Reimagining the American West to Reach Half-Earth

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Abstract

National parks in the United States require improved connectivity to maintain resilience in the midst of climate change. Additionally, biodiversity losses and encroaching human-modifications are widely documented inside parks and outside their greater ecosystems. Conservationists have called for big, bold, and innovative strategies to complete and connect protected areas, which includes parks and wilderness areas. E.O. Wilson and others have stated that setting aside 17% of land units, which is suggested by the Aichi target 11 of the Convention on Biological Diversity, is not enough to halt species losses and that we must set aside half of the Earth as a protected area network. The protected area network must be permeable to allow for species movements; however, this is difficult amidst heavy human encroachment. Here, I combined two studies to provide insights into priorities for maintaining connectivity of national parks at the scale of greater park ecosystems across the contiguous United States (U.S.) and reimagined the protected area network in the American West to reach half-earth.

In the first study, I used ArcGIS to develop a coarse-scale greater ecosystem model (GEM) to evaluate the permeability of national parks and their surrounding landscapes. Since much is unknown about species' behavioral responses to human encroachment, the GEM model used one variable "wildness" and three potential species responses. Previous greater ecosystem models are species and habitat-suitability specific, and therefore, are difficult to compare across the continent. Since wildness has been evaluated on a national level, I concluded that the GEM model can be used across the continent to evaluate protected areas' greater ecosystems. Secondly, the GEM model could aid the National Park Service's Inventory and Monitoring program outside parks'

administrative boundaries. Thirdly, the GEM model can analyze ecosystem representation and the conservation status of a parks' greater ecosystems. By ranking protected areas to determine conservation priorities and identifying the most intact wildlands, protected area expansions can be evaluated to complete a vital protected area network.

In the second study, I used ArcGIS to model an innovative conservation strategy and evaluate if two scenic trails in the national park system could serve as green infrastructure for continental wildlife corridors over the next century. In cities, green infrastructure, such as parks and greenways, are employed as a climate mitigation and adaptation strategy. Therefore, on a continental scale I used Beier's two-kilometer wildlife corridor method (2018) and buffered the Pacific Crest Trail (PCT) and the Continental Divide Trail (CDT) to analyze if a trail corridor held three vital conservation values for wildlife corridors: wildness, connectivity and diversity. To determine the feasibility of using my model in the field and to inform policy on if new land acquisitions or designations are needed, I also calculated the conservation status and land management that the trails traversed.

The PCT and the CDT corridors were both found to be remarkably wild and connected when compared to other land units in the U.S. Eighty-six percent of the PCT and 87% of the CDT were in the top 50% of the most wild and connected landscapes. Secondly, many of the ecosystems along the proposed corridor are already represented in the American reserve. Thirdly, both the PCT (99.96%) and CDT (94.96%) follow the route of the best corridor values in the U.S. and match the forward centrality models for the next 100 years. Fourthly, the public already owns 90% of the land the corridors traverse and land units that are not permanently protected (12%) are managed by two primary agencies: The U.S. Forest Service (USFS) and the Bureau of Land Management (BLM). Therefore, it is recommended that these scenic trails become re-designated as “critical wildlife corridors” and act as an anchor for the protected area network.

These two studies seek to provide a vision and road map to meeting Wilson’s half-earth in the American West where wildlands are well represented and 40% of land units are publicly owned. By anchoring our protected area network with the largest intact public wildlands in America and using existing green infrastructure (i.e. scenic trails) as continental wildlife corridors, we have the opportunity to meet a big bold conservation target of preserving 50% of landmass in the West by 2050.

Dedication

Here's to the wild ones. Here's to the "dirt baggers" (Chouinard, 2006), who spend countless evenings on ground tarps under moonlit skies and who live for conversations by open fires. Here's to the first ones, the outliers, who put in their 10,000 hours to run big rivers and climb rugged peaks. Here's to the headlamp wearers, the compass bearers, and the lead climbers. May you always have places to become, to connect, to lead, and to go when the light goes out (Roosevelt, 1884).

Here's to the wild places. Here's to the landscapes that raised me: The San Bernardinos with Jeffrey and Ponderosa Pines that smell like root beer, the Grand where I stood with my father on the edge in 1986, the Smokies that showed me southern graces and deep roots, to J-Tree and the Great Death who remind me that "necessary undulations" (Lewis, 1942) are part of life, to Yosemite and Yellowstone that taught me that firsts are worth fighting for, and to the small islands like the Channel and Virgin who teach me life on a tiny scale. May you always be wild. May we always be connected. May you ever stay diverse.

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My thanks go to a long list of men whom over the years have allowed me to join their ranks. My father, Jerry, often took me to the mountains, above the smog of our SoCal town (like his father had done), and my land ethic was formed. I knew I wanted to live and be in wild places and that there was life beyond human invention.

In undergrad, I longed to only hike and paddle, and Dr. Brad Daniel took a chance and called me his TA. Over the next 20 years, I fell hard for scholarship, taught alongside him at over 28 National Parks, and eventually became his colleague.

My husband, Captain Charlie MacPhail, trusted me to belay him on our first date and I quickly became his first mate. Nineteen years later, he still tells me to “go for it” and thinks I can sail better than I can. Your strength and love allow me to be wild.

Dr. Mark Leighton of Harvard University and Rafe Boulon of Windswept on St. John, USVI at some point you two smiled and told me to go where the world has the greatest need. I ended up on a hurricane-torn island, that even on its bad days, is the most stunning landscape on the planet. I have become more passionate, more purposeful, and more joyful since being among you. You have taught me that saving land for the next generation is a worthy life, and I am proud to be your student.

Muir, Thoreau, Leopold, Marsh, Roosevelt, Chouinard, Berry, and E.O. Wilson you taught me that I have something to say. Dr. Wilson thank you for listening to me and reminding me that worthy ideas arise in unlikely lands by unlikely people.

Dr. Travis Belote of The Wilderness Society we are of the same places. Whenever, I begin a journey I always imagine the best people to walk the mountain with; now I can't imagine walking with anyone, but you. Your humility was born in wilderness, and yet the largest landscapes in the West rely on you. Your work, your connection, and your drive inspire me to become. Many thanks for letting me run beside you. You are like the peaks you live among-- leading the way so fearlessly and with such simple grandeur. May we forever keep the American West wild, diverse, and free of restraint. And when you are in "half an inch of water", I will be there paddling hard like John Wesley Powell. Thank you is not enough.

To Cailin, Riana, Connie, Brigette, Lamya, Katrina, Sandra, Liz, Zeyneb, and Alla we are the next ones. We are the women conservationist with something worthy to say. Thank you for adventuring: Snorkeling the mangroves looking for refugia, hiking the ruins among the Kapok and Bay Rum trees, late night card games in jungle-based research stations, dancing in Cambridge, talks in the Yard and quiet studies in Widener, inventing new scientific methods when all the power goes out, hard edits with coffee in hand, sunset walks on the Charles with rosé, and late afternoon salty swims when the day's work ends. Your creativity, your mission, your woman to work balance, and your "global collective brain" makes me want to be smarter, stronger, and braver.

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Chapter I

Introduction

National Parks in the American West are losing biodiversity (Haddad et al., 2015). Climate change is altering habitat diversity and species compositions inside parks (Monahan & Fisichelli, 2014), while human modification surrounding parks is fragmenting landscapes constricting ecological flows (Belote et al., 2016; Jenkins, Van Houtan, Pimm, & Sexton, 2015). Set aside for future generations, we now realize that protecting parks is an "evolving idea" (Williams, 2016; Hobbs et al., 2010). To uphold the National Park Service's (NPS) original mission, to preserve landscapes unimpaired, it is essential to evaluate their greater ecosystem context (Hansen et al., 2011; Monahan & Fisichelli, 2014).

A 22-year review of biodiversity management practices found that the two most vital conservation initiatives in the 21st century are increasing connectivity, a populations' ability to permeate a landscape, and resilience, the ability for an ecosystem to persist amid external changes (Heller & Zavaleta, 2008). Biologist E.O. Wilson proposes protecting half of the Earth to halt biodiversity losses (Wilson, 2017). Unfortunately, only 13% of the United States is set aside in conservation reserves (United Nations Environmental Programme, 2016) and 41% of the contiguous United States (CONUS) contains enough wildlands, or non-human modified land, to facilitate species movements throughout the next century (McGuire, Lawler, McRae, Nuñez, & Theobald, 2016).

Extirpations, or native species extinctions (Pringle, 2017), and continued land degradation surrounding parks (DeFries, Hansen, Turner, Reid, & Liu, 2007) indicate the need to model connectivity and resilience. Evaluating protected area-centered ecosystems (PACEs), or the ecological boundaries of parks and wilderness areas rather than administrative boundaries, is essential in the Anthropocene (Hansen et al., 2011; Monahan & Fisichelli, 2014). Mapping connected and resilient landscapes to procure new land acquisitions (Anderson et al., 2016) and modeling wildness, connectivity, and resilience of protected areas based on the human development index and climate projections (Belote, Dietz, McKinley, et al., 2017) is equally important. Lastly, developing ecoregional conservation plans (The Wildlands Network, 2004) are vital to supporting parks in this century.

To foster landscape resilience, Chile is expanding their park boundaries and connecting them via a continental corridor, the "Ruta de Parques" (Bisharat & Chin, 2017; Hilty, Lidicker, & Merlender, 2017). Built in partnership between the Chilean government and the Tompkins Foundation, a private land conservation organization, the corridor seeks to use existing recreational trails to add ecological, educational, and economical value to Chilean National Parks (Royte & Greshko, 2018). Unfortunately, the conservation value of recreational trails as an anchor for landscape connectivity has not been evaluated. Instead, current connectivity and resilience models use ecological flows (i.e. abiotic and biotic processes), landscape diversity, the human footprint, and focal species as indicators (M.G. Anderson et al., 2014; Belote et al., 2016; Hansen et al., 2011; Krosby et al., 2015).

Recreational trails could be a pivotal anchor for a continental wildlife corridor. On a smaller scale, greenways in cities add ecological value to the human-matrix by acting as green infrastructure-- connecting city parks to each other (Ahenn, 1995; Fabos, 2004; Matthews & Byrne, 2015). Initially set aside for recreation, greenways are urban wildlife corridors-- facilitating animal migrations, species dispersals, and ecological flows (Hilty, Lidicker, & Merlander, 2006**)**. Therefore, on a continental scale, recreational trails could serve a similar role between protected areas. Trails are a sensible framework for a continental corridor because they generally follow streams or ridge lines (natural pathways for other species), traverse wild habitats, intersect rare and diverse ecosystems, and begin and end at protected areas (P. Kahn, personal communication, May 22, 2018). In addition, trails are more likely to receive public support due to their multifaceted values (i.e., recreation, aesthetic, educational, and ecological) (Beier, 2018; Fábos, 2004; Hilty, Lidicker, & Merenlender, 2006).

The National Park System (NPS) needs to be reimagined. Maintaining or restoring landscape permeability, or a species ability to move through a landscape, will allow biodiversity and ecological flows to persist within the greater ecosystem context (Hunter & Gibbs, 2007; Newmark, Jenkins, Pimm, McNeally, & Halley, 2017). Connecting protected areas, parks and wilderness areas (Belote et al., 2016) expands their footprint, allowing for increased species movements (Hunter & Gibbs, 2007; Pringle, 2017). Increased movement (dispersal, gene flow, migrations) aids in population viability (Hunter & Gibbs, 2014). Secondly, connected protected areas increase recreation, education, and tourism (Bisharat & Chin, 2017) and are more publicly endorsed (Pringle, 2017). Thirdly, larger and connected protected areas have stronger resilience as the climate changes due to higher permeability and microclimate diversity, and lessened edge effect (Diamond, 1975; Hunter & Gibbs, 2014). Fourthly, completing the American reserve system through expansion and connectivity is a top priority for conservationist and land managers alike because it is hypothesized that we will see increased extirpations as the human footprint expands (Aycrigg et al., 2016; Belote et al., 2017; Heller & Zavaleta, 2009; Jenkins et al., 2015).

Research Significance and Objectives

For this study, I sought to develop a landscape scale model that evaluates the connectivity of national parks within their greater ecosystem context. To quantify park connectivity, I determined the permeability of five national parks and their adjoining wilderness areas using ArcGIS (ESRI, Redlands, CA). Then, I asked how wild, connected, diverse, and protected are the national parks' greater ecosystems? The five national parks and adjoining wilderness areas (hereafter, parks) chosen as a sample were in the western region of the contiguous United States and represent a variety of ecosystems and latitudinal gradients. This sample analysis allowed me to build a methodology for defining and evaluating protected areas within their greater ecosystems. This approach can inform policy on ways to protect parks as human modification expands and the climate changes (Ordonez, Martinuzzi, Radeloff, & Williams, 2014). This model can be applied to protected areas throughout the contiguous United States (hereafter, U.S.).

