Adaptive capacity

Adaptive capacity, or the capacity of species in a refuge to cope with climate change, increases when species are able to shift to more suitable local microhabitats or to migrate to more suitable regions (Dawson et al. 2011). Both latitudinal and elevational range within a refuge increases the potential for species migration along climate gradients (McNeely 1990). Species in many taxa have already responded to recent climate change by shifting northward in latitude and upward in elevation (Parmesan and Yohe 2003). Therefore, a refuge with a large latitude range or elevation range has greater adaptive capacity. We used the northern and southern extent of each refuge to calculate latitude range, and the minimum and maximum elevation of a refuge (USGS 1999) to calculate the elevation range as indicators of adaptive capacity (Table 1). We sorted refuges into large, moderate, and small climate-gradient categories, using a threshold of 0.28 decimal degrees of latitude range and a 31 m elevation range (Fig. 1). In the northern hemisphere, species ranges have expanded an average of 6.1 km/decade northward and 6.1 m/decade upward in response to recent climate change (Parmesan and Yohe 2003). Our thresholds are equivalent to 6.1 km/decade and 6.1 m/decade over 50 years.

Other anthropogenic drivers, such as road development and land-use conversion, also influence the capacity of species to move and migrate and therefore affect adaptive capacity (McNeely 1990). Roads increase mortality and avoidance behaviors, creating a partial barrier to population movements and affecting population persistence (Forman et al. 2003). Lands outside of the conservation network are subject to land-use conversion and corresponding habitat fragmentation, habitat degradation, and reduced landscape connectivity (Forman 1995). We used road density (m/ha; U.S. Census Bureau 2001) and the percentage of protected lands (The Conservation Biology Institute 2010) in the watershed(s) (USGS 2006) in which a refuge was located as indicators of anthropogenic factors that influence adaptive capacity (Table 1). Refuges embedded in watersheds with high road density and low percentage of lands in protection were considered to have less adaptive capacity than refuges in watersheds with low road density and a high percentage of protected lands. We used thresholds of 12 m/ha of roads and 25% watershed protection to delineate large, moderate, and small anthropogenic footprint (Fig. 1). To define the road density threshold, we doubled the 0.6 km/km^2 threshold above which populations of large mammals, such as wolves and cougars, decline (Forman et al. 1997). In the conservation literature, thresholds for the percentage of protected lands vary from 8 to 80%, depending on the conservation target (Svancara et al. 2005). We chose a threshold of 25% protected because it corresponded with conservative recommendations for biodiversity protection (Noss 1996). Finally, we categorized refuges with high, moderate, and low adaptive capacity based upon the climate gradient and anthropogenic footprint thresholds (Fig. 1). The thresholds that we selected were reasonable, based on current literature, but could be modified based on improved information or to address particular issues (e.g., birds vs. trees vs. fire risk).

Evaluating vulnerability

We combined the sensitivity and adaptive capacity information into an index of resilience. The properties of resilience include both the ability to absorb disturbance without fundamental change (sensitivity) and the ability of the system to reorganize, learn and adapt (adaptive capacity; Carpenter et al. 2001). We used the categories of high, moderate and low resilience and high, moderate, and low exposure to assign a vulnerability category to each refuge (Fig. 1). We then used both resilience (sensitivity and adaptive capacity) and exposure to define four

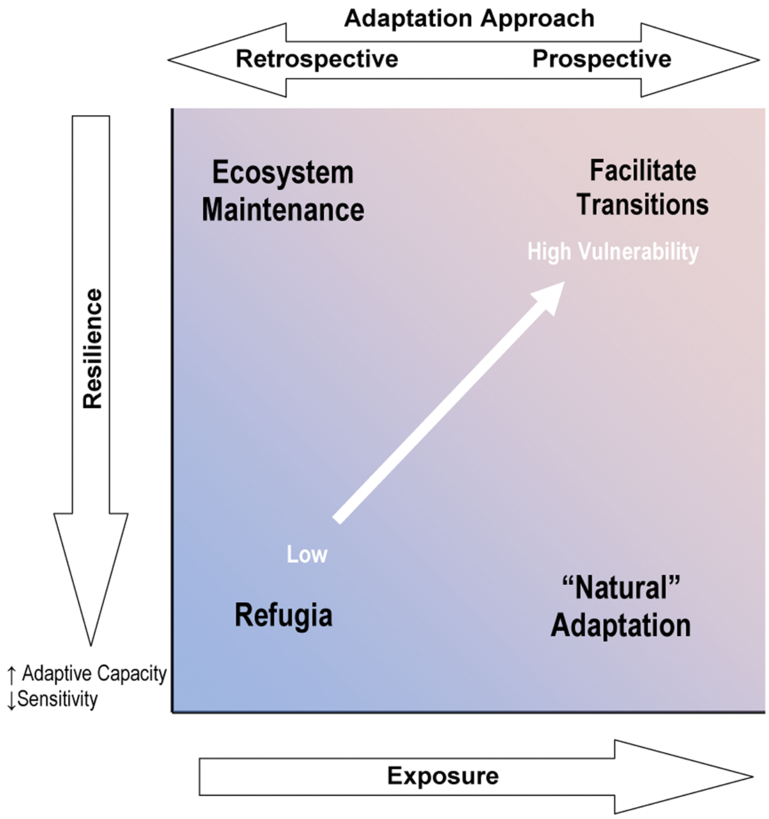

Fig. 2. Adaptation framework based on vulnerability. Management strategies can focus on refugia, ecosystem maintenance, "natural" adaptation, or facilitated transitions, based on relative levels of exposure and resilience (sensitivity and adaptive capacity).

management strategies for refuges to coordinate adaptation efforts across reserve networks: refugia, ecosystem maintenance, "natural" adaptation, and facilitated transitions (Fig. 2).

Results

After limiting the analysis to the U.S. and excluding refuges with no climate data, 501 refuges were assessed for vulnerability. The average size for these refuges was 1,356 km^2 with a median size of 43 km^2. Alaska accounted for most of the large refuges, with their 16 refuges contributing 57% of the total land area currently in the NWRS or slated for acquisition. Alaskan refuges have a median size of 15,618 km^2. At the opposite extreme, nearly 20% of refuges are <5 km^2 in size.

Climate change exposure

NWRS refuges have warmed an average of 0.010°C/yr (SD = 0.011) over the past 50 years. Warming trends ranged from −0.008 to +0.043°C/yr. We classified 229 of 501 refuges as having low exposure based on annual temperature change rate: 11 refuges had slight cooling trends (≤0.008°C/yr), 180 refuges had no statistically significant temperature trend ($p > 0.10$), and 38 refuges had warming trends <0.005. The remaining 272 vulnerable refuges included 206 with warming ≥0.005°C/yr but <0.024°C/yr (moderate exposure) and 66 refuges exceed the vulnerability threshold of 1.2°C with warming ≥0.024°C/yr (high exposure). In Alaska, the Yukon Flats and Bercharof NWRs have already experienced warming trends >0.04°C/yr (Appendix).

Sensitivity

Critical habitat for threatened and endangered

Table 2. Count of refuges and relative percentage (in parentheses) by biome (Olson et al. 2001) with high, moderate, and low vulnerability.

Biome	Vulnerability		
	High	Moderate	Low
Boreal forests/taiga	1 (13)	7 (87)	0 (0)
Deserts and xeric shrublands	2 (4)	10 (20)	37 (76)
Flooded grasslands and savannas	2 (50)	2 (50)	0 (0)
Mediterranean forests, woodlands and scrub	12 (50)	9 (38)	3 (12)
Temperate broadleaf and mixed forests	11(7)	47 (32)	89 (61)
Temperate conifer forests	14 (13)	36 (32)	61 (55)
Temperate grasslands, savannas and shrublands	24 (19)	36 (29)	65 (52)
Tropical and subtropical dry broadleaf forests	2 (66)	1 (33)	0 (0)
Tropical and subtropical grasslands, savannas and shrublands	5 (25)	7 (35)	8 (40)
Tropical and subtropical moist broadleaf forests	1 (33)	2 (66)	0 (0)
Tundra	2 (29)	4 (57)	1 (14)

species occurs on 111 refuges. Sixty-three refuges are located on a biome edge. We assigned 21 refuges as having high sensitivity because they included critical habitat and biome edge, 132 with moderate sensitivity because they had either critical habitat or biome edge, and 348 with low sensitivity.

Adaptive capacity

Refuges encompass an average of 0.339 (SD = 1.181) decimal degrees in latitude, which is equivalent to approximately 37.3 km. The median latitude range was 0.111 decimal degrees. The refuges with the smallest latitude range (0.001 degrees) were the 0.56 ha Susquehanna NWR and the 3.8 ha Caloosahatchee NWR. Maritime NWR, which includes many islands distributed across the state of Alaska, had the largest latitude range of 19.1 degrees. Refuges contain an average of 135.7 m (SD = 344.4) of elevation. Elevation ranges of refuges vary from 0 to 2621 m. The distribution of elevation range within the NWRS is skewed to small values with a median value of 28 m. Thus most refuges are small and have modest latitudinal and elevational ranges.