Next, I mimicked Chile's conservation strategy and evaluated two recreational trails to determine if they could serve as green infrastructure for a continental corridor that connects national parks and wilderness areas. In urban landscapes, green infrastructure is a network of parks or greenways used in for climate adaptation or mitigation (J. G. Fábos, 2004; Julius Gy Fábos & Ryan, 2006; Matthews, Lo, & Byrne, 2015). On a continental scale, The Pacific Crest Trail (PCT) and the Continental Divide Trail (CDT) could be used as green infrastructure across the continent. The PCT and CDT scenic trails were chosen for this study because they pass through a variety of elevational and latitudinal gradients and are well established in the outdoor recreation industry. By mapping a two-kilometer wildlife corridor buffer (Beier, 2018) in ArcGIS, I determined if their green infrastructure anchored vital conservation values: wildness, connectivity and diversity for species movements as the climate changes. To analyze the feasibility of using my model in the field, I calculated the conservation status and land management that the trails overlay. This second analysis informs policy on whether new land acquisitions or land designations could elevate the conservation status of high value areas along the trails.

The American West was chosen for this analysis because western protected areas are closer in proximity to each other, represent a variety of landscapes and elevational gradients, and are wilder (i.e. less human modified) (Belote et al., 2016). Secondly, connectivity and resiliency initiatives in California and the Yellowstone to Yukon (Y2Y) are already underway (Anderson et al., 2016; Yellowstone to Yukon Conservation Initiative, 2018) and both the PCT and the CDT intersect these initiatives. Thirdly, the outdoor recreation industry is a thriving economy in the American West (Outdoor Industry Association, 2017) and 76% of outdoor recreation (hiking, mountain biking, backcountry skiing, paddling, and rock climbing) occurs on western public lands

(Outdoor Alliance, 2017). Fourthly, there are a variety of scenic trails that cross multiple longitudes and latitudes in the West, which means that a continental corridor could eventually become a continental corridor network that counteracts the degradation of the human matrix.

My objectives were:

- To identify the greater ecosystems and permeability of five national parks
- To develop a coarse-scale greater ecosystem model that evaluates protected areas for wildness, connectivity, diversity and protection
- To model if scenic trails could serve as green infrastructure for a continental corridor
- To inform policy by evaluating the conservation status and management of landscapes surrounding national parks and scenic trails.

This research is presented in two chapters drafted as journal articles. Chapter II covers a new model for delineating the greater ecosystems of national parks to further understand protected area permeability. Chapter III evaluates the conservation value of two scenic trails in the national park system to determine if they could serve as a continental wildlife corridor.

Chapter II

A Coarse-Scale Model for Identifying Greater Ecosystems Around Protected Areas

In the U.S., 10% of land is conserved in a reserve system (Jones et al., 2018)) and 82% is managed by four major entities (Belote et al., 2016). The National Park System (NPS) (23.8% of the reserve) preserves ecological, recreational, educational, and scientific values for future generations (Belote et al., 2016; Hunter & Gibbs, 2014), while wilderness areas are set aside to hold key ecosystems in their natural and untrammeled condition (Hunter & Gibbs, 2014). The U.S. Forest Service (USFS) (33.9%) conserves natural resources for all people and for equitable economic return (Belote et al., 2016; Hunter & Gibbs, 2014). The Bureau of Land Management (BLM) (14.5%) sustains diverse landscapes for health and production, and the Fish and Wildlife Service (FWS) preserves and manages wildlife (10%) (Belote et al., 2016; Park & Allaby, 2017). Each component of America's reserve has a distinct purpose and administrative boundaries. However, it is evident that it must be reevaluated beyond its current boundaries to fulfill its mission (Aycrigg et al., 2013; Haddad et al., 2015; Jenkins et al., 2015; Monahan & Fisichelli, 2014).

Background

Conservation biologist E.O. Wilson estimated that 50% of a land mass must be protected in order to preserve 85% of the species present (2016). Wilson's "half-earth" plan means saving half of the earth for humanity and the other half for other species (2016) and is a call-in response to the sixth major extinction on Earth. If long term conservation is our goal, it is time to rethink America's reserve system by expanding the habitat area of protected areas (Haddad et al., 2015; Jenkins et al., 2015; Saunders, Hobbs, Margules, 1991; Wilson, 2016), reducing edge effects around reserve sites (Hunter & Gibbs, 2014; Diamond, 1975), adding connecting corridors to protect fluxes (Mark G Anderson, Clark, & Sheldon, 2012; Belote et al., 2016; Diamond, 1975; Hunter & Gibbs, 2014), planning for climate shifts (Anderson et al., 2016; Belote et al., 2017), and partnering with outdoor recreation industry and private land trusts to build a reserve system that influences a healthy land ethic (Leopold, 1962; Louv, 2005; Kellert, 2012).

Fragmentation and Remnants

The most significant biological changes on Earth are caused by ecosystem fragmentation and human modification (Jenkins et al., 2015; Saunders, Hobbs, & Margules, 1991; Tucker et al., 2018; Venter et al., 2016). As human settlements increase, the landscape matrix becomes more human-modified and less wild (Haddad et al., 2015). Fragmentation leaves remnants or patches that are greatly influenced by the landscape context surrounding them. MacArthur and Wilson's "theory of island biogeography" can be applied as a theoretical framework to further understand fragmentation (1967). Remnants are habitat islands floating in a sea of human development (Saunders, Hobbs, & Margules, 1991). Similar to islands, a remnant's size, shape, and location within the overall landscape can buffer both biogeographic and physical changes adding resiliency to the remnant (Haddad et al., 2015). Larger close remnants have increased immigration rates and larger remnants have lower extinction rates (Macarthur & Wilson, 1967).

Fragmentation decreases biodiversity 13-75% (Haddad et al., 2015) because species' habitats and ranges are reduced causing smaller population sizes. In general, species extirpations occur when populations are at low sizes, either because they exist at low densities, need large habitats, or rely solely on native vegetation (Haddad et al., 2015). With greater remnant isolation genetic diversity plummets (Hunter & Gibbs, 2014). Over time, smaller isolated remnants experience less residency, species abundance and richness, and community composition (Haddad et al., 2015). While, protected area remnants that are larger, wild, connected, and diverse will see greater dispersal and gene flow bolstering resilience (Belote et al., 2017; Hunter & Gibbs, 2014).

Furthermore, at finer scales (i.e. associated with fragmented forest patches) increased isolation impairs ecosystem functioning since isolated remnants experience less permeability, nutrient retention, pollination, and trophic dynamics (Haddad et al., 2015). Ecosystem functioning wanes because radiation, wind and water fluxes create new microclimates that alter vegetation patterns. New local vegetative patterns modify evapotranspiration, soil moisture, and ultimately groundwater flows (Haddad et al., 2015). Vegetation removal leaves topsoil to erode into streams and rivers affecting aquatic habitats and other terrestrial habitats downstream which in turns once again affects biodiversity (Haddad et al., 2015).

In addition, we must not think that protected area remnants are untouched by the human-matrix (Jones et al., 2018; Simberloff & Abele, 1982). The protected area network in the U.S. is highly influenced by its landscape context. Invasive species, pollution, livestock, poaching, and extractive land-use outside protected areas can all infiltrate protected area biota and ecosystem services (Hunter & Gibbs, 2014). Human modification even influences protected areas with the highest levels of protection (e.g. wilderness) (Cole & Landers, 1996).

When reimagining the protected area network in America, we must consider protected areas as remnants and evaluate their remoteness (wildness), distance from remnant to remnant (connectivity), and context within their greater ecosystems (diversity and level of protection). It is these three major landscape quality factors that determine biodiversity losses, ecosystem functioning, and resilience (Haddad et al., 2015).

The U.S. Reserve System and Protected Areas

The U.S. reserve system "like jazz, is an American invention" (Brewer, 2005, p.14). In the 1800s, Americans turned to conservation as a tool to preserve the American aesthetic and landscape. Thoreau and Muir engaged the public to conserve land by encouraging the state and federal government to set aside land for ecological and aesthetic values, while Roosevelt and Pinchot fought to conserve land and natural resources for utilitarian purposes (Brewer, 2005). In 1891, the Forest Reserve Act gave the president power to set aside reserves for the citizenry (Park & Allaby, 2017) and within twenty-five years, in 1916, the National Park service became established to preserve and protect the nation's natural resources (Monahan & Fishnelli, 2014). Wilderness areas, established by Congress via the Wilderness Act of 1964, delineated landscapes where humans were mere visitors (Park & Allaby, 2017). The use of public ownership of protected areas allowed for equitable land use and a variety of conservation values (i.e. aesthetic, recreational, utilitarian, ecological, cultural, and historical) to co-exist.

The Protected Area Database for the United States (PAD-US) classifies the reserve system into four levels of protection (United States Geographic Survey [USGS], 2011). GAP Status 1 areas are permanently protected areas where disturbance events are allowed, while GAP Status 2 areas are permanently protected and disturbance events are suppressed (USGS, 2011). GAP Status 3 areas are utilitarian areas where extractive use (e.g. timber, mining, fracking, etc.) are allowed. GAP Status 4 areas unprotected or not listed as being managed (USGS, 2011).

Only 7.1% of the contiguous United States is protected as GAP Status 1 or 2 (national park or wilderness) (Jenkins et al., 2015). Protected areas in the U.S. fall short of conserving a full suite of vegetative communities, and therefore a diverse suite of vertebrates and invertebrates (Aycrigg et al., 2013). In addition, parks and wilderness areas have not been intentionally connected in most cases (Belote et al., 2016). Instead, reserves managed by land trusts, private universities, the BLM, the Department of Energy, the USFS and 27 other agencies are wilder and more connected than national parks (Belote et al., 2016).

The U.S. has the most well-established reserve system in the world (Dietz, Belote, Aplet, & Aycrigg, 2015), and yet it does not adequately protect the country's unique species in the Anthropocene (Jenkins et al., 2015). While the majority of the American reserve system is under federal ownership in the West, over 70% can be used for utilitarian purposes (mining, timber, fracking) (Belote et al., 2016). In addition, many protected areas were originally conserved for recreational and aesthetic values, and not to specifically to preserve biodiversity (Aycrigg et al. 2013, Brewer, 2003; Dietz et al. 2015). The most vulnerable species are in the East while the majority of protected areas are in the West (Jenkins et al., 2015) and habitats in the West may be too fragmented to keep megafauna population sizes viable (Newmark, 1995). Our selection of protected areas-- their size, ecosystem context, and connectivity ultimately drive species' survival

(Haddad et al., 2015; Saunders, Hobbs, & Margules, 1991) and we must rethink our reserve system for resilience (Belote et al. 2017).

When determining the best reserve design for the American West we should consider six best design practices (Diamond, 1975; Williams, ReVelle, & Levin, 2005). Protected areas should be as large as possible, housing a diversity of habitats, elevations, and moisture gradients (Anderson, Clark, & Sheldon, 2011). Large reserves or several small are best (Diamond, 1975; Wintle et al. 2019). Reserves that are closer together or connected via corridors are more effective (Berger & Cain, 2014). Corridors should allow for increased movement of species and abiotic factors (Belote et al. 2016; Hunter & Gibbs, 2014) and four types of species movement should be considered: daily species movements, annual migration patterns, dispersal movements, and range shifts of species that are responding to climatic changes (Hunter, 1997). Round reserve shapes rather than rectangular reserves shapes should decrease edge effect and buffer zones should help with human encroachments (Williams et al., 2005).

Remnants in the Anthropocene

In the Anthropocene, we are experiencing a new type of climate risk that impacts landscape resilience (Belote et al., 2017; Lowenstein, 2017) including national parks, more than ever before (Monahan & Fishnelli, 2014). While climate changes occurred during the quaternary, very few species went extinct (Botkin et al., 2007). Fortunately, we can plan for climatic changes because landscapes that are geophysically diverse, indicated by the number of geology classes, latitude, amount of calcareous bedrock, and elevational ranges allow for a diverse set of species to persist (Anderson & Feree, 2010). Secondly, when those diverse landscapes are permeable or connected to other diverse landscapes, “microclimate buffering” occurs allowing species to persist even as the climate changes (Willis & Bhagwat, 2009). Permeability assists species to move from unfavorable to favorable microclimates; therefore, if a remnant is geophysically diverse and connected to other remnants it is more resilient (Anderson et al., 2014).

Quantitative measures for permeability have also included landscape complexity, local connectedness, and regional flow patterns (Anderson et al., 2014; 2016). Wildlands (landscapes with minimal human footprint) are generally considered more permeable than more human-altered landscapes (Belote et al., 2016; Martin and Watson, 2016). Outlining the permeability of landscapes allows conservation organizations, such as The Nature Conservancy and Wilderness Society, and reserve managers with the NPS, USFS, BLM, FWS to identify priority areas in need of protection, innovation, or restoration.

Identifying priority areas to protect as the climate shifts is crucial (Monahan & Fishelli, 2014) and understanding protected areas within their landscape context is imperative (National Academy of Public Administration, 2010; National Parks Second Century Commission, 2009). Shifting climate and management factors call for managers to consider land units outside their administrative boundaries, since most protected areas are well protected within their borders (Bruner, Gullison, Rice, & Da Fonseca, 2001). The NPS Inventory and Monitoring program has encouraged delineating the greater ecosystem of parks (Hansen et al., 2011) and national parks continue to advocate for buffers especially as extractive use on public lands and human modification increases (Shafer, 1999; Williams, 2018).

Delineating the extent of a park’s greater ecosystem is challenging, and the protected area-centered ecosystem (PACE) model aids in determining two zones-- (1)

landscapes where human modification influences park ecosystems and (2) landscapes where native organisms need to remain to be viable (Jones et al., 2009; Hansen et al., 2011). In the PACE model, a diverse set of criteria (ecological flows, crucial habitats, effective size, and human edge effects) are used to quantify and map the landscapes outside of park boundaries that directly affect park resilience. The PACE model aggregates disturbance regimes, hydrology, and atmospheric dynamics to map ecological flows. Then, crucial habitats for key species in the park are summed, and species area relationships assessed. The effective park size is mapped by determining contiguous suitable habitats, and the human edge effect is mapped using a 25 km buffer around each park.

The PACE model is built upon a series of earlier studies, each of which greatly benefit conservation (Craighead, 1978; Davis & Ogden, 1994; DeFries et al., 2010). However, a coarse-scale approach to identifying the larger context of national parks focusing on permeability of adjacent lands could be an effective complementary method to Hansen et al's PACE model. Focusing on how connected parks are to their surrounding landscapes could benefit ecological flows and wildlife movements in and out of parks, as many species connectivity models assume human modification influences movement (Krosby et al. 2015). Species can have a suitable habitat, be in the right area of the watershed, and experience great air quality, and still be greatly affected by the human degradation. Noting that human environmental modification is the primary driver of species losses (Hansen et al., 2011), further modeling of the human footprint and species responses is warranted.

Here, I developed a coarse-scale greater ecosystem model (GEM) to evaluate the permeability of parks and their surrounding landscapes. This model aids in delineating a park's greater ecosystems (GEMs) and allows land managers to query landscapes surrounding parks for a variety of parameters and identifying priorities for better representing ecosystem and species diversity in lands adjacent to existing parks, the composition of land ownership and protected status, and human impacts in landscapes surrounding parks.

I was interested in this problem because national parks are currently experiencing species extirpations (Newmark, 1995) and it is hypothesized that there will be additional losses in the next 100 years as the climate changes (Theobald et al., 2013). Secondly, with increased climate-induced disturbances, such as fires, pests, and invasive species, land managers are asking for a greater delineation of the ecosystems surrounding parks (Jones et al., 2009; Monahan & Fisichelli, 2014). Thirdly, national park boundaries have historically grown in an ad hoc fashion, and it is now evident that parks need landscape level adaptive management plans (Aycrigg et al., 2015; Dietz et al., 2015). Finally, as human modification expands and species' ranges shift, national park expansions are warranted, (Belote, et al., 2017; Groves et al., 2012; Heller & Zavaleta, 2009) and a landscape level evaluation of their greater ecosystems is paramount (Hansen et al., 2011). My analysis focused on the American West where over 70% of land is public and where megafauna are in need of large landscapes for movement (Tucker et al., 2018).

Methods

To build the greater ecosystem model (GEM), I obtained three datasets (Table 1) and projected them to USA Contiguous Albers Equal Area Conic (USGS) in ArcGIS with a cell size of 1 km x 1 km (ESRI, 2011). The Protected Area Database for the United States Conservation Biology Institute Edition (PAD-US CBI) v 2.1 was obtained to locate five national park units and their adjacent wilderness areas (hereafter, parks): Grand Canyon National Park, Yosemite National Park, Sequoia National Parks, Yellowstone National Park, and Grand Teton National Park (USGS, 2011). Yosemite and Sequoia National Park and Yellowstone and Teton National Park were evaluated as one landscape level unit because they have touching park boundaries. Additionally, a park's adjacent wilderness that shared an administrative boundary with a park was considered part of a park's total footprint. The human footprint database (Venter et al., 2016) was inverted to represent wildness surrounding parks, and therefore, permeability rather than human modification. The ecosystem representation dataset (Aycrigg et al., 2014) was used to determine the diversity of the five parks and their surrounding ecosystems at varying distances outside their current boundaries.

In this study, I assumed that wildness modeling is a complementary approach to species-specific models and first conducted a sensitivity analysis to test varying degrees of permeability irrespective of the type of ecosystems or terrestrial species. While it is known that permeability promotes movement (gene flow, range shifts, dispersal), these models generally rely on least cost distances built off landscape resistance (Zeller, McGarigal, & Whiteley, 2012). In a species-specific model, resistance is hypothesized based on a species' habitat suitability (Keeley, Beier, & Gagnon, 2016). While, many have modeled this relationship as a linear function, the Keeley et al. (2016) method assumes that species move along pathways of lower cumulative resistance, and that this can be modeled using a series of transformation functions (Figure 1). One option that does not seem to be present in the literature is movement that is completely hindered until high habitat suitability (R. Belote, personal communication, January 26, 2019).

Table 1. Datasets for coarse-scale greater ecosystem model (GEM).

Data	Source	Website
Protected Area Database		
PAD-US Gap Status (CBI Edition)	Foster et al., 2016	https://consbio.org/products/projects/pad-us-cbi-edition
Wild and Connected		
Human Footprint Database	Venter et al., 2016	https://doi.org/10.1038/ncomms12558
Diverse		
Ecosystem Representations	Aycrigg et al., 2014	https://doi.org/10.5849/jof.15-050

For my coarse-scale model, I needed habitat suitability to be an estimate for a variety of species, therefore I chose "wildness" rather than species-specific habitats and created a cost weighted distance analysis from national parks to their surrounding landscapes. Since, my model is for a variety of terrestrial species, I tested three possible movements of species based on the degree of wildness (Figure 2). I assumed that species will have varying degrees of movement or permeability dependent on the amount of wildness (lack of human footprint) present and the accumulated cost distance from a park boundary. It is uncertain if this relationship is linear, so I chose to model both semilinear and nonlinear transformations and assumed that the relationship of wildness and permeability is positive (Keeley et al., 2016). By modifying Keeley et al.'s (2016) resistance and habitat suitability equation to $P = 100-99*((1-\exp(c*W)/(1-\exp(c)))$, where C is the curve variable, W is degree of wildness and P is permeability, I was able to create a raster permeability surface for three plausible species responses and ran a

ArcGIS cost weighted distance from each national park in the U.S. C=1 is a nearly linear relationship. C=16 represents areas with high human footprint and relatively undisturbed species movements. C=(-16) represents areas with low human footprint and extreme species avoidance (Figure 1).

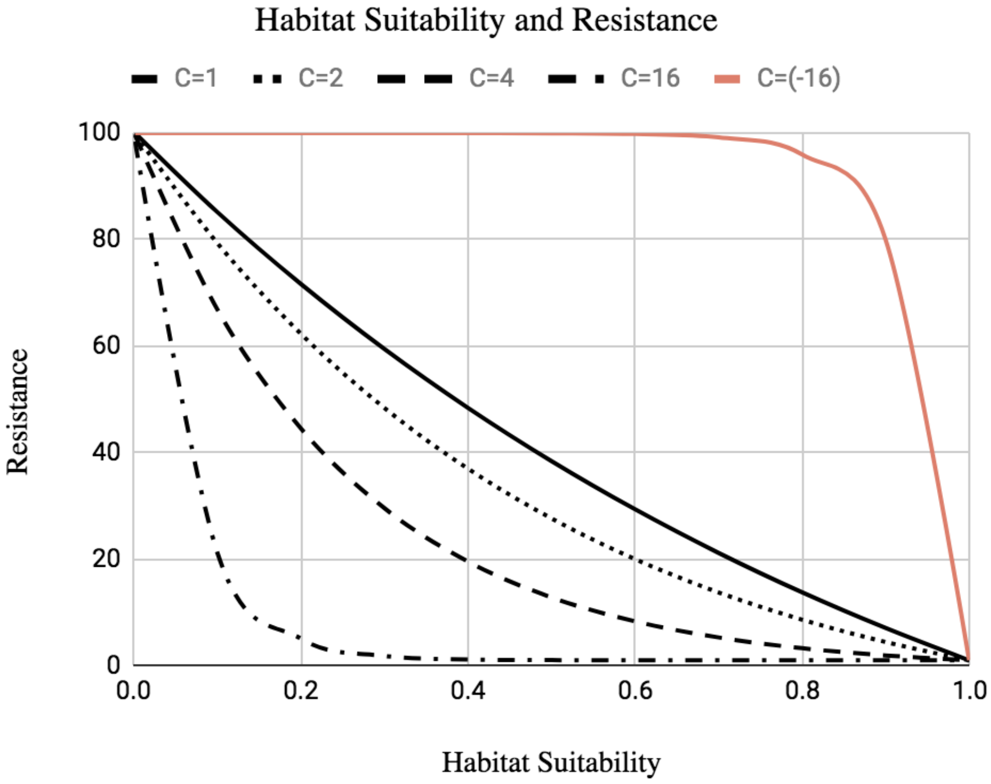

Figure 1. Habitat suitability and resistance (adapted from Keeley et al., 2016). Curves for this relationship are based on the transformation function R= 100-99 * ((1-exp(-c*H)/(1-exp(-c))) where R is the resistance, H is the habitat suitability, and C is value that determines curve shape. C= (-16) species movement is completely hindered by unless habitat suitability is high.

Second, I binned the raster permeability layer based on 20 breaks creating 5% increments to model the wildness value at concentric increments around parks (Table 2).

The top twenty percent (5%, 10%, 15%, 20%) of wild landscapes around each park were then mapped based on the different models of permeability (i.e., where c was either 16, 1, or -16).

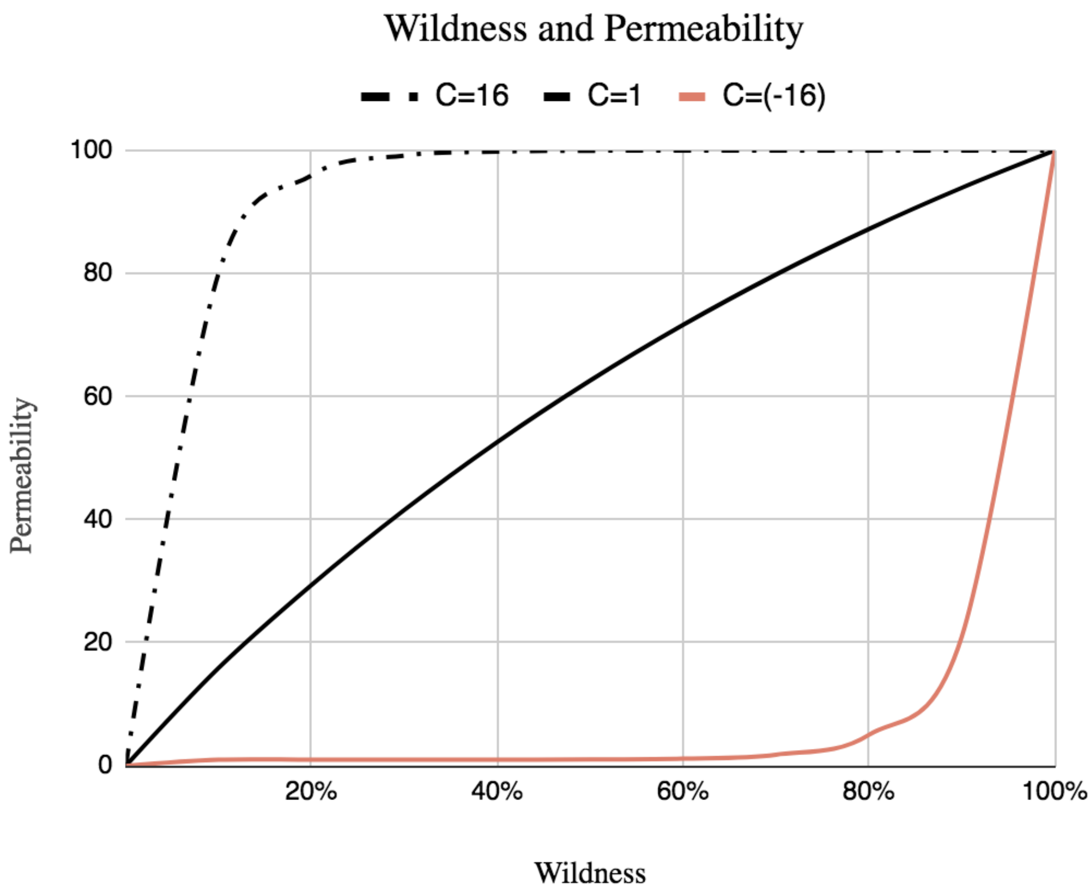

Figure 2. Model of assumptions of wildness and permeability. Curves represent degrees of wildness and the ease of species' permeability. The degree of human avoidance is assumed to be species-specific, therefore these curves allow me to model varying degrees of wildness and permeability for a variety of species. Equation for model P =100-99*((1-exp(c*W)/(1-exp(c))), where C is the curve variable, W is degree of wildness and P is permeability.