Refuge watersheds had road densities that averaged 15.4 m/ha (SD = 12.33) with a median 12.8 m/ha of roads in the watershed(s) where they are embedded. Road density ranged from 0.07 m/ha at Koyukuk NWR in Alaska to 104.6 m/ha at Seal Beach NWR near Los Angeles, California. On average, 20.4% (SD = 23.2) of the watershed(s) in which refuges are embedded are in permanent conservation protection. However, the median watershed protection was 9.2% and ranged from <1% to 97.2% for the Elk NWR in Wyoming.

Given their climate gradient and anthropogenic footprint, 300 refuges were categorized as having low adaptive capacity. Of the remaining 201, 112 were categorized as having moderate adaptive capacity and 89 as having high adaptive capacity.

Evaluating vulnerability

When our categories for sensitivity and adaptive capacity were combined into an index of resilience (Fig. 1), we categorized 144 refuges as having high resilience, 284 with moderate resilience, and 73 with low resilience. Vulnerability was widely distributed across the U.S. and not delineated by biome or region, although many of the reserves that were highly or moderately vulnerable were in northern or in populous coastal zones (Table 2, Fig. 3). Seventy-six refuges were classified as having high vulnerability and 264 as having low vulnerability. Of the 161 refuges classified as having moderate vulnerability, 104 had intermediate exposure and resilience, 27 had high exposure and high resilience, and 30 had low exposure and low resilience. Refuges were separated into management strategies based on resilience and exposure and a range of management strategies existed across biomes and regions (Table 3, Fig. 4).

Discussion

In our analysis, the vulnerability of individual refuges, including the main components of resilience (sensitivity and adaptive capacity) and exposure to climate change, varies spatially

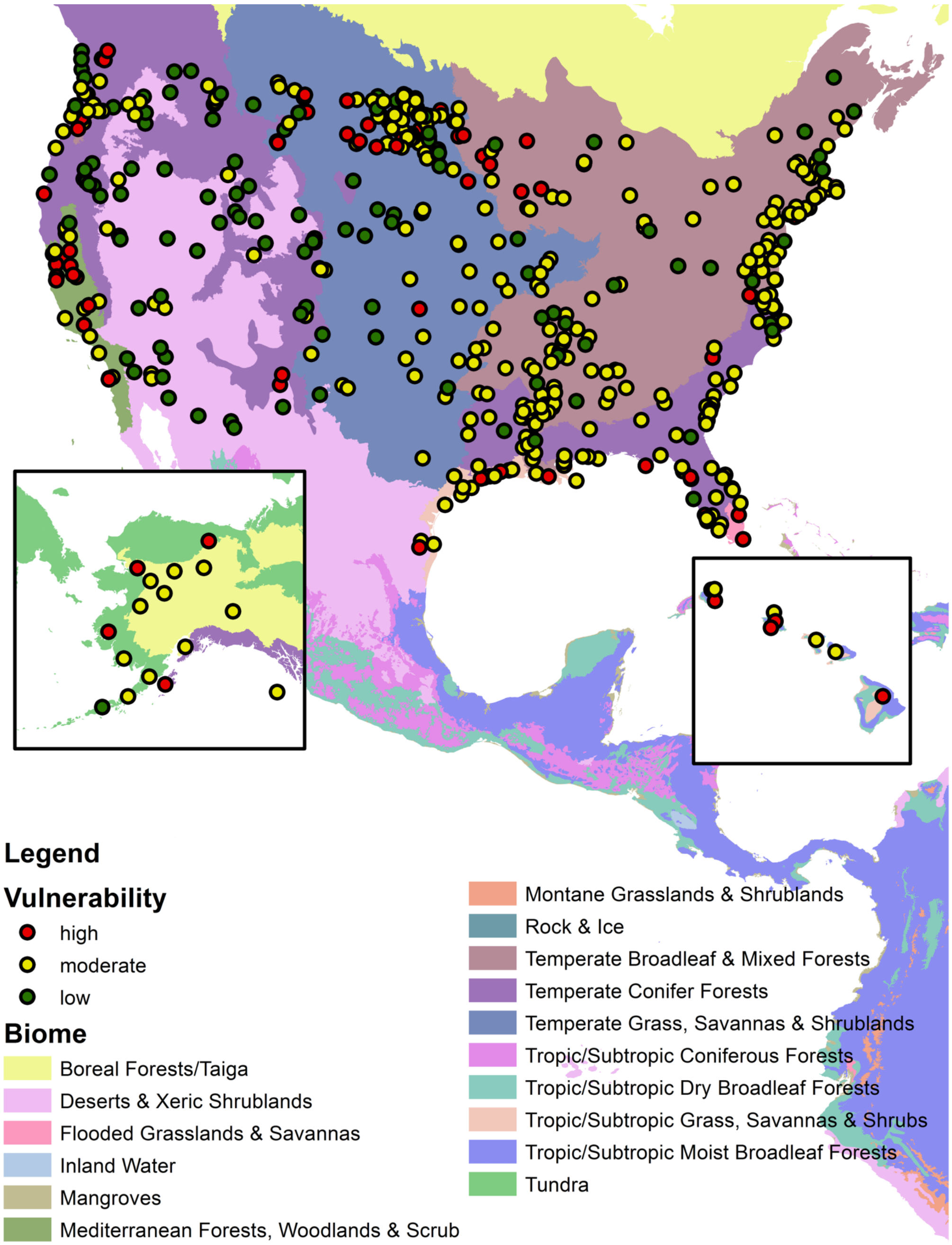

Fig. 3. Refuges sorted into high, moderate, and low vulnerability categories. Major biomes (Olson et al. 2001) are also shown.

within and among biomes. Therefore, we suggest that spatial variability in resilience and exposure be used to define suites of management actions that captilize on local conditions to facilitate adaptation and help spread ecological risk across the reserve network.

Various management approaches are available to facilitate adaptation in reserves, and the rationale underlying the choice of adaptation goals for any individual refuge will be influenced

Table 3. Count of refuges assigned to each management category by biome.

Biome	Management category for adaptation framework							
	NA	NA or FT	FT	EM or FT	EM	EM or R	NA or R	R
Boreal forests/taiga	7 (87)	1 (13)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Deserts and xeric shrublands	4 (9)	0 (0)	0 (0)	2 (5)	1 (2)	2 (5)	22 (50)	13 (29)
Flooded grasslands and savannas	0 (0)	0 (0)	0 (0)	2 (100)	0 (0)	0 (0)	0 (0)	0 (0)
Mediterranean forests, woodlands and scrub	1 (6)	1 (6)	2 (13)	9 (56)	0 (0)	2 (13)	1 (6)	0 (0)
Temperate broadleaf and mixed forests	0 (0)	7 (7)	2 (1)	2 (1)	7 (7)	68 (64)	7 (7)	14 (13)
Temperate conifer forests	3 (3)	4 (4)	0 (0)	10 (11)	13 (14)	29 (32)	21 (23)	11 (12)
Temperate grasslands, savannas and shrublands	9 (9)	17 (17)	2 (2)	5 (5)	4 (4)	38 (37)	12 (12)	15 (15)
Tropical and subtropical dry broadleaf forests	0 (0)	0 (0)	0 (0)	2 (100)	0 (0)	0 (0)	0 (0)	0 (0)
Tropic/subtropical grass, savannas and shrubs	0 (0)	0 (0)	1 (6)	4 (24)	4 (24)	8 (47)	0 (0)	0 (0)
Tropic/subtropic moist broadleaf forests	0 (0)	0 (0)	0 (0)	1 (100)	0 (0)	0 (0)	0 (0)	0 (0)
Tundra	3 (50)	2 (33)	0 (0)	0 (0)	0 (0)	0 (0)	1 (17)	0 (0)

Notes: Values in parentheses are percentages. Management category abbreviations are: NA, natural adaptation; FT, facilitated transition; EM, ecosystem maintenance; R, refugia.

by local goals, planning timescales, uncertainty, and risk (Heller and Zavaleta 2009). Retrospective strategies, which maintain historic conditions, are generally risk-averse because they focus on tested conservation practices such as the mitigation of non-climatic stressors, habitat restoration, and land acquisition based on current ecological patterns. Retrospective strategies are most likely to meet conservation goals in refuges with slow rates of environmental change. Even in areas with rapid change, retrospective strategies may be valuable over the short term as a bet-hedging strategy when the uncertainty about future conditions is high and to give extant species time to transition to future conditions.