Table 2. Breaks for permeability types and wildness value.

	Wildness Value			
Permeability	Top 5%	Top 10%	Top 15%	Top 20%
C= 1	1.51	2.80	3.98	5.07
C= 16	0.37	0.65	0.88	1.10
C= (-16)	14.31	27.85	39.21	50.28

A permeability and wildness value composite map were created next. I prepared each permeability layer (c=16, c=1, c=(-16)) by breaking apart the datasets and assigning each bin a fuzzy membership. For example, for the c=1 permeability layer the top 5% bin received a value of one and all other cells received a value of zero. I repeated this procedure for the other two permeability layers and then combined all three 5% bin layers using a fuzzy sum overlay analysis. The fuzzy sum overlay surveyed each cell from each layer and asked, “Is the cell in the top 5%?” ArcGIS fuzzy sum overlay uses the equation and considers the combined evidence of all three layers to be more important than any single occurrence while never exceeding 1 (Theobald et al., 2013). If more than one layer had a top 5% cell (value= 1) then the fuzzy overlay had more reliability since the operation is “increasive”. This process was repeated for the additional bins: top 10%, top 15%, and top 20% to create a fuzzy overlay for each bin.

To re-combine the bin layers, I reclassified each fuzzy overlay. Then, I used the reclassified fuzzy overlays to create a composite map with the cell statistics minimum value tool. The cell statistics minimum value tool surveys each cell from each layer and ask, “What is the minimum value for each cell?” and assigns that value to the cell. This final step created a composite map of concentric circles of permeability and wildness value surrounding protected areas. In this model wildness is used to model permeability based on distance from a park.

The top 5%, 10%, 15% and 20% wildness value for each permeability type in the composite map was turned into a polygon to determine the area of each park's greater ecosystem. Originally, I decided a priori that my analysis of the greater ecosystem would terminate after 120 miles since seasonal ungulate ranges vary between 50 to 120 miles beyond Yellowstone National Park (Middleton, 2016) and I hoped to keep the extent of my analysis consistent across all five parks. However, after mapping the minimum (50 mile) and maximum (120 mile) buffers I realized that the greater ecosystems would intersect populated cities over 75,000 people.

While understanding the complexities of the intersection of cities and a park's greater ecosystem is a worthy pursuit, it was beyond the scope of this study. In addition, I realized that the 50 to 120-mile buffers were not based on a cost weighted distance layer, and therefore, are less realistic than my semilinear and nonlinear permeability models. Therefore, I assumed that my permeability layers were more reliable, and I clipped my further analysis at the 5% wildness value around each park boundary. Although this was a logical construct it gave me the opportunity to develop a methodology that can be revisited and updated as more is known. This analysis allowed me to develop a methodology that uses wildness and permeability to identify the greater ecosystems surrounding parks.

Using the composite map and the top 5% wildness values, I assessed the composition of vegetation types and conservation status of the greater ecosystem of each park. The vegetation composition and diversity of the greater ecosystems was calculated by counting the number of current National Vegetation Classification (NVC) ecosystems at macrogroup (level 5) present and the percentage of area that those ecosystems were already represented bin GAP Status 1 and 2 reserves. Next, the number of macrogroup ecosystems in each park was compared to each greater ecosystem around the park. The total number of new macrogroup ecosystems for each park was tabulated as unique ecosystems found in the greater ecosystems surrounding parks. A count on if the ecosystem is currently present or underrepresented in America's GAP Status 1 or 2 reserve system was completed. Underrepresentation was defined as represented in less than 50% in GAP Status 1 or 2 reserves. Ecosystem representation targets have been outlined by the Aichi target 11 of the Convention on Biological Diversity (17% by 2020) and Wilson's half Earth proposal (50%), and Nature Needs Half (NNH) initiative (50%) (Cunningham & Beazley, 2018). Fifty-percent was chosen for this analysis in order to meet the "big bold conservation targets" proposed by Wilson and NNH (Dudley et al., 2018). The NVC classifications for non-ecosystems (i.e. open water, disturbed lands, barren lands, urban lands, or quarries and mines) were counted as" restoration opportunities" or "other" rather than as ecosystems.

Additionally, restoration opportunities in the greater ecosystems were documented by counting the hectares of barren land, herbaceous agriculture, pasture and hayfield crops, developed, recently disturbed or modified areas, and quarries, mines, and open pit found. The percentage of each greater ecosystem that is GAP Status 1, 2, 3, or 4 was then recorded. This query-based analysis allowed me to determine if the greater ecosystems surrounding parks are wild, connected, diverse, or protected.

Results

The results of this study include a sensitivity analysis of the greater park ecosystems using four different models, an identification of the greater ecosystem of five park units, and the diversity and GAP Status of each greater ecosystem.

Sensitivity Analysis of the Size of Park Greater Ecosystems

The variability in total area of the top 5% of wildness values (permeable lands) around Yosemite-Sequoia GEM varied between 74,545 and 110,668 square kilometers (Table 3, Figure 3). In addition, the Grand Canyon GEM was 80,273 square km (c=1), 77,289 square km (c=16), and 23,052 square km (c=-16). Yellowstone National Park varied between 62,839 square kilometers and 71,863 square kilometers (Table 4, Figure 4). The GEM area size average (n=4) for each greater ecosystem in the top 5% of wildlands was 94,034 ± 15,172 km^2 for the Yosemite-Sequoia GEM (Figure 5), 66,322 ± 28,973 km^2 for the Grand Canyon GEM (Figure 6), and 68,869 ± 4,177 km^2 for the Yellowstone GEM (Figure 7).

Identifying the Wild and Connected Greater Ecosystem of National Parks

The composites for each park allowed me to compare the top 5% and top 10% permeable wildlands surrounding parks (Table 3, Figure 3). The total area for each park and their greater ecosystem (GEM) is represented for each curve and the composite. Multipliers represent the amount that each park boundary is increased for each model of permeability that varied C (Table 3). If the top 5% permeable wildlands surrounding Yellowstone and Grand Teton National Parks are used to identify the greater ecosystems, the total area beyond the park boundaries is multiplied by three. Specifically, the total area increases from 22,198 of the Yellowstone and Grand Teton National Parks to 71,487 km^2 of the greater ecosystem. If the top 10% of permeable wildlands surrounding the park is considered, the reserve increases by five times from 22,198 to 110,879 km^2. The Grand Canyon GEM increases 16 or 33 times depending on if the top 5% or top 10% wildlands are evaluated, and Yosemite-Sequoia GEM is increased by 9 or 13 times.

Since it is assumed that wildness estimates the permeability of the ecosystems, the landscapes around the Grand Canyon are the most permeable, then Yosemite-Sequoia, and finally Yellowstone-Grand Teton. This ranking is based on the top 5% permeable wildlands surrounding parks.

Table 3. Sensitivity analysis of the size of park greater ecosystems.

	C=16 (SqKm)	Multiplier	C=1 (SqKm)	Multiplier	C=(-16) (SqKm)	Multiplier	Composite (SqKm)	Multiplier
Yellowstone GEM								
Yellowstone-Grand Teton	22,198		22,198		22,198		22,198	
Top 5%	62,839	2.83	71,863	3.24	69,288	3.12	71,487	3.22
Top 10%	91,017	4.10	107,429	4.84	106,454	4.80	110,879	5.00
Top 15%	116,112	5.23	239,098	10.77	135,941	6.12	300,136	13.52
Grand Canyon GEM								
Grand Canyon	5372		5,372		5372		5372	
Top 5%	77543	14.44	80527	14.99	23,052	4.29	84,167	15.67
Top 10%	133911	24.93	157513	29.33	96,214	17.91	179,165	33.36
Yosemite GEM								
Yosemite-Sequoia	12,748		12,748		12,748		12,748	
Top 5%	74,545	5.85	91,589	7.18	99,336	7.79	110,668	8.68
Top 10%	111,920	8.78	164,153	12.88	156,052	12.24	170,377	13.36

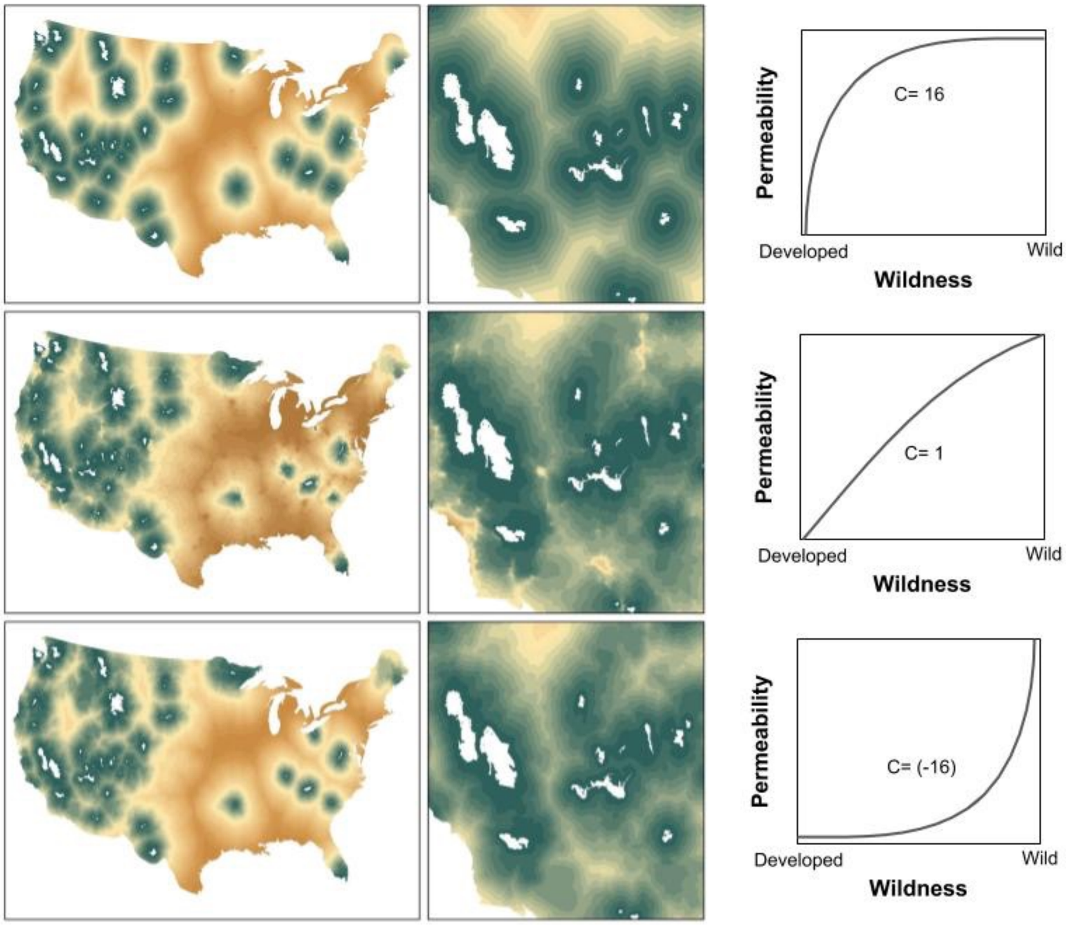

Figure 3. Wildland curve comparisons for greater ecosystems around parks.

Greater Ecosystem Model (GEM) Diversity

The greater ecosystems of these five parks held an extra 28 unique National Vegetation Classification Level 5 (NVC) macrogroup ecosystems that were not already represented within park administrative boundaries (Table 5). The Grand Canyon GEM contained nine macrogroup ecosystems, the Yellowstone-Teton greater ecosystem eight, and the Yosemite-Sequoia greater ecosystem eleven that were not already represented within adjacent park boundaries. Two ecosystems, Central Rocky Mountain Montane-Foothill Grassland & Shrubland and Southern Rocky Mountain Lower Montane Forest, were represented in two park greater ecosystems and counted once. Six restoration opportunities were found in Grand Canyon's GEM and five in Yellowstone-Teton and Yosemite-Sequoia's GEMs. These restoration opportunities are land units that are currently barren land, herbaceous agriculture, pasture and hayfield crops; developed, recently disturbed or modified areas; and quarries, minds, and open pits.

The Grand Canyon greater ecosystem had 17 NVC macrogroup ecosystems that are currently underrepresented in GAP Status 1 and 2 reserves (Appendix 1, Table 16). Underrepresentation is defined as represented in less than 50% in GAP Status 1 or 2 reserves. Within the Grand Canyon's GEM, the southern rocky mountain montane shrubland (6%), the Great basin-intermountain dwarf sagebrush steppe & shrubland (12%) and the warm interior chaparral (16%) were all represented in less than 20% of the current reserves and would add ecosystem diversity to the park (Table 6). Secondly, nine unique ecosystems can be found in the Grand Canyon GEM that are not found in the park. Seven of these macrogroup ecosystems are underrepresented in the American system of reserves. The Yellowstone-Teton GEM held 16 macrogroup ecosystems that are underrepresented; nine of which are in less than 20% of current reserves (Appendix 1, Table 17). The great plains mixed grass and fescue prairie (3,556 hectares), the great plains saline wet meadow and marsh (421 hectares), the central rocky mountain mesic lower (1,175 hectares), and the southern rocky mountain montane shrubland (14,681 hectares) are in less than 5% of current reserves and represent large areas of the greater ecosystem. There were fifteen underrepresented macrogroup ecosystems in Yosemite-Sequoia's GEM. The California annual and perennial grassland was 1,573 hectares and is only represented in 18% of GAP Status 1 or 2 reserves. As well the great basin saltbrush scrub (4,453 hectares) is represented in less than 25% of current reserves.

Restoration opportunities, including barren lands, mines and open pits, agricultural lands, disturbed lands, and developed and urban areas, were found in all three greater ecosystems. The Grand Canyon GEM had 406 hectares of quarries, mines, gravel pits and oil wells while Yellowstone-Teton (8 hectares) and Yosemite-Sequoia (2 hectares) greater ecosystems only had ten hectares combined. Recently disturbed or modified land units can be found in the Grand Canyon GEM (481 hectares), Yellowstone-Teton GEM (1,179 hectares), and the Yosemite-Sequoia GEM (191 hectares).

Table 4. Top 5% wildland curve comparisons for greater ecosystems around parks.

	Greater Yellowstone GEM Area (sq km)	Greater Grand Canyon GEM Area (sq km)	Greater Yosemite GEM Area (sq km)
c= 1	71,863	80,527	91,589
c= 16	62,839	77,543	74,545
c= (-16)	69,288	23,052	99,336
Composite	71,487	84,167	110,668
Average	68,869	66,322	94,034
Standard Deviation	4,177	28,973	15,172
Sample size	4	4	4
Confidence Coefficient	1.96	1.96	1.96
Margin of Error	4,093.88	28,394.06	14,868.83
Upper bound	72,963	94,716	108,903
Lower bound	64,775	37,928	79,165
Max	71,863	84167	110,668
Min	62,839	23052	74,545
Range	9,024	61,115	36,122

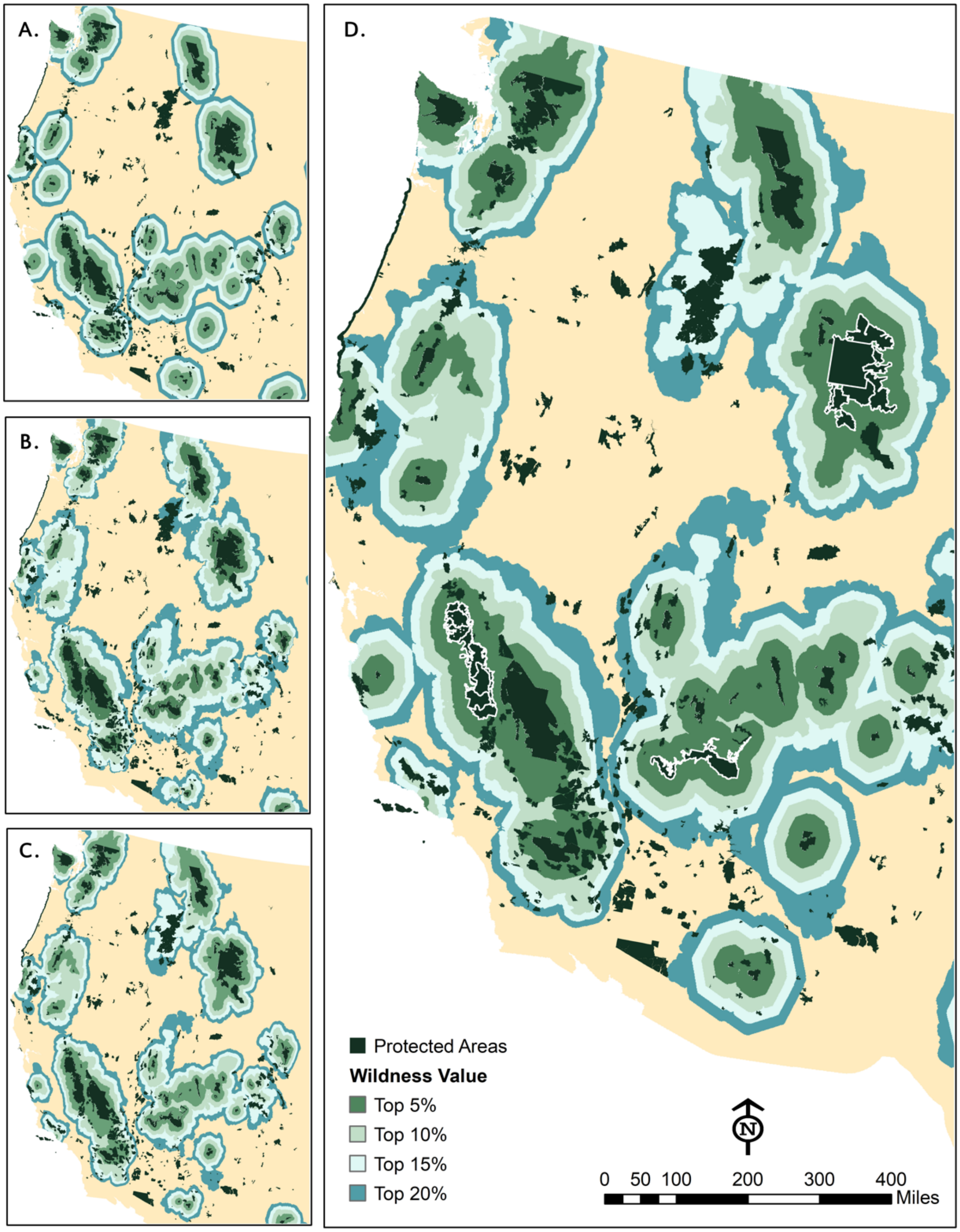

Figure 4. Sensitivity analysis of permeability based on three types of wildness. (A) Represents c= 16 curve (B) Represents c= 1 curve and (C) Represents c= (-16) curve. (D) Models a composite of all three representations using a fuzzy sum overlay analysis. Protected areas outlined in white represent the focal national park and adjacent wilderness areas.

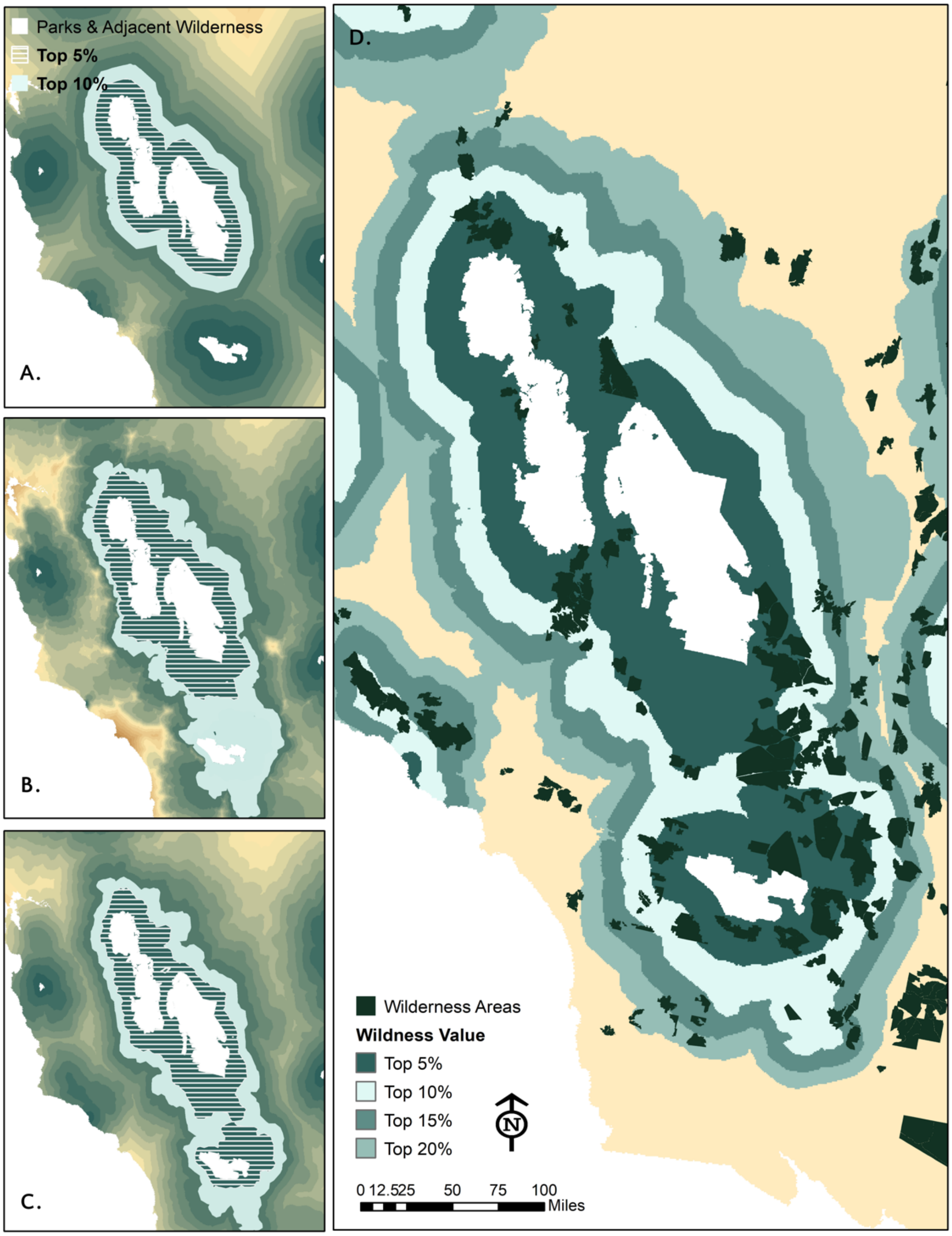

Figure 5. Yosemite greater ecosystem model (GEM). (A) Represents c= 16 curve (B) Represents c= 1 curve and (C) Represents c= (-16) curve. (D) Models a composite of all three representations using a fuzzy sum overlay analysis.