Prospective actions, which seek to facilitate ecological transitions that are congruent with future climatic conditions, are riskier in the short term because they mold future conditions based on expectations or model outcomes (Heller and Zavaleta 2009). Prospective strategies can increase the likelihood of systems adapting without intervention (natural transition) by ensuring landscape connectivity along climate gradients or with forecasts of ecosystem change that inform more active interventions (Chapin et al. 2007, Murphy et al. 2010). More radical prospective strategies may include management actions to foster ecological transition to a desirable future condition. Desirable future conditions imply active choices by managers about future habitat and species composition, and might involve translocating plant and animal species or genotypes to places they have never occurred (McLachlan et al. 2007), developing genetically modified organisms (e.g., acid tolerant corals), or hydrologic management in anticipation of sea-level rise.

The adaptation goals for any individual refuge will depend on local conditions and constraints, but coordination across the reserve system could enable the NWRS to meet a continental-scale adaptation goal of minimizing species extinction in ways that might not be perceived by local refuge managers. The system-wide mission of the NWRS specifically highlights the importance of maintaining biological integrity, diversity, and environmental health for future generations. Climate change, in conjunction with other anthropogenic drivers, has the potential to cause mass extinction (Barnosky et al. 2011, Thomas et al. 2004). Across taxa, 20–30% of all species will face an increasingly high risk of extinction if global mean temperatures exceed 2 to 3°C above pre-industrial levels (IPCC 2007). The high likelihood of species extinctions and shifts in climate-envelopes across large geographic areas demand that refuges be managed as a true system, with consideration given to spatial scales larger than the adjacent lands immediately surrounding any given refuge. With information about relative rates of climate change exposure and resilience of refuges across broader geographic areas, refuge managers may be able to address local needs and contribute to continental-scale goals like minimizing species extinction. Managers will have the opportunity to coordinate management approaches among refuges in order to spread the ecological risks associated with climate change and to increase the likelihood of success given spatial variability in

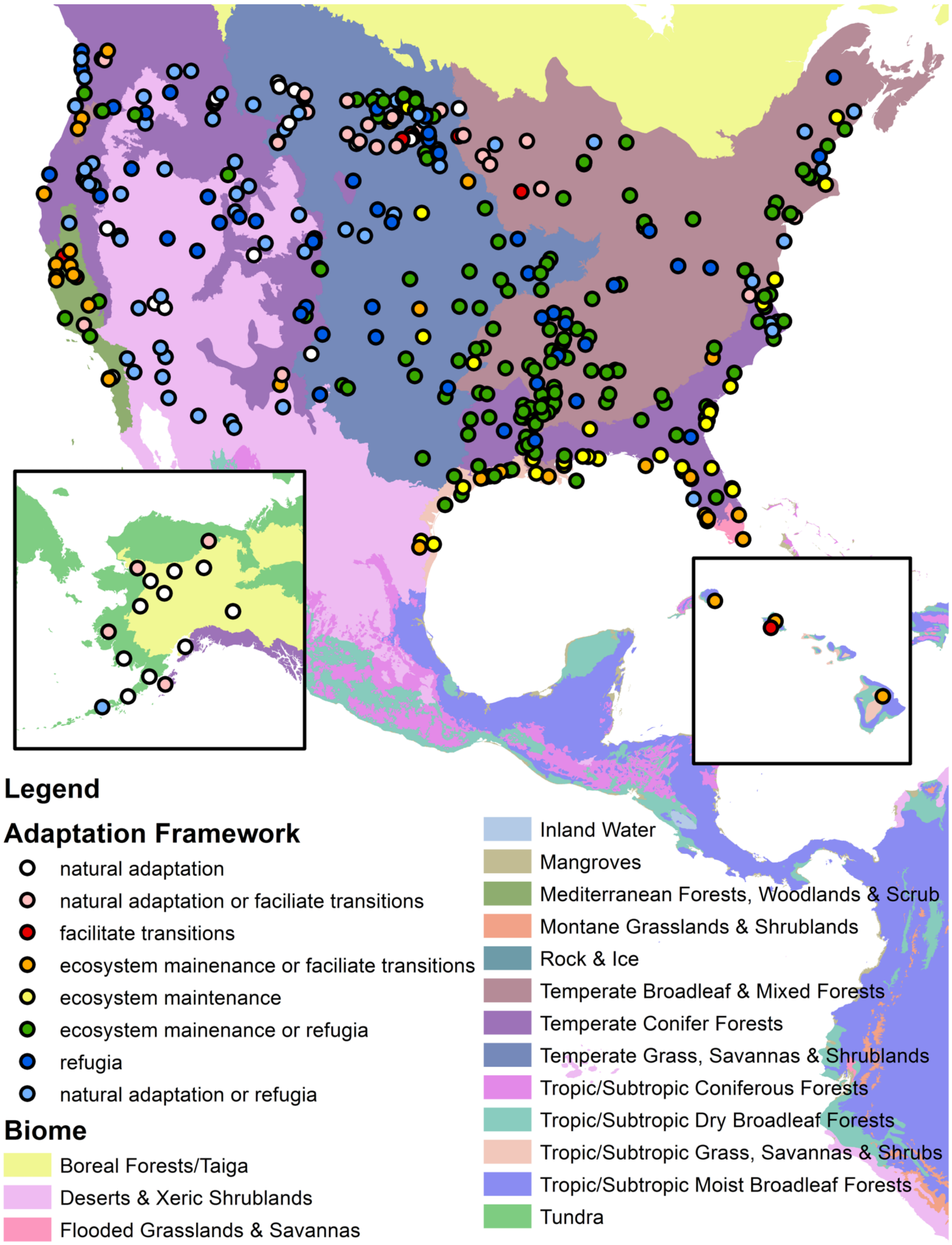

Fig. 4. Refuges sorted into management strategies for facilitating adaptation based on climate change exposure and resilience (sensitivity and adaptive capacity). Major biomes (Olson et al. 2001) are also shown.

vulnerability.

Adaptation framework based on vulnerability

To coordinate individual reserves under the continental-scale adaptation goal of minimizing species extinction, we conceptually define 4 divergent management strategies that facilitate adaptation based on resilience (sensitivity and adaptive capacity) and climate change exposure (Fig. 2). The categories of refugia, ecosystem maintenance, "natural" adaptation, and facilitate transitions help to delineate whether retrospective or prospective approaches are more appropriate. In all cases, an adaptive management framework will be vital to measure progress toward adaptation goals and to maintain flexibility to react to emerging conditions (Griffith et al. 2009, Lawler et al. 2008).

Refugia.—We suggest that reserves with high resilience and low exposure to climate change could serve as refugia. These reserves will function as strongholds where historic ecological conditions and the associated species assemblages may be maintained over foreseeable climate-change scenarios. Appropriate management activities in these reserves, at least in the short term, would be retrospective and focused on maintaining historic conditions (e.g., managing invasive, exotic species). To maintain species assemblages in refugia, managers may use standard conservation principles to ensure that the reserve size and connectivity are adequate to maintain viability. If not already in place, inventories to document which species are represented and protected in these areas should receive high priority (Dawson et al. 2011). Refugia are also potential sources of biodiversity for other transitioning reserves, so these lands should be assessed for their potential to serve as population sources within the larger region or biome. To this end, partnerships and other collaborative land ownership regimes can help to maintain or enhance connectivity and other landscape qualities that confer resilience. Even refugia may eventually experience climate change and reduced resilience, so maintaining historic conditions in perpetuity may not be a viable long-term management goal.

In our spatial analysis of ecosystem vulnerability, we identified refuges with high resilience. However, in agreement with Scott et al. (2004), our analysis indicates that most refuges within the NWRS are small islands within an anthropogenic and fragmented matrix. In addition, most refuges are undergoing some directional climate change. Therefore, modeling and monitoring of exposure (e.g., climate, sea level) and resilience (e.g., watershed protection and connectivity) provide forewarning of the need to reassess management strategies.

Ecosystem maintenance.—Reserves with low resilience and low exposure to climate change may function as areas where tested conservation principals can work toward ecosystem maintenance. We suggest that adaptation options in these areas, at least in the near future, should be retrospective with the goal of maintaining or restoring historic conditions. Reserves working toward ecosystem maintenance will benefit from standard conservation approaches that manage anthropogenic stressors such as fragmentation, land-use change, invasive species, contamination, and over-exploitation. Within the NWRS, where many refuges are small islands in a fragmented landscape, managers should ensure that the plants, animals, and habitats represented are redundant within the network (Griffith et al. 2009). The low resilience of these refuges may increase the likelihood of ecological transition into non-desirable states. In this case, these refuges may be important for testing the viability and cost of retrospective restoration efforts. In addition, ecosystem maintenance reserves have potential to serve as stepping stones for species shifts across the landscape.

"Natural" adaptation.—We suggest that reserves with high resilience (low sensitivity and high adaptive capacity) and high exposure to climate change are compatible with "natural" adaptation. Within a reserve network, these areas present an opportunity to study how species and ecosystems adapt to directional change without deliberate human intervention. Scientific uncertainty about how ecosystems will respond to climate change is high, so there is a need for some reserves to function as research areas to learn about the costs and benefits of novel assemblages, phenological shifts, dispersal constraints, and functional reorganization. Monitoring in "natural" adaptation reserves will provide the background and context to understand how rapid climate change affects extant ecosystems and landscapes. Context monitoring, which tracks a suite of variables that are not related to specific management actions, may prove valuable in these reserves (Holthausen et al. 2005). Context monitoring has been criticized for being inefficient and unfocused (Nichols and Williams 2006), but climate change will likely interact with other local social-ecological changes to create unexpected ecological changes that may not be captured by narrowly focused monitoring pro-

grams.

Although we suggest there is a need to learn about how species and ecosystems will adapt without intervention, uncertainty about ecosystem change is high, so management interventions may be necessary when unanticipated threats emerge (e.g., novel, injurious, invasive species) or species extinction is likely. In addition, the landscape matrix where these reserves occur may foster a diverse, spatial mosaic of adaptation strategies. Geographic diversity in adaptation approaches would allow for learning about adaption without intervention, testing prospective approaches, and engaging in retrospective strategies that maintain historic conditions. The use of retrospective approaches may be costly or impossible to achieve in the long term (Hobbs and Harris 2001, Choi 2007). However, in the short-term, retrospective adaptation may be an important precautionary strategy where future conditions are highly uncertain or when rare and/or endemic species would benefit from additional time to cope with changes.

Understanding directional climate change should be a priority for research and adaptive management on these reserves because they will function to reduce the uncertainty about future conditions for the entire reserve network. Therefore, an understanding of likely future conditions will be necessary. Spatial forecasts based on climate models and vulnerability assessments for species of concern provide tools to understand future conditions. Forecasts should be treated as hypotheses and linked to monitoring efforts in order to reduce uncertainty (Lawler et al. 2008).

Finally, these reserves also present an opportunity to form conservation partnerships that protect resilience elements in regions where development has not yet irreparably impaired landscape integrity and connectivity adjacent to reserves. For example, many rural refuges in the contiguous U.S. would benefit from these partnerships because, although natural cover is available in the surrounding landscape, protection tends to be low and human populations are increasing (Svancara et al. 2009). Even large Alaskan refuges would benefit from efforts that maintain large-scale connectivity as biomes shift (Murphy et al. 2010).

Facilitated transitions.—Reserves with low resilience (high sensitivity and low adaptive capacity) and high climate-change exposure can function as areas to test active management to facilitate transitions. These areas have a high probability of ecological reorganization, so managers need to be aware of probable future climate conditions and the species assemblages that could be supported under emerging conditions. When transformations are likely, managers must consider whether the likely future conditions are desirable. In reserves managed to facilitate transitions, managers will engage in prospective actions that include risk and uncertainty. Lower-risk prospective actions include assessing the potential of the reserve to serve as a "stepping stone" for dispersal to other areas and increasing landscape connectivity based on probable future development patterns. However, in some cases, these areas may benefit from higher-risk management due to their isolation and small size. Higher-risk prospective actions include habitat manipulation and introduction of new species assemblages. These activities provide an opportunity to document and disseminate information about whether prospective management can successfully facilitate the non-linear and complex responses of ecosystems.

Reserves with high levels of anthropogenic stressors (low resilience) may have difficulty identifying the impacts of climate change because these effects may be masked or operate synergistically with other drivers. Managers mistakenly focusing on the wrong drivers of change may apply ineffective (and costly) conservation strategies.

Uncertainty

Several sources of uncertainty are inherent in any vulnerability assessment. These range from model-based uncertainty (the model structure and variables that were included) to uncertainty in parameter values used in the application of the model (IPCC 2007). Our model structure was derived from the definition of vulnerability (exposure, sensitivity and adaptive capacity). We chose the historic trend in annual temperature to represent exposure to climate change because there is more certainty that ecosystem change and biodiversity loss can be linked to temperature than to other climate variables (IPCC 2007). Other potentially important measures of climate change include precipitation and sea level rise. Any of these variables could be represented as historical or projected means, extremes, or variance. For sensitivity and adaptive capacity, we selected variables that were likely to influence many types of ecosystems and species. Variables tailored to a specific ecosystem or species could also be used and would likely change the outcome of the analysis. The outcome of our vulnerability assessment was also influenced by the thresholds (parameters) we chose to represent breaks between high, moderate and low categories. We used scientific literature to define these thresholds, but in most cases, a range of values may be meaningful. Finally the accuracy of the GIS data layers provides a source of uncertainty.

Adaptive management is a process for planning and managing in the face of inevitable uncertainty (Nichols et al. 2011). Adaptation to changes in climate, land use, and societal goals requires adaptive adjustments that incorporate new information as it becomes available and to respond to emerging conditions, many of which will be unanticipated. We suggest that transparent vulnerability assessments can be useful for strategic planning because the spatial variation in vulnerability helps spread ecological risk across a conservation network. However, the information used and variables engaged should be constantly reassessed and refined to make sure that the refuges categorized as refugia, ecosystem maintenance, "natural" adaptation, and facilitated transitions are able to function in that capacity. In addition, the general approach of using spatial variability in vulnerability for strategic planning may be useful at different spatial scales (e.g., regional) or when tailored to a species of concern.

Conclusion

In a world with accelerating climate change, we suggest that conservation reserve networks should be focused on minimizing species extinction by facilitating the adaptation of fish, wildlife, and habitats to emerging conditions (Scott et al. 2008). However, adaptation approaches used by individual managers within a reserve network need to be strategically coordinated to meet the continental-scale goal of minimizing species extinction while being responsive to local conditions and stressors. We use the concept of vulnerability to develop a strategic adaptation framework for coordinating management approaches across conservation reserves. Based on spatial variability in resilience and exposure to climate change, managers could tailor local-scale adaptation approaches toward refugia, ecosystem maintenance, "natural" adaptation, or facilitated transitions. This adaption framework helps define the role of individual reserves in responding to climate change (and other stressors) within a larger network. We suggest that this adaptation framework be used to identify opportunities for individual reserves to contribute substantively to continental-scale species conservation. The actual strategy or strategies selected on a particular reserve would integrate this network-scale goal with local needs and priorities. In our case study, we applied the framework to the NWRS, a network of over 500 refuges across the U.S. However, the framework could also be applied at regional or smaller scales or across networks with diverse management objectives (e.g., wilderness areas, National Park Service network, and private or public lands managed as working landscapes). In addition, assessments of ecosystem vulnerability could include other variables not considered in this study (e.g., future projections of climate and population). We suggest that our approach to the strategic landscape-level conservation of biodiversity in the face of rapid climate change has broad application to reserve networks elsewhere in the world.

Acknowledgments

D.R.M. received support from the Resilience and Adaptation Program (IGERT, NSF), EPSCOR Alaska, the Center for Global Change, EWHALE, and the USFWS through their Student Career Employment Program. We also thank Drs. J. Michael Scott and Dennis B. Griffith for helpful comments on previous versions of this manuscript. This is EWHALE Publication 91.