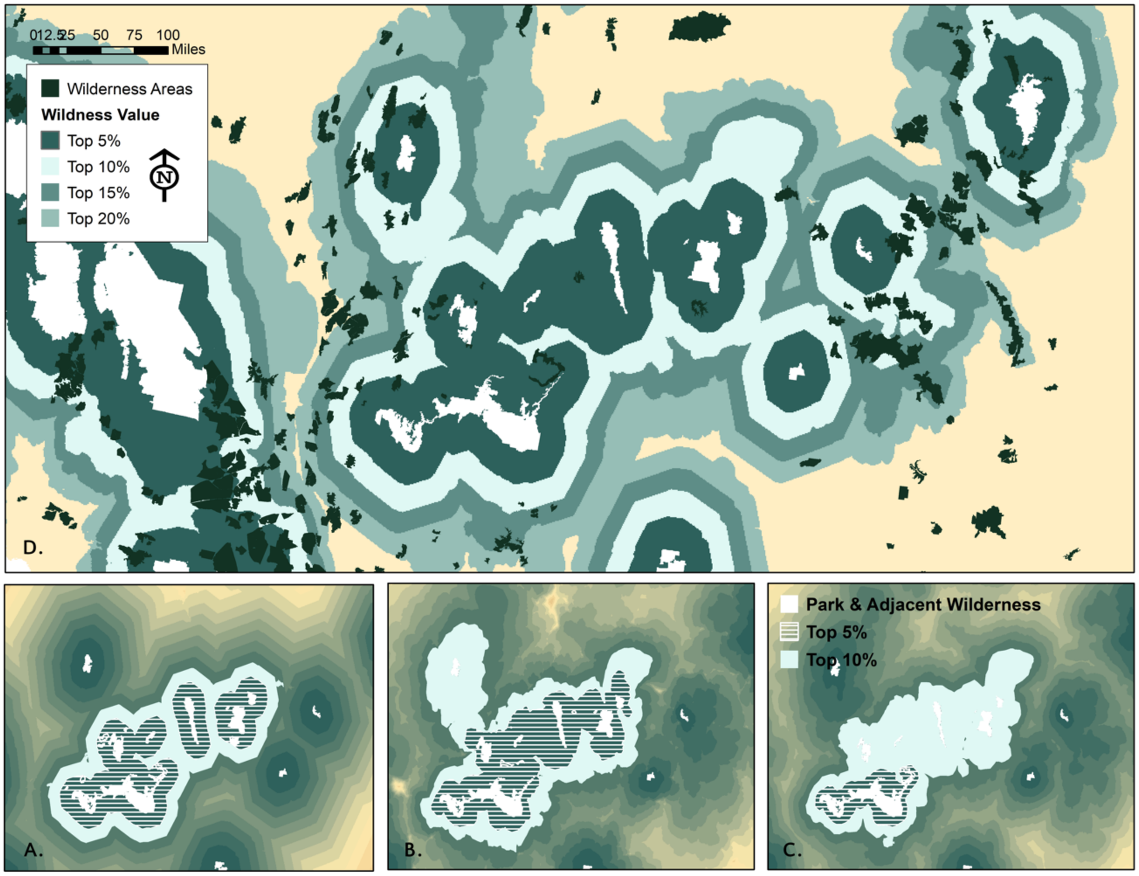

Figure 6. Grand greater ecosystem model (GEM). (A) Represents c= 16 curve (B) Represents c= 1 curve and (C) Represents c= (-16) curve. (D) Models a composite of all three representations using a fuzzy sum overlay analysis.

Greater Ecosystem Model (GEM) GAP Status

The majority of land units surrounding National Parks is GAP Status 3 or managed for multiple use including extraction (Table 7, Figure 8). The Yosemite-Sequoia GEM has 43% of its land preserved as GAP Status 1 or 2. Then 28% is GAP Status 3, 14% is GAP status 4, and 15% is unknown. Forty percent of the Grand Canyon GEM is GAP Status 1, 36% is GAP status 3, 9% is GAP Status 4, and 15% is unknown. In the Greater Yellowstone GEM, 9% is GAP Status 1, 60% is GAP Status 2, 27% is Gap Status 3, and 4% is unknown.

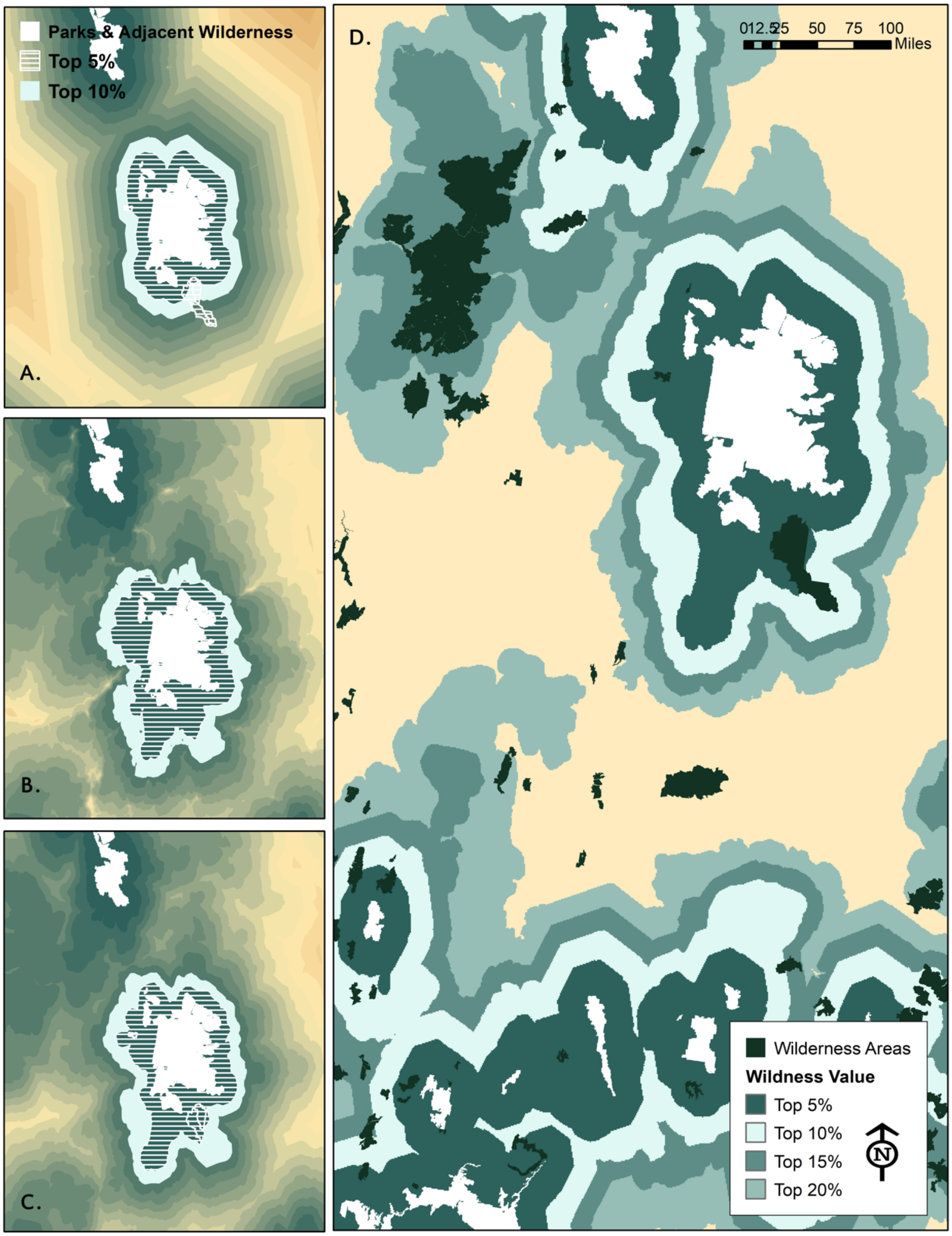

Figure 7. Yellowstone greater ecosystem model (GEM). (A) Represents c= 16 curve (B) Represents c= 1 curve and (C) Represents c= (-16) curve. (D) Models a composite of all three representations using a fuzzy sum overlay analysis.

Table 5. Alpha diversity for parks and their greater ecosystems.

Park	Number of Ecosystems	Additions in Greater Ecosystems	Restoration Opportunities & Other
Grand Canyon	26	9	6
Yellowstone-Teton	28	8	5
Yosemite-Sequoia	33	11	5

Table 6. Gamma diversity of unique ecosystems in parks' greater ecosystems.

Unique Ecosystems	Ecosystem Class (Level 5)	Hectares Added	Representation GAP Status 1 or 2
	Yosemite-Sequoia Greater Ecosystem		
1	Californian Coastal Scrub	5	12
2	Central Rocky Mountain Montane-Foothill Grassland & Shrubland	<1	10
3	Great Plains Floodplain Forest	<1	4
4	Introduced & Semi Natural Vegetation	35	33
5	North American Coastal Salt Marsh	<1	32
6	North Pacific Bog & Fen	<1	43
7	Pacific Coastal Beach & Dune	<1	23
8	Rocky Mountain-Great Basin Montane Riparian Forest	<1	28
9	Southern Rocky Mountain Lower Montane Forest	3	32
10	Southern Rocky Mountain Montane Shrubland	0	6
11	Warm Interior Chaparral	2	52
	Grand Canyon Greater Ecosystem		
	Central Rocky Mountain Montane-Foothill Grassland & Shrubland	<1	10
12	Chihuahuan Semi-Desert Grassland	1	6
13	Interior Warm & Cool Desert Riparian Forest	6	18
14	Madrean Lowland Evergreen Woodland	<1	16

15	North American Warm Desert Ruderal Scrub & Grassland	17	3
16	Rocky Mountain-Great Basin Montane Riparian Forest	141	7
17	Rocky Mountain-Sierran Alpine Tundra	132	127
18	Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland	64	69
19	Western North American Temperate Cliff, Scree & Rock Vegetation	416	26
	Yellowstone-Teton Greater Ecosystem		
20	Great Basin Saltbush Scrub	23	10
21	Great Basin-Intermountain Dry Shrubland & Grassland	109	24
22	Great Plains Cliff, Scree & Rock Vegetation	7	3
23	Great Plains Forest & Woodland	27	3
24	Great Plains Marsh, Wet Meadow, Shrubland & Playa	36	27
25	Great Plains Sand Grassland & Shrubland	170	1
	Southern Rocky Mountain Lower Montane Forest	137	32
27	Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland	6	29

Table 7. GAP status in greater ecosystems surrounding national parks.

	Greater Yosemite-Sequoia GEM		Grand Canyon GEM		Greater Yellowstone GEM	
GAP Status	Hectares	Percentage	Hectares	Percentage	Hectares	Percentage
1	1,426,025	18%	171,674	2%	273,885	6%
2	1,993,135	25%	2,841,412	38%	157,546	3%
3	2,242,964	28%	2,672,718	36%	2,879,245	60%
4	1,070,523	14%	667,563	9%	1,311,821	27%
Unknown	1,177,757	15%	1,157,108	15%	210,160	4%

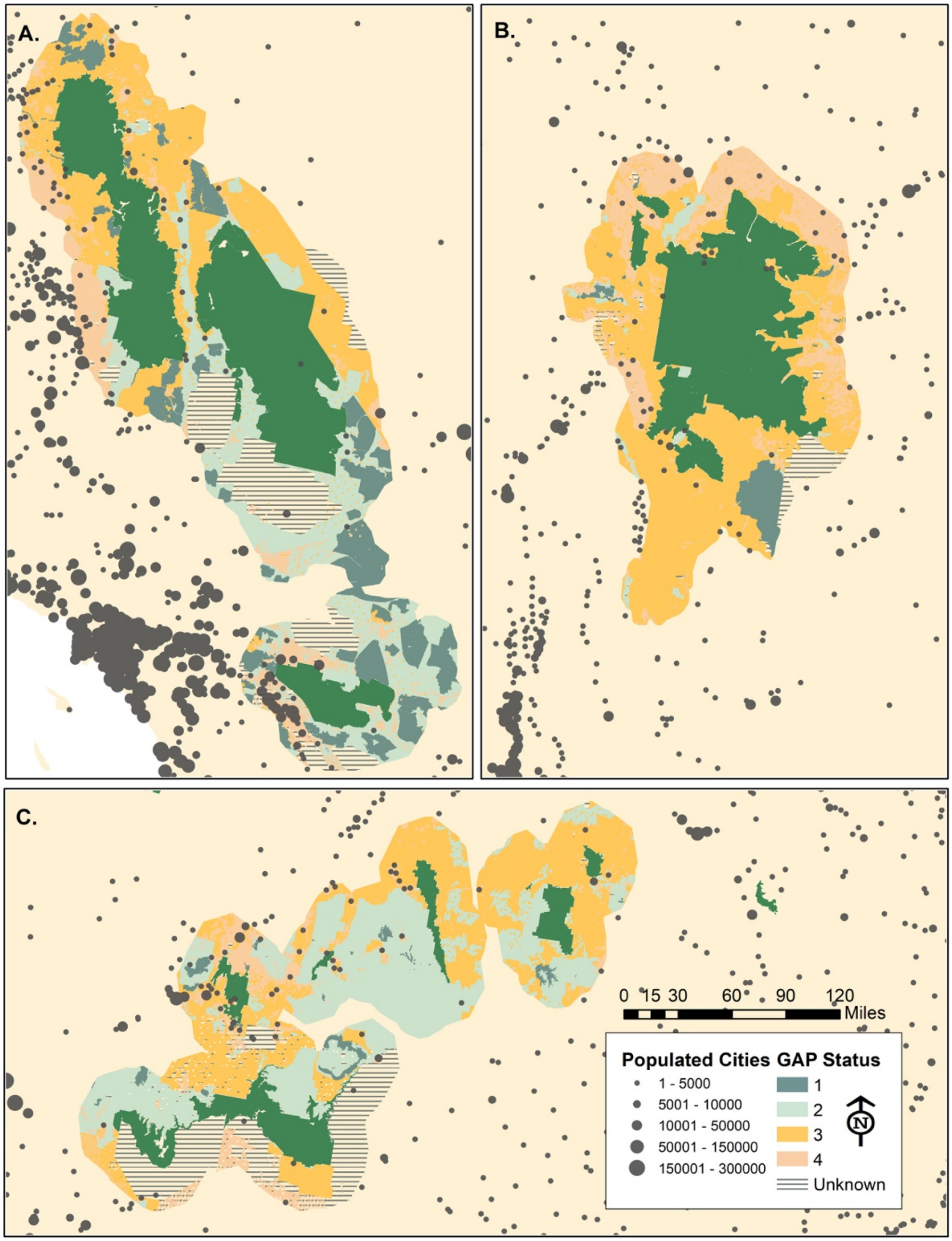

Figure 8. GAP Status surrounding national parks. Areas shaded 1-2 represent protected areas, 3 allows extractive use, and 4 is no known mandate. A) Yosemite Greater Ecosystem, B) Yellowstone Greater Ecosystem, and C) Grand Canyon Greater Ecosystem.