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Appendix

Table A1. Exposure, sensitivity and adaptive capacity variable values by refuge.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Agassiz	0.037	No	No	0.162	25	7.8	48.4
Alamosa	0.000	No	No	0.117	14	12.6	31.2
Alaska Maritime	0.016	Yes	Yes	19.119	2510	0.3	49.3
Alaska Peninsula	0.031	No	Yes	3.122	2375	0.1	62.3
Alligator River	0.010	Yes	No	0.449	4	9.3	42.6
Amagansett	0.019	No	No	0.005	0	77.7	8.7
Anaho Island	0.032	No	No	0.020	70	4.7	69.8
Anahuac	0.009	Yes	No	0.301	7	14.1	6.7
Ankeny	0.016	No	Yes	0.049	44	19.7	30.0
Antioch Dunes	0.025	No	Yes	0.005	2	15.8	10.9
Appert Lake	0.029	No	No	0.015	14	9.4	6.3
Aransas	0.002	No	Yes	0.480	8	10.7	9.4
Arapaho	0.017	No	No	0.398	317	9.2	57.3
Archie Carr	0.000	No	Yes	0.257	2	35.8	35.1
Arctic	0.039	Yes	Yes	3.428	2621	0.2	67.4
Ardoch	0.031	No	No	0.051	10	13.5	1.3
Aroostook	0.002	No	No	0.098	90	6.7	18.0
Arrowwood	0.028	No	Yes	0.202	64	11.6	3.7
Arthur R. Marshall Loxahatchee	0.017	Yes	Yes	0.331	1	22.0	49.5
Ash Meadows	0.014	No	Yes	0.138	278	4.5	93.7
Assabet River	0.000	No	No	0.045	31	40.0	19.5
Atchafalaya	0.000	No	Yes	0.147	6	7.6	6.3
Attwater Prairie Chicken	0.000	No	No	0.149	30	15.4	1.2
Audubon	0.019	No	Yes	0.079	14	9.2	7.7
Baca	0.000	No	No	0.267	98	7.2	59.3
Back Bay	0.011	No	No	0.162	4	13.9	18.6
Balcones Canyonlands	0.000	No	No	0.219	239	22.9	2.4
Bald Knob	0.000	No	No	0.111	18	13.6	6.7
Bamforth	0.000	No	No	0.031	35	10.5	34.7
Bandon Marsh	0.019	No	No	0.037	13	14.5	26.3
Banks Lake	0.000	No	No	0.055	18	15.1	1.7
Baskett Slough	0.023	No	Yes	0.050	51	24.4	3.6
Bayou Cocodrie	0.000	No	Yes	0.131	3	9.7	14.7
Bayou Sauvage	0.000	No	Yes	0.211	1	9.7	2.7
Bayou Teche	0.000	Yes	Yes	0.154	2	12.6	7.5
Bear Butte	0.000	No	No	0.011	1	6.1	12.6
Bear Lake	0.021	No	No	0.150	32	8.9	35.4
Bear River	0.003	No	No	0.157	19	4.6	35.4
Bear Valley	0.004	No	No	0.051	406	10.6	62.2
Becharof	0.043	No	Yes	1.128	1340	0.1	70.2
Benton Lake	0.021	No	No	0.087	40	6.5	26.6
Big Boggy	0.000	No	No	0.054	2	11.8	7.8
Big Branch Marsh	0.000	No	Yes	0.157	5	15.3	7.7
Big Lake	0.000	No	No	0.152	3	15.1	2.5
Big Muddy	0.000	Yes	No	1.047	150	18.4	2.3
Big Oaks	0.000	No	No	0.224	57	22.0	8.4
Big Stone	0.023	No	No	0.087	39	12.2	6.5
Bill Williams River	0.016	No	Yes	0.068	232	5.7	79.2
Bitter Creek	0.029	No	No	0.088	920	18.8	18.0
Bitter Lake	0.000	No	Yes	0.259	56	9.7	23.4
Black Bayou Lake	0.000	No	No	0.078	5	15.5	3.6
Black Coulee	0.032	No	No	0.025	50	5.3	5.4
Blackbeard Island	0.000	No	Yes	0.104	27	13.8	21.6
Blackwater	0.012	No	No	0.137	2	7.7	7.0
Blue Ridge	0.000	Yes	Yes	0.036	304	6.2	52.6
Bogue Chitto	0.000	No	No	0.324	16	16.7	11.0
Bombay Hook	0.019	No	No	0.152	6	8.9	10.3
Bon Secour	0.000	No	Yes	0.149	21	13.2	2.7
Bond Swamp	0.000	No	No	0.179	46	21.5	3.6
Bone Hill	0.021	No	No	0.014	19	11.5	7.0
Bosque Del Apache	0.008	Yes	Yes	0.185	422	13.8	44.5

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Bowdoin	0.031	No	Yes	0.076	32	7.2	7.3
Boyer Chute	0.019	No	No	0.074	32	21.2	1.7
Brazoria	0.011	No	No	0.237	6	23.9	5.1
Browns Park	0.013	Yes	No	0.148	222	6.7	76.0
Brumba	0.000	No	No	0.044	13	10.4	6.9
Buenos Aires	0.015	No	No	0.374	1198	7.4	74.9
Buffalo Lake	0.000	No	No	13.181	717	12.7	3.5
Cabeza Prieta	0.023	No	No	0.544	743	4.4	89.2
Cache River	0.000	No	No	0.982	26	12.4	9.4
Caddo Lake	0.000	No	No	0.059	52	14.3	3.4
Cahaba River	0.000	No	No	0.088	82	18.6	11.8
Caloosahatchee	0.011	No	Yes	0.001	0	na	na
Camas	0.000	No	No	0.094	24	12.2	29.3
Cameron Prairie	0.000	No	No	0.061	1	9.1	10.4
Camp Lake	0.026	No	No	0.036	43	10.4	5.1
Canaan Valley	0.000	No	No	0.209	388	14.8	25.4
Canfield Lake	0.022	No	No	0.012	13	10.4	5.1
Cape May	0.009	No	No	0.326	10	18.2	20.0
Cape Meares	0.022	Yes	Yes	0.015	67	20.9	50.9
Cape Romain	0.000	No	Yes	0.234	9	12.4	44.7
Carolina Sandhills	0.010	Yes	No	0.244	115	18.9	3.8
Castle Rock	0.000	No	No	0.002	0	na	na
Cat Island	0.000	No	No	0.172	29	15.0	2.8
Catahoula	0.000	No	No	0.219	20	13.2	18.2
Cedar Island	0.000	No	No	0.148	7	14.5	22.0
Cedar Keys	0.000	No	Yes	0.098	0	0.1	36.7
Cedar Point	0.000	No	No	0.040	4	3.5	0.5
Charles M. Russell	0.026	Yes	Yes	0.754	392	5.0	21.4
Chase Lake	0.024	No	Yes	0.047	27	9.4	6.3
Chassahowitzka	0.011	Yes	No	0.168	3	40.6	24.1
Chautauqua	0.002	No	No	0.738	10	16.5	3.2
Cherry Valley	0.014	No	No	0.147	365	26.7	20.5
Chickasaw	0.000	No	No	0.277	47	12.5	4.1
Chincoteague	0.000	Yes	No	0.492	5	16.8	14.2
Choctaw	0.000	Yes	No	0.087	8	9.3	1.0
Cibola	0.017	Yes	Yes	0.174	33	6.2	77.6
Clarence Cannon	0.010	No	No	0.104	6	13.3	1.9
Clarks River	0.000	No	No	0.189	40	18.5	4.3
Clear Lake	0.012	No	No	0.134	170	10.6	62.2
Coachella Valley	0.023	No	Yes	0.044	81	9.0	63.2
Cokeville Meadows	0.001	No	No	0.234	109	9.3	67.3
Cold Springs	0.007	No	No	0.037	49	9.8	9.3
Coldwater River	0.000	No	No	0.128	8	15.0	3.1
Columbia	0.013	No	No	0.181	187	10.6	15.2
Colusa	0.012	No	No	0.080	7	11.9	3.5
Conboy Lake	0.000	No	No	0.096	89	13.8	32.0
Conscience Point	0.015	No	No	0.008	8	77.7	8.7
Copalis	0.002	No	No	0.350	61	7.6	57.4
Cottonwood Lake	0.027	No	No	0.024	24	11.1	6.1
Crab Orchard	0.000	No	No	0.184	108	17.9	9.2
Crane Meadows	0.031	No	No	0.118	24	13.3	1.5
Creedman Coulee	0.033	No	No	0.036	32	7.6	10.7
Crescent Lake	0.020	No	No	0.262	109	7.0	4.4
Crocodile Lake	0.019	No	Yes	0.165	4	34.3	57.1
Cross Creeks	0.000	No	No	0.119	66	15.1	10.3
Crystal River	0.011	Yes	Yes	0.119	3	40.8	23.7
Currituck	0.011	No	No	0.322	4	13.9	18.6
Cypress Creek	0.000	No	No	0.302	33	14.6	9.6
Dahomey	0.000	No	No	0.085	2	15.9	7.0
Dakota Lake	0.000	No	No	0.112	21	11.5	7.0
D’arbonne	0.000	No	No	0.111	33	14.1	3.3
Deep Fork	0.000	No	No	0.201	83	16.9	1.9
Deer Flat	0.023	Yes	No	0.992	180	11.9	23.2
Delevan	0.012	No	No	0.066	21	11.9	3.5
Delta	0.000	No	No	0.183	1	13.8	32.0
Des Lacs	0.021	No	No	0.411	67	12.7	5.1