Discussion

Mapping the greater ecosystems of parks or protected areas has been consistently recognized as challenging (Hansen et al., 2011). Though parks have clear administrative boundaries, the ecological processes and populations that enter and exit parks are less concrete (Theberge, 1989). The coarse-scale greater ecosystem model (GEM) aids in evaluating the permeability of parks and their surrounding landscapes. Different than the protected area-centered ecosystem (PACE) model, the GEM model allows for one input, wildness, to be used to model permeability and greater ecosystem delineation.

Using wildness as the basis for estimating permeability, GEM simplifies the PACE model mapping process and allows land managers to quickly determine the greater ecosystem boundaries at varying degrees using one map layer. The use of wildness as an estimate of permeability is considered compatible with using habitat-suitability (Krosby et al., 2015), however much is unknown about different terrestrial species responses to wildness and human modification. By merging three alternative relationships between wildness and permeability the GEM model considers variability of permeability. The three alternative models of wildness and permeability resulted in three mapped estimates of connectivity around parks. The size of the greater ecosystems of the parks assessed here depended on assumptions of how the human footprint (reduced wildness) influences permeability. The relationship between wildness and permeability where $c = 16$ produced maps more similar to Euclidean distance away from parks suggesting that gradients in wildness had little effect on permeability. In contrast, where $c = (-16)$, permeability away from parks was strongly influenced by the human footprint and degraded degrees of wildness.

Many permeability models currently use a linear or semilinear model; however, in the GEM model, the semilinear model alone can yield results that could be overly liberal and define a greater ecosystem boundary that is larger than actual species movements. Keeley et al.'s (2016) equations for resistance helped me to consider alternative species responses. By combining the three potential species responses into a composite, the GEM model seeks to be more realistic about varied species movements and uncertainty surrounding exactly how the loss of wildness through the human footprint can influence connectivity around parks. More research and further modeling are needed to further understand species movements in regard to wildness and permeability.

Secondly, in other permeability models, resistance layers built from multiple habitat-suitability inputs yield divergent results causing conflicts when being compared across regions (Zeller et al., 2016). Therefore, the coarse-scale GEM model streamlines the delineation of a parks' greater ecosystems and aids in large scale modeling across the continent. When determining the permeability from park to park, across the continent, it became obvious that wilderness areas outside of parks greatly affect permeability. Parks with less wilderness areas surrounding them had smaller greater ecosystem sizes in three of four models (Figure 5). When using the GEM model in the future, I suggest creating the cost weighted distance layer from protected areas (parks and wilderness) rather just than from parks. By including wilderness areas in the analysis, a relationship of protected area size and permeability might emerge especially since when modeling the five Parks in this study, I found that small wilderness areas surrounding parks increase permeability. Additionally, more certain delineations of GEMs could become more evident if parks and wilderness areas were included in the model.

Park Monitoring using the Greater Ecosystem Model

Since it is generally agreed that parks are too small and greatly affected by their greater ecosystem context, the GEM model can serve as monitoring tool for a variety of factors outside parks. As the climate shifts and human expansions increase, the GEM model can be used to monitor changes to land use, ecosystem representation, biodiversity, and other human impacts surrounding parks. Many of these variables are monitored inside parks by the NPS Inventory & Monitoring program (Hansen et al., 2011), however the GEM model allows for connections to the surrounding lands to be queried quickly. Increased monitoring of these factors can aid in further identifying and quantifying the drivers of biodiversity losses within parks and aid in protecting them.

Lastly, the GEM model ranks the permeability of landscapes surrounding parks. Because permeability and connectivity are important for landscape level resilience, classifying parks or wilderness areas that are more permeable or less permeable helps conservationists know which parks need the greatest protection. For instance, since wildlands within GEMs represents permeability, then Grand Canyon has the most permeable greater ecosystem in this study. The top 5% of permeable wildlands around the Grand Canyon increases the Grand Canyon (5,372 km^2) by 1,467%, or sixteen times the original reserve size (84,167 km^2). The Yosemite-Sequoia GEM increases the two park units by 768%, or nine times the original size (22,197 to 110,667 km$^{2)}$. Meanwhile, the Yellowstone-Grand Teton GEM only increases the reserve three times or 222% (22,197 to 71,487 km$^{2)}$. The Greater Yellowstone Coalition, a conservation organization aimed at protecting Yellowstone and the surrounding lands identifies the Greater Yellowstone Ecosystem as being 80,937 km^2.

GEM model maps and ranks allow ecologists and conservationists to ask new questions about connectivity, human modification, and resilience of our National Parks. For example, Yellowstone-Teton National Park is larger than Grand Canyon and Yosemite-Sequoia National Park, however it is less wild and connected to its surrounding landscape. The Grand Canyon, set in the middle of the southwest, is in close proximity to other protected areas and wilder, causing it to be more resilient to climatic changes or human-matrix expansions. Ranking GEMs can also help to determine the appropriate size for park expansions or corridor planning. Parks with lower rankings (lower permeability) need greater expansions and increased corridors to other protected areas to be viable in the future. Parks with higher rankings (greater permeability) might simply need landscape buffers.

Diverse and Protected GEMs

The GEM model allowed me to determine the alpha diversity of parks and the gamma diversity of the national parks and their surrounding landscapes. Yosemite-Sequoia National Park and its GEM had the greatest alpha diversity with 44 ecosystems represented, ten of which are underrepresented or found in less than 50% of GAP status 1 or lands in the American reserve. Grand Canyon National Park and its GEM had 37 ecosystems represented (seven of which are underrepresented) and the Yellowstone-Teton National Parks and its GEM had 36 ecosystems represented (eight of which are underrepresented). In addition, all three park units had five or more restoration opportunities. Specifically, the Grand Canyon GEM had 406 hectares of quarries, mines, gravel pits, or oil wells. While the Grand Canyon GEM has the greatest permeability, the extractive uses mentioned within the top 5% of wildlands surrounding the Grand Canyon could greatly impact its resilience and protection.

I also surveyed GEMs for their current GAP Status to determine how protected they are for the future. The Yosemite-Sequoia GEM has 43% of its land units protected in GAP Status 1 or 2 lands, 28% is multi-use in GAP Status 3, and 29% is GAP Status 4 or unknown meaning that no known mandates are in place. The Grand Canyon GEM has 40% protected in GAP Status 1 or 2 lands, 36% can be used for multiple uses, and 24% is GAP status or unknown.

The Yellowstone-Teton GEM is the least protected out of the three national parks in the study. Only 9% of its GEM is protected in GAP Status 1 or 2 lands, 60% can be used for multiple uses (including extractive), and 31% is unmandated. This may be due to the fact that wilderness areas sharing a boundary with Yellowstone and Grand Teton were considered part of the overall park complex used as core areas (and thus not counted as part of the conservation status of surrounding landscape). Yellowstone-Teton National Park also had less small wilderness areas and national parks in close proximity to its administrative boundaries when compared to Grand Canyon and Yosemite-Sequoia National Park. Yellowstone National Park has been coined a “crown jewel” of the American reserve system (Chandler, 1988); however, in delineating and surveying its greater ecosystem it is apparent that it is less connected and protected than the other national parks in this study. If long term protection of America’s brightest landscapes is our aim, it is time to reimagine the American reserve.

Conclusions

The greater ecosystems around national parks and wilderness areas within the American reserve system need to each be identified and then surveyed for wildness, connectivity, diversity, and protection. Secondly, park expansions and wildlife corridors need to be considered for parks that lack wildness, connectivity, and diversity. Thirdly, extractive use within GEMs need to be halted and reconsidered. If the top 5% of permeable wildlands surrounding national parks is still intact, then the time is now to buffer parks before human modification further degrades landscapes around parks causing species losses within parks.

Historically, the National Park System in the U.S. set aside landscapes that were gems for future generations. In doing so, America's national parks became our "best idea" and a great inspiration to national park systems around the world. To preserve parks in the Anthropocene a reimagination of the American reserve is essential. In addition, to reach Wilson's half-earth plan it is logical to begin with preserving the wildest landscapes first. These landscapes should be adjacent to current protected areas to aid in buffering park lands and therefore buffering species losses. Secondly, these landscapes should be connected to one another in order to influence permeability across the continent. Since 40% of land in the West is publicly owned it is also plausible that by connecting protected areas we could at least increase public lands in the West to 50%. While, not all of those lands would be permanently protected (GAP Status 1 or 2 lands), it could be a start to Wilson's half-earth plan and aid in preserving 85% of species in the West.

Chapter III

The Conservation Value of Recreational Trails as Continental Corridors

Increasing landscape connectivity, the ability of individuals or populations of wildlife to permeate a landscape, is a crucial conservation initiative in the new millennia (Heller & Zavaleta, 2008). Landscape connectivity mitigates the effects of habitat fragmentation and enhances landscape resilience (Haddad et al., 2015). Only 41% of the contiguous United States (U.S., hereafter) is intact enough to allow for species movements (McGuire et al., 2016). Connectivity from isolated areas, or remnants, can be fostered through the use of corridors (Hilty, 2006). Corridors promote landscape permeability and flows across ecosystems, in turn reducing extinction rates and maintaining ecosystem processes. Corridors also enhance wildlife movement, add aesthetic appeal, provide new foraging areas, and act as "refugia" during disturbances (Haddad et al., 2015).

Background

Facilitating movement for wildlife is essential as the climate continues to shift. With a 2.7° Celsius temperature change, corridors between all-natural areas in the U.S. would allow for 65% of species to move to their new habitats (McGuire et al., 2016). In addition, the projected human footprint from 2001 to 2051 will expand 67%, causing major threats to biodiversity in protected areas (national parks and wilderness areas) (Martinuzzi, 2015). Land managers for protected areas realize that current land unit boundaries are simply too small and disconnected to facilitate species movements (Aycrigg et al. 2013; Jenkins et al., 2014; Monahan & Fishnelli, 2014). Therefore, a series of agencies are modeling potential corridors across the country (Anderson et al., 2016; Belote et al., 2016; Wildlife Resources Policy Committee, 2018). Corridors can be unplanned or planned as strips or networks (Hilty, 2006). Corridor design often follows streams and ridgelines which are natural features that species use for movement and dispersal (Hilty, 2001; Hilty & Merlander, 2004).

On a large scale, The Landscape Conservation Cooperative Network is designing connective corridors for the U.S. (2015). Additionally, the Nature Conservancy (Anderson et al., 2016), the U.S. Fish and Wildlife Service (Wildlife Resources Policy Committee, 2018), the Wilderness Society (Belote et al., 2016) and several state institutions are using connectivity analysis to model resilient landscapes and plausible migrations as the climate changes (Alagador, Cerdeira, Araújo, & Anderson, 2016; Amnet, 2016; Bakker et al., 2015). Analyzing the best locations for corridors takes a well-researched, interagency, large scale approach (Majka, Jenness, & Beier, 2007).

On a small scale, greenways are corridors that increase connectivity in urban spaces where landscapes are highly fragmented and influenced by the human-matrix. Boston’s Emerald Necklace, a greenway designed by Frederick Law Olmsted, adds recreational, cultural, aesthetic, and ecological values to Boston’s city parks and urban spaces (Ahenn, 1995). When corridors such as greenways are added as green infrastructure to cities, landscape resilience is improved even amidst the human-matrix. Adding green infrastructure facilitates migrations, dispersal, and gene flow (Hilty, 2006; Matthews & Byrne, 2015). Green infrastructure also aids in climate adaptation because it buffers urban heat island affects, reduces storm water runoff, and afford recreational opportunities and climate mitigation because wildlands naturally reduce greenhouse gas emissions (Matthews et al., 2015). Lastly, the benefits of green infrastructure are multi-faceted and have large public appeal, which makes them easier to implement (Emmanuel & Loconsole, 2015; Foster, Lowe, & Winkelman, 2011).