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Desert	0.024	No	Yes	0.948	2216	7.1	92.3
Desoto	0.011	No	No	0.070	14	28.2	3.1
Detroit River Inter	0.000	No	No	0.549	21	14.7	1.4
Don Edwards San Francisco Bay	0.021	No	Yes	0.278	15	36.0	18.6
Driftless Area	0.010	Yes	No	2.869	297	14.2	5.0
Dungeness	0.025	No	Yes	0.164	30	8.7	74.1
Eastern Neck	0.013	No	No	0.046	4	8.7	4.9
Eastern Shore Of Virginia	0.000	No	No	0.114	11	5.5	2.0
Edwin B. Forsythe	0.017	No	No	0.619	31	32.1	35.0
Elizabeth Alexandra Morton	0.013	No	No	0.033	16	77.7	8.7
Ellicott Slough	0.019	No	Yes	0.052	74	16.7	13.9
Emiquon	0.000	No	No	0.092	39	14.9	2.5
Erie	0.000	No	No	0.243	113	16.3	5.2
Ernest F. Hollings Ace Basin	0.018	No	No	0.103	11	16.7	8.2
Eufaula	0.000	No	No	0.143	26	13.6	12.1
Fallon	0.018	No	No	0.116	1	6.6	74.8
Featherstone	0.000	No	No	0.025	11	43.8	10.3
Felsenthal	−0.008	Yes	No	0.817	28	11.8	5.0
Fern Cave	0.000	No	No	0.019	181	17.2	7.3
Fish Springs	0.002	No	No	0.095	63	4.6	91.4
Flattery Rocks	0.000	No	No	0.350	79	11.7	60.6
Flint Hills	0.000	No	No	0.116	23	12.4	4.6
Florence Lake	0.022	No	No	0.040	25	9.8	5.9
Florida Panther	0.017	Yes	No	0.099	1	11.6	60.0
Fort Niobrara	0.008	No	No	0.094	103	5.5	7.8
Fox River	0.020	No	No	0.029	2	15.4	2.1
Franz Lake	0.003	No	No	0.016	52	30.4	24.1
Glacial Ridge	0.021	No	No	0.117	53	12.6	2.9
Grand Bay	0.000	No	Yes	0.132	5	15.0	2.9
Grand Cote	0.000	No	No	0.093	13	14.1	9.0
Gravel Island	0.000	No	No	0.047	0	0.1	0.1
Grays Harbor	0.015	No	No	0.026	45	13.7	26.8
Grays Lake	0.008	Yes	No	0.166	60	6.6	32.4
Great Bay	0.015	No	No	0.144	26	25.1	11.4
Great Dismal Swamp	0.001	No	No	0.335	14	18.8	16.6
Great Meadows	0.005	No	No	0.211	56	40.0	19.5
Great River	0.000	No	No	0.958	49	12.8	1.4
Great Swamp	0.013	No	No	0.060	37	55.2	24.0
Green Bay	0.000	No	No	0.075	11	0.1	0.1
Grulla	0.000	No	No	0.040	17	13.0	1.9
Guadalupe-Nipomo Dunes	0.005	No	Yes	0.117	46	13.5	37.9
Hagerman	0.000	No	No	0.091	20	13.9	18.9
Hailstone	0.026	No	No	0.044	31	9.9	6.3
Hakalau Forest	0.014	Yes	Yes	0.559	1447	12.1	0.47
Halfbreed Lake	0.026	No	No	0.055	12	9.9	6.3
Half-Way Lake	0.024	No	No	0.007	10	9.4	6.3
Hamden Slough	0.033	Yes	No	0.126	16	13.1	8.4
Hanalei	0.018	No	No	0.025	37	15.7	0.36
Handy Brake	0.000	No	No	0.027	13	12.4	3.9
Harbor Island	0.000	No	No	0.022	25	0.1	0.1
Harris Neck	0.000	No	No	0.034	18	13.8	21.6
Hart Mountain	0.010	Yes	Yes	0.498	1043	6.4	74.8
Hatchie	0.000	No	No	0.073	36	13.2	2.4
Havasu	0.018	No	Yes	0.352	497	8.6	68.0
Hewitt Lake	0.031	No	No	0.022	25	7.7	7.6
Hiddenwood	0.019	No	No	0.015	16	9.2	7.7
Hillside	0.000	No	No	0.156	19	14.8	5.8
Hobart Lake	0.000	No	No	0.044	25	11.6	41.9
Hobe Sound	0.010	No	Yes	0.556	0	22.4	47.8
Holla Bend	0.000	No	No	0.059	12	13.7	21.7
Holt Collier	0.000	No	No	0.086	15	15.9	7.0
Hopper Mountain	0.005	No	Yes	0.031	586	12.7	61.3
Horicon	0.004	No	No	0.126	28	19.8	3.5
Huleia	0.017	Yes	No	0.009	6	15.7	0.36
Humboldt Bay	0.016	No	Yes	0.244	23	12.9	26.6

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Hutchinson Lake	0.018	No	No	0.015	13	9.4	6.3
Hutton Lake	0.000	No	No	0.044	7	10.5	34.7
Imperial	0.016	Yes	Yes	0.232	188	6.2	77.6
Innoko	0.037	Yes	No	2.138	732	0.3	28.5
Iroquois	0.015	No	No	0.053	22	16.9	4.0
Island Bay	0.012	No	Yes	0.035	1	32.7	54.6
Izembek	0.019	No	Yes	0.513	1705	0.2	58.5
J. Clark Salyer	0.012	No	No	0.502	48	11.8	4.3
J.N. 'Ding' Darling	0.014	No	Yes	0.093	2	30.8	43.4
James Campbell	0.016	No	No	0.029	24	30.7	0.35
James River	0.019	No	No	0.058	24	13.0	4.6
John H. Chafee	0.018	No	No	0.082	47	35.8	14.7
John Hay	0.013	No	No	0.006	48	17.3	14.9
John Heinz At Tinicum	0.015	No	No	0.030	15	61.5	11.3
John W. And Louise Seier	0.018	No	No	0.040	28	3.2	6.4
Johnson Lake	0.023	No	No	0.049	48	10.6	2.8
Julia Butler Hansen	0.011	No	No	0.151	54	17.2	15.6
Kakahaia	0.017	No	No	0.004	18	14.7	0.15
Kanuti	0.036	No	No	0.909	877	0.2	37.1
Karl E. Mundt	0.000	No	Yes	0.044	135	12.3	9.4
Kealia Pond	0.018	No	No	0.173	4	17.9	0.28
Kellys Slough	0.021	No	No	0.036	9	13.2	3.4
Kenai	0.032	Yes	No	1.607	1848	2.0	67.0
Kern	0.016	No	No	0.072	7	22.0	6.3
Key Cave	0.000	No	No	0.019	33	16.3	4.5
Kilauea Point	0.018	No	No	0.029	5	15.7	0.36
Kirwin	0.000	No	No	0.094	30	11.7	1.0
Klamath Marsh	0.019	No	No	0.251	92	12.0	70.0
Kodiak	0.030	Yes	Yes	1.738	1239	0.5	54.7
Kofa	0.022	No	No	0.610	1223	5.7	80.5
Kootenai	0.016	No	Yes	0.056	104	10.8	58.4
Koyukuk	0.037	Yes	No	1.470	908	0.1	45.7
Lacassine	0.002	No	No	0.141	2	8.1	8.4
Lacreek	0.003	No	No	0.131	89	7.2	2.7
Laguna Atascosa	0.001	Yes	Yes	0.603	10	25.2	6.2
Lake Alice	0.000	No	No	0.103	12	10.4	6.9
Lake Andes	0.006	No	No	0.094	21	8.4	6.8
Lake George	0.025	No	No	0.051	34	9.4	6.3
Lake Ilo	0.036	No	No	0.044	29	9.7	2.8
Lake Isom	0.000	No	No	0.057	4	13.1	5.3
Lake Mason	0.018	Yes	No	0.247	185	8.0	15.4
Lake Nettie	0.011	No	Yes	0.053	17	10.4	5.1
Lake Ophelia	0.000	No	Yes	0.156	9	10.1	23.1
Lake Otis	0.035	No	No	0.015	16	10.4	5.1
Lake Patricia	0.021	No	No	0.022	11	6.1	3.3
Lake Thibadeau	0.027	No	No	0.058	57	7.7	7.6
Lake Wales Ridge	0.003	No	No	1.052	25	14.8	15.5
Lake Woodruff	0.000	No	Yes	0.126	17	17.4	34.0
Lake Zahl	0.000	No	No	0.054	21	11.9	3.7
Lambs Lake	0.000	No	No	0.022	14	12.5	0.9
Lamesteer	0.026	No	No	0.015	26	7.2	10.5
Las Vegas	0.028	No	No	0.069	106	8.6	19.7
Lee Metcalf	0.021	No	No	0.055	37	9.8	72.3
Leslie Canyon	0.015	No	No	0.149	681	8.1	12.9
Lewis And Clark	0.005	No	No	0.099	76	22.0	15.5
Little Goose	0.000	No	No	0.011	10	12.5	0.9
Little Pend Oreille	0.020	No	No	0.475	1044	12.8	53.0
Little River	−0.005	Yes	No	0.999	68	15.7	7.0
Little Sandy	0.000	No	No	0.037	14	16.9	0.6
Logan Cave	0.000	No	No	0.008	32	19.6	7.4
Long Lake	0.030	No	Yes	0.144	31	9.4	6.3
Lords Lake	0.000	No	No	0.025	15	11.9	4.7
Lost Lake	0.020	No	No	0.022	23	10.4	5.1
Lost Trail	0.020	No	Yes	0.060	248	14.6	51.7
Lostwood	0.001	No	Yes	0.188	65	9.6	7.4
Lower Hatchie	0.000	No	No	0.123	55	11.5	5.2