Noting that 50-70% of the Earth is human-modified (Tucker et al., 2018) adding green infrastructure to the current U.S. landscape on a larger scale could counteract the negative effects of the human footprint. The human footprint affects habitats, biodiversity, and species movements (Tucker et al., 2018) and significantly contributes to species extirpations (Pringle, 2001; Di Marco et al., 2018). Currently, there is uncertainty on the exact effects the human-footprint has on species, since responses can occur at the level of an individual animal via behavioral responses, based on occurrence, or be observed by impacting long range migrations (Tucker et al., 2018). However, there is agreement that the human footprint restricts landscape permeability (Keeley et al., 2016). Moreover, using the landscape planning strategy of cities on a continental scale, large scale green infrastructure could aid in climate mitigation and adaptation.

Building a Protected Area Network

Building a national protected area network of national parks and wilderness areas allows the American reserve system to respond to both climatic shifts and the expanding human footprint. In North America, protected areas (GAP status 1 or 2) are set aside as refuges for a variety of species and ecological processes (Brewer, 2005). Climate modeling suggests that over 700 mammals, birds and amphibians will use these locations as conduits or stopovers for migrating to more desirable locations (Majka, 2016).

However, national parks in the U.S. are not resilient for their current populations due to struggling population viabilities (Haddad et al., 2015; Jenkins et al., 2014). Small park sizes and fragmented ecosystems surrounding parks have contributed to ecosystem degradation and the loss of species (Aycrigg et al. 2013; Jenkins et al., 2014; Monahan & Fishnelli, 2014). Though most public lands and protected areas are in the West, many are surrounded by lands with policies that permit extractive use (GAP status 3). Without a buffer between extractive use and protected areas ecosystem degradation and species extirpations will continue.

In South America, Chile has made a commitment to expand and buffer their national parks, and then connect them through a "Ruta de Parques" (Bisharat & Chin, 2017). The Ruta de Parques uses existing rural roads, trails, and ferry ways to connect 17 national parks. Capitalizing on existing green infrastructure as an anchor for continental connectivity, Ruta de Parques focuses on connecting reserve sites for both human recreation and biodiversity conservation (Bisharat & Chin, 2017). To complete the project, Chile's President, Michelle Bachelet, partnered with the Tompkins Foundation, a private land trust, to procure the largest land donation in history and the new corridor is slated to make the Chilean reserve system the longest in the world (Bisharat & Chin, 2017).

Similar to Chile's, the original intent of the U.S. park system was for human enjoyment and recreation, and then ecological benefits followed (Brewer, 2005). Noting the recreational value of scenic trails in the West, I wondered what conservation values trails might also hold. Here, I evaluated if two of the National Park Service's (NPS) scenic and historic trails could be the anchor for landscape connectivity throughout the

West, by providing green infrastructure for a continental scale wildlife corridor. Set aside by Congress for their historic, recreational, scenic, and cultural values (16 U.S.C. § 1241) two scenic trails the Pacific Crest Trail (PCT) and the Continental Divide Trail (CDT) traverse a variety of latitudes and elevational gradients. Additionally, they pass through 85 wilderness areas and 10 parks in the American West.

Trails as Green Infrastructure for Corridors

Using trails as infrastructure for connectivity is currently underdeveloped. Connectivity studies have instead focused on the best route for corridors based on wildness, ecological flows, and climate projections (Belote et al., 2016 and 2017; Carroll et al., 2018; McGuire et al., 2016). Trails generally follow ecological flows: riparian zones which are natural flow zones and/or ridgelines which humans and animals migrate along (P. Kahn, personal communication, 2018). Secondly, trails traverse landscapes with high aesthetic values, which could be correlated with species richness and ecosystem diversity (P. Kahn, personal communication, 2018). Thirdly, the PCT provides a logical corridor route because it is was set aside in 1936 by mountain clubs in the West as preservation tool (Mann, 2011). Eventually, recreationists sought to place protected areas sprung up around the PCT because it provided a recreational walking path from Canada to Mexico (Mann, 2011).

Trails could combine both the private and public sector for continental conservation initiatives (Aycrigg et al., 2016) because conservation that promotes human recreation enlists a diverse set of stakeholders (Hilty, 2006; Beier, 2014). The National Park Service is interested in connectivity surrounding parks due to current large-scale impacts of land use and climate change (Hansen et al., 2011) and the Wilderness Society has mapped corridors among large protected areas nationally (Belote et al., 2016). Equally, the U.S. Forest Service and Bureau of Land Management are currently reviewing land units with high conservation values that could become further protected and function as corridors (Belote et al., 2016).

Likewise, increasing private conservation in the West through land trusts and conservation easements seems like a valid next step for connectivity. The Nature Conservancy has modeled connectivity and resilience in the northeast and is now focusing on the rest of the country (Anderson et al., 2014). In the U.S., land trusts often fall along important corridors (Belote et al., 2016) and could be key to building a connected protected area network. Similar to Chilean Land Trust and the Tompkins Foundation, a targeted approach leveraging both public and private protected areas, would extend connectivity, and therefore, build a more resilient protected area network.

Landscape Connectivity Modeling

Landscape connectivity models for the U.S. map suitable linkages considering a suite of conservation values (Anderson et al., 2004; Belote et al., 2016). Species-specific models often use a flagship species to evaluate large landscapes (Simberloff, 1998). However, species-agnostic connectivity models based on naturalness or wildness approaches have relative spatial agreement with species-specific approaches (Krosby et al., 2015). This is likely due to the fact that species-specific connectivity models include data representing human infrastructure (e.g., roads and altered land cover) as part of their maps of landscape resistance (Zeller et al. 2012). These same features are typically important variables included in maps of naturalness, wildness, or the human footprint. In a wildness-based connectivity approach, the human footprint index is used as a resistance layer to model least cost corridors between core areas (Belote et al., 2016; Theobald et al., 2013; Venter et al., 2016).

Furthermore, landscape connectivity models often consider how regionally connected they are to their surrounding ecosystems (see Chapter II). Multiple inputs such as forward and backwards centrality (e.g., predicted geographic displacements of climate analogs) (Carroll et al., 2018) or corridor value which includes naturalness paired with a cost of movement away from a location (Belote et al., 2016) are considered when determining "connectedness". Thirdly, landscape connectivity models evaluate landscape diversity measures. These can include the number of microclimates present or the range of elevation (Anderson et al., 2016; Carroll et al., 2017), the GAP species richness (McKerrow et al., 2018), biodiversity priority (Jenkins et al. 2015), or ecosystem representation (Aycrigg et al. 2013).

Using a combination of conservation values with a wide range of parameters allows for a diverse set of questions to be answered by a variety of stakeholders. For instance, Belote et al. (2017) calculated the wildland conservation value of lands outside of protected areas in the U.S. by asking how wild, connected, and diverse they were in comparison to the all the landscapes in the U.S.

For this study, my analysis focused on the American West-- where public lands are already plentiful and where charismatic megafauna persist. While Jenkins et al. (2015) suggest that new conservation areas should be in the East, since it houses larger numbers of endemic species— specifically fish, reptiles, and amphibians--- I realized that the majority of protected areas were in the West, making connectivity opportunities closer to one another and on less private land. Here, I modeled a suite of conservation values to answer:

1. Could the Pacific Crest Trail (PCT) and the Continental Divide Trail (CDT) serve as continental corridors between protected areas in the American West?
2. Will the PCT and CDT be essential green infrastructure in the midst of climatic changes and human expansions?
3. How much of the PCT and CDT occurs on protected land and who manages it?

I was interested in this set of questions because current landscape level connectivity models have centered around finding the best route for corridors throughout the U.S. and predicting paths for species movements as the climate changes. I wondered if we already had the best corridor routes established through existing green infrastructure. If the route is established, we could spend our conservation effort on designating GAP Status 3 lands as protected areas (U.S. Forest Service and BLM), procuring new land agreements, and buffering currently protected areas.

Methods

I used a suite of conservation values to determine how wild, connected, and diverse the Pacific Crest Trail (PCT) and Continental Divide Trail (CDT) are compared to the rest of the land units in the U.S. I quantitatively evaluated wildness, connectivity priority, and biodiversity using seven datasets representing conservation value in a geographic information system, ArcGIS (Table 8). Five of the seven conservation values

Table 8. Datasets for the assessment of Pacific Crest Trail and Continental Divide Trail.

Data	Source	Website
Protected Area Database		
PADUS Gap Status	Gage, 2018	https://www.gagecarto.com
National Scenic and Historic Trails		
Pacific Crest Trail	Pacific Crest Trail Association, 2015	https://nps.maps.arcgis.com/home/item.html?id=4d59fc03928a4b07b83c84d823321f34
Continental Divide Scenic Trail	National Park Service, 2017	https://nps.maps.arcgis.com/home/item.html?id=908e9a2442bb4da48a4d979d98e02902
Wild		
Wildland Conservation Value	Belote et al., 2017	https://doi.org/10.1002/eap.1527
Human Footprint Database	Venter et al., 2016	https://doi.org/10.1038/ncomms12558
Connected		
Corridor Value	Belote et al., 2016	https://doi.org/10.1371/journal.pone.0154223
Forward Shortest Path Centrality	Caroll et al., 2018	https://doi.org/10.1111/gcb.14373
Diverse		
Gap Species Richness	McKerrow et al., 2018	https://doi.org/10.1111/ddi.12779
Biodiversity Priority	Jenkins et al., 2015	https://doi.org/10.1073/pnas.1418034112
Ecosystem Representation	Aycrigg et al., 2014	https://doi.org/10.5849/jof.15-050

have been previously used to determine the best locations for corridor routes and the other two have been used to evaluated protected areas in the U.S. I quantified wildland value using two values, the first being a composite wildland value (Belote et al., 2017) which includes ecological integrity (Theobald, 2013), connectivity (Belote et al., 2016), representation of ecosystems (Aycrigg et al., 2013), and biodiversity priority (Jenkins et al., 2016). Secondly, I modeled wildness by inverting the human footprint index to represent wildness rather than human modification (Venter et al., 2016).

Thirdly, I measured connectivity value using two datasets: corridor value, a human modification resistance surface with 2,084 core protected areas and the least cost paths between them (Belote et al., 2016), and forward centrality, a measure of climate analog displacement paths from current (1981-2010) to the projected (2071-2100) locations (Carroll et al., 2018). Fourthly, I measured three variables to quantify biodiversity: GAP species richness (McKerrow et al., 2018), biodiversity priority (Jenkins et al., 2015), and ecosystem representation priority (Aycrigg et al., 2014). I projected each layer to USA contiguous Albers equal area conic projection (USGS) with output cells at a 1 kilometer using bilinear resampling. Next, I batched all the files to raster grids and converted all datasets with floating point data to integers (multiplying by 1,000 to preserve significant digits and gradients in each value).

Question 1 The Conservation Value of the PCT and CDT

To evaluate the recreational trails, I buffered the PCT and CDT with a 1 km buffer on either side of the centerline to create 2 km lateral swaths around each trail per Beier et al. (2018). Beier et al. suggested that a 2-km corridor size could be used as a rule of thumb corridor width to accommodate large megafauna. The buffered PCT and CDT, which represent two potential continental corridors, was extracted from each of the seven variable datasets. I categorized each of the seven values by binning data into percentiles, including the top 5%, 10%, 20%, 25% and 50% of land in the U.S. for each conservation value. I was interested in analyzing if the land units in the PCT and CDT buffers were above the national median of most wild, connected, and diverse landscapes in the U.S.

In addition, I was curious to see if the PCT and CDT landscapes were in the 90th percentile of landscapes in the U.S., since much of the land along the buffer had been set aside long ago. By comparing values along each buffered trail to national percentiles, I was able to evaluate nationally significant sections of trails.

The resulting datasets allowed me to query the raster cells within the PCT and CDT. I kept the wildland conservation value (Belote et al., 2017) as a composite and then chose to analyze each of the other six values as separate queries rather than as a composite. By using an unaggregated analysis, I expected to be able to communicate my results to a wide group of stakeholders with varied interests. Locations along each trail that are above the 90th percentile for the country were identified and I visually inspected their geographic settings and elevations.

Question 2 The PCT and CDT Value as the Climate Shifts

I assessed the feasibility of the PCT and CDT being an essential green infrastructure for wildlife movements now and in the future as the climate changes by analyzing both trails corridor and forward climate velocity centrality values. The corridor value allowed me to visualize and quantify if the PCT and CDT aid in connecting protected areas for a series of terrestrial species. Since the corridor value base layer was built using the human modification data and the least cost paths between protected areas I was able to evaluate if the PCT and CDT will innately serve as a framework for wildlife movements. Secondly, the forward centrality analysis allowed me to determine if species will continue to use these routes in the future and if these routes will be helpful to migrations