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Lower Klamath	0.017	No	No	0.295	105	10.6	62.2
Lower Rio Grande Valley	0.005	Yes	Yes	0.945	175	16.5	2.8
Lower Suwannee	0.000	No	Yes	0.691	20	16.7	15.7
Mackay Island	0.009	No	No	0.080	2	14.0	18.5
Malheur	−0.001	No	No	0.590	352	9.1	67.6
Mandalay	0.012	Yes	No	0.147	1	7.4	3.4
Maple River	0.000	No	No	0.029	21	11.0	3.6
Marais Des Cygnes	0.000	No	No	0.069	29	14.5	4.0
Marin Islands	0.016	No	No	0.019	1	2.2	2.8
Mashpee	0.007	No	No	0.120	42	41.6	21.1
Mason Neck	0.005	No	No	0.041	27	43.8	10.3
Massasoit	0.000	No	Yes	0.018	31	41.6	21.1
Mathews Brake	0.000	No	No	0.051	8	12.6	3.4
Matlacha Pass	0.012	No	Yes	0.208	2	13.3	58.2
Mattamuskeet	0.013	No	No	0.117	1	6.8	44.3
Maxwell	0.000	No	No	0.040	35	7.9	2.2
Mcfaddin	0.002	No	No	0.247	4	15.7	14.2
Mckay Creek	0.013	No	No	0.054	70	10.4	11.8
Mclean	0.000	No	No	0.018	19	9.2	7.7
Mcnary	0.002	Yes	No	0.532	55	9.9	11.2
Medicine Lake	0.029	No	Yes	0.196	66	6.7	4.4
Merced	0.030	No	Yes	0.058	9	17.9	12.5
Meredosia	0.000	No	No	0.100	9	13.4	1.6
Merritt Island	0.013	No	Yes	0.443	12	35.5	35.7
Middle Mississippi River	0.000	No	No	1.458	36	21.2	6.8
Mille Lacs	0.015	No	No	0.028	0	14.1	7.5
Mingo	0.000	No	No	0.117	48	15.2	3.3
Minidoka	0.000	No	No	0.101	48	7.5	36.4
Minnesota Valley	0.020	Yes	No	0.854	96	27.4	3.7
Missisquoi	0.016	No	No	0.081	3	12.6	12.9
Mississippi Sandhill Crane	0.000	No	Yes	0.133	20	19.2	17.6
Moapa Valley	0.024	No	No	0.051	49	3.5	94.4
Modoc	0.000	No	No	0.105	46	10.9	60.9
Monomoy	0.015	No	No	0.124	10	41.4	21.2
Monte Vista	0.001	No	No	0.073	75	12.6	31.2
Montezuma	0.007	No	No	0.245	54	20.6	3.9
Moody	0.010	Yes	No	0.077	2	14.4	15.1
Moosehorn	0.008	No	Yes	0.390	104	9.5	19.7
Morgan Brake	0.000	No	No	0.085	22	12.6	3.4
Mortenson Lake	0.000	No	No	0.015	12	10.5	34.7
Mountain Longleaf	0.007	No	No	0.091	344	20.3	11.1
Muleshoe	0.000	No	No	0.072	62	13.0	1.9
Muscatatuck	0.000	No	No	0.398	33	16.6	8.3
Nansemond	0.000	Yes	No	0.018	0	37.6	6.1
Nantucket	0.020	No	No	0.003	0	39.1	35.6
National Bison Range	0.026	Yes	No	0.091	638	10.3	15.6
National Elk Refuge	0.023	No	Yes	0.161	289	4.0	97.2
Neal Smith	0.000	No	No	0.082	40	14.5	2.4
Necedah	0.025	No	No	0.226	24	15.5	6.1
Neches River	0.000	No	No	0.256	78	16.6	2.0
Nestucca Bay	0.016	Yes	No	0.111	135	20.9	50.9
Nine-Pipe	0.025	Yes	No	0.218	338	10.3	15.6
Ninigret	0.019	No	No	0.055	33	23.2	23.2
Nisqually	0.012	No	Yes	0.215	80	22.0	25.8
North Platte	0.009	No	No	0.080	86	8.2	4.1
Northern Tallgrass Prairie	0.009	Yes	Yes	7.495	381	13.7	6.7
Nowitna	0.039	No	No	1.272	673	0.3	24.1
Noxubee	0.000	No	No	0.214	99	10.0	10.2
Oahu Forest	0.020	No	Yes	0.043	361	30.7	0.35
Occoquan Bay	0.000	No	No	0.015	6	43.8	10.3
Ohio River Islands	0.001	No	No	2.052	161	18.7	4.4
Okefenokee	0.002	No	No	0.596	34	13.7	17.8
Optima	0.000	No	No	0.053	36	10.4	7.6
Oregon Islands	0.014	Yes	Yes	4.258	299	17.8	32.9
Ottawa	0.000	No	No	0.470	63	6.9	0.4

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Ouray	0.032	No	Yes	0.111	104	7.5	70.2
Overflow	0.001	No	No	0.167	22	12.7	2.9
Oxbow	0.000	No	No	0.085	47	29.1	22.2
Oyster Bay	0.004	No	No	0.049	37	31.1	3.4
Ozark Cavefish	0.000	No	No	0.340	0	17.1	1.8
Ozark Plateau	0.000	Yes	No	1.537	380	17.2	5.0
Pablo	0.026	No	No	0.029	20	10.3	15.6
Pahranagat	0.019	No	No	0.130	107	5.1	95.9
Panther Swamp	0.000	No	No	0.388	11	14.6	5.7
Parker River	0.006	No	No	0.112	14	35.8	14.4
Pathfinder	0.017	No	No	0.312	94	10.4	76.9
Patoka River	0.000	No	No	0.088	49	17.3	3.1
Patuxent	0.017	No	No	0.084	54	38.8	10.3
Pea Island	0.000	No	No	0.168	2	23.0	45.6
Pearl Harbor	0.024	Yes	No	0.093	14	30.7	0.35
Pee Dee	0.000	No	No	0.073	40	14.7	2.2
Pelican Island	0.000	No	Yes	0.080	1	28.6	25.2
Petit Manan	0.000	No	Yes	1.942	39	13.4	9.5
Piedmont	0.000	No	No	0.183	73	21.9	4.6
Pierce	0.000	No	No	0.012	101	30.4	24.1
Pilot Knob	0.000	No	No	0.006	92	11.6	17.8
Pinckney Island	0.016	No	No	0.061	2	17.2	8.4
Pine Island	0.014	No	Yes	0.200	0	2.7	41.3
Pinellas	0.010	No	No	0.046	1	5.4	43.4
Pixley	0.019	No	Yes	0.159	24	22.0	6.3
Pleasant Lake	0.000	No	Yes	0.025	24	11.9	4.7
Plum Tree Island	0.000	No	No	0.066	3	4.5	1.6
Pocosin Lakes	0.013	Yes	No	0.340	6	10.8	31.9
Pond Creek	0.000	No	No	0.148	47	14.9	12.9
Pond Island	0.000	No	Yes	0.004	0	na	na
Port Louisa	0.000	No	No	1.364	138	15.2	2.3
Presquile	0.024	No	No	0.039	29	28.3	6.0
Pretty Rock	0.027	No	No	0.022	24	9.0	3.7
Prime Hook	0.023	No	No	0.110	1	18.9	21.6
Protection Island	0.024	No	Yes	0.017	61	84.1	76.4
Quillayute Needles	0.011	No	No	0.400	98	8.9	62.3
Quivira	0.007	No	Yes	0.160	21	13.9	1.8
Rabb Lake	0.000	No	No	0.009	0	11.9	4.7
Rachel Carson	0.003	No	No	0.517	75	18.8	17.5
Rappahannock River Valley	0.011	No	No	0.571	68	18.7	10.4
Red River	0.000	No	No	1.527	47	14.6	7.9
Red Rock Lakes	0.018	No	No	0.207	579	5.7	53.2
Reelfoot	0.000	No	No	0.121	19	13.1	5.3
Rice Lake	0.019	No	No	0.507	107	12.7	11.6
Ridgefield	0.022	No	No	0.121	26	19.9	50.6
Roanoke River	0.002	No	No	0.598	22	13.3	8.8
Rock Lake	0.000	No	No	0.116	16	10.5	5.4
Rocky Flats	0.006	No	Yes	0.044	151	18.8	12.5
Rocky Mountain Arsenal	0.006	No	No	0.072	54	19.0	4.7
Rose Lake	0.000	No	No	0.027	26	10.4	6.9
Ruby Lake	0.001	No	No	0.261	198	7.2	87.9
Rydell	0.021	No	No	0.035	17	12.0	3.2
Sabine	0.008	Yes	No	0.174	5	13.3	7.4
Sachuest Point	0.012	No	No	0.022	0	54.1	6.5
Sacramento	0.015	No	No	0.088	17	11.9	3.5
Sacramento River	0.016	No	No	0.944	82	12.8	5.3
Saddle Mountain	0.013	Yes	No	0.430	927	12.4	14.6
Salinas River	0.014	No	Yes	0.024	11	19.3	27.7
Salt Plains	0.000	No	Yes	0.207	19	12.8	1.6
San Andres	0.017	No	No	0.418	1065	7.2	76.7
San Bernard	0.004	Yes	Yes	1.032	39	15.7	2.5
San Bernardino	0.010	No	Yes	0.023	61	4.9	25.8
San Diego Bay	0.019	No	Yes	0.072	6	34.8	30.9
San Diego	0.030	No	Yes	0.411	675	29.5	36.2
San Joaquin River	0.021	No	Yes	0.154	17	16.3	3.0
San Juan Islands	0.020	No	Yes	0.460	15	28.5	3.0

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
San Luis	0.023	No	Yes	0.137	7	17.9	12.5
San Pablo Bay	0.021	No	No	0.167	73	20.7	11.3
Sand Lake	0.000	No	No	0.240	22	11.5	7.0
Santa Ana	0.014	Yes	No	0.036	4	23.7	24.2
Santee	0.010	No	No	0.153	7	14.8	21.8
Sauta Cave	0.000	No	No	0.007	20	16.0	9.2
Savannah	0.000	No	No	0.248	18	16.6	7.9
School Section Lake	0.000	No	No	0.017	21	11.8	5.2
Seal Beach	0.023	No	No	0.025	1	104.6	10.9
Seatuck	0.025	No	No	0.016	3	77.7	8.7
Seedskadee	−0.004	No	No	0.251	80	11.5	87.1
Selawik	0.033	Yes	Yes	1.032	904	0.1	46.4
Seney	0.016	No	No	0.613	64	1.2	6.8
Sequoyah	0.000	Yes	No	0.117	73	13.0	9.2
Sevilleta	0.031	No	Yes	0.234	1177	12.1	38.0
Shawangunk Grasslands	0.000	No	No	0.017	12	23.6	14.4
Sheldon	0.011	No	No	0.449	914	4.1	91.7
Shell Lake	0.000	No	No	0.043	41	9.2	7.7
Sherburne	0.024	No	No	0.137	33	17.6	9.5
Sheyenne Lake	0.022	No	No	0.029	20	11.3	6.3
Shiawassee	0.001	No	No	0.160	12	19.6	7.5
Sibley Lake	0.010	No	No	0.029	17	10.6	2.8
Siletz Bay	0.017	No	No	0.041	76	21.1	14.6
Silver Lake	0.000	No	No	0.082	15	10.4	6.9
Silvio O. Conte	0.012	Yes	No	4.033	1766	18.6	22.4
Slade	0.022	No	No	0.036	14	9.4	6.3
Snyder Lake	0.000	No	No	0.058	13	10.4	6.9
Sonny Bono Salton Sea	0.019	No	No	0.187	0	9.0	63.2
Springwater	0.022	No	No	0.015	9	10.2	1.7
Squaw Creek	0.000	No	No	0.078	66	13.1	2.9
St. Catherine Creek	0.000	No	No	0.218	54	11.3	16.3
St. Johns	0.016	No	No	0.141	7	17.4	34.0
St. Marks	0.000	No	Yes	0.337	28	15.1	23.1
St. Vincent	0.011	No	Yes	0.092	4	18.8	13.7
Steigerwald Lake	0.022	No	No	0.020	143	30.3	24.1
Stewart B. Mckinney	0.015	No	No	0.329	25	26.2	11.0
Stewart Lake	0.024	No	No	0.029	7	7.6	40.2
Stillwater	0.016	No	No	0.438	124	8.0	72.2
Stone Lakes	0.022	No	Yes	0.197	11	20.1	6.2
Stoney Slough	0.000	No	No	0.022	24	11.6	41.9
Storm Lake	0.021	No	No	0.022	14	11.9	82.7
Stump Lake	0.000	No	No	0.022	41	10.4	6.9
Sullys Hill	0.018	No	No	0.038	54	10.4	6.9
Sunburst Lake	0.024	No	No	0.015	22	7.9	4.0
Sunkhaze Meadows	0.000	No	Yes	0.083	31	10.0	5.0
Supawna Meadows	0.011	No	No	0.059	6	13.0	17.6
Susquehanna	0.021	No	No	0.001	0	2.5	1.9
Sutter	0.021	No	No	0.100	2	14.2	5.0
Swan Lake	0.000	No	No	0.077	14	11.6	1.9
Swan River	0.022	No	Yes	0.045	82	7.6	69.6
Swanquarter	0.012	No	No	0.164	2	6.7	44.4
Tallahatchie	0.000	No	No	0.132	15	12.9	2.9
Tamarac	0.028	No	No	0.196	74	12.5	8.4
Target Rock	0.000	No	No	0.005	24	80.1	7.3
Ten Thousand Islands	0.017	No	Yes	0.187	3	11.6	60.0
Tennessee	0.000	No	No	0.774	70	13.9	8.8
Tensas River	0.000	No	Yes	0.454	11	10.2	8.6
Tetlin	0.032	No	No	0.795	1893	0.6	66.6
Tewaukon	0.000	No	No	0.064	30	11.9	82.7
Texas Point	0.000	No	No	0.053	1	16.7	13.5
Thacher Island	0.011	No	No	0.003	0	na	na
Theodore Roosevelt	0.000	No	No	0.061	5	15.5	6.7
Three Arch Rocks	0.022	No	No	0.008	0	na	na
Tijuana Slough	0.018	No	Yes	0.040	8	14.2	51.2
Tishomingo	0.000	No	No	0.103	29	10.5	15.1

Table A1. Continued.

Name	Temp annual trend (C/yr)	Biome edge	Critical habitat for T&E species	Latitude range (decimal degrees)	Elevation range (m)	Road density in watershed (m/ha)	Protected watershed (%)
Togiak	0.036	No	Yes	1.733	1465	0.2	67.1
Tomahawk	0.000	No	No	0.014	4	11.6	41.9
Toppenish	0.010	No	No	0.095	48	15.2	13.8
Trempealeau	0.028	Yes	No	0.052	128	12.4	6.9
Trinity River	0.000	Yes	No	0.517	41	13.8	0.4
Trustom Pond	0.020	No	No	0.045	41	23.2	23.2
Tualatin River	0.020	No	No	0.134	90	26.3	4.2
Tule Lake	0.017	No	No	0.192	246	10.6	62.2
Turnbull	0.000	No	No	0.174	97	10.6	6.3
Two Ponds	0.000	No	No	0.005	23	24.8	47.0
Two Rivers	0.000	Yes	No	0.511	35	16.4	2.3
Tybee	0.000	No	No	0.022	0	16.6	7.9
Ul Bend	0.016	Yes	No	0.255	106	3.9	32.5
Umatilla	0.000	No	No	0.110	16	9.2	6.9
Umbagog	0.012	No	No	0.263	478	10.2	20.3
Union Slough	0.000	No	No	0.131	13	13.8	1.0
Upper Klamath	0.017	No	No	0.302	55	9.4	38.1
Upper Mississippi River	0.013	Yes	No	2.749	189	13.8	6.3
Upper Ouachita	−0.001	No	No	0.275	19	12.4	13.3
Upper Souris	0.001	No	Yes	0.449	80	13.0	4.9
Valentine	0.000	No	No	0.190	78	4.3	5.4
Waccamaw	0.001	No	No	0.339	11	19.1	5.0
Wallkill River	0.002	No	No	0.166	214	26.6	16.8
Wallops Island	0.000	Yes	No	0.116	11	23.4	8.3
Wapack	0.000	No	No	0.032	281	24.2	15.0
Wapanocca	0.000	No	No	0.051	9	15.2	4.0
War Horse	0.027	No	No	0.291	57	5.0	8.8
Washita	0.000	No	No	0.094	22	10.8	3.8
Wassaw	0.000	No	Yes	0.074	24	26.9	9.8
Watercress Darter	0.000	No	No	0.214	92	21.3	1.9
Waubay	0.023	No	No	0.044	44	9.4	6.0
Wertheim	0.023	No	No	0.401	14	77.7	8.7
Wheeler	0.000	No	No	0.168	76	17.2	7.3
White Lake	0.028	No	No	0.015	10	9.0	3.7
White River	0.000	No	No	0.760	28	11.9	8.2
Whittlesey Creek	0.028	No	No	0.017	4	1.1	2.9
Wichita Mountains	−0.006	No	No	0.145	273	13.9	4.2
Wild Rice Lake	0.005	No	No	0.019	10	11.9	82.7
Willapa	0.013	No	Yes	0.401	195	16.6	14.3
William L. Finley	0.010	No	Yes	0.060	104	18.8	6.9
Willow Lake	0.000	No	No	0.040	29	11.9	4.7
Wintering River	0.022	No	No	0.011	12	11.1	6.1
Wolf Island	0.000	No	Yes	0.077	10	13.8	21.6
Wood Lake	0.019	No	No	0.015	10	10.4	6.9
Yazoo	0.000	No	No	0.111	15	14.2	5.7
Yukon Delta	0.032	Yes	Yes	3.856	1220	0.2	58.2
Yukon Flats	0.041	No	No	1.746	1335	0.3	61.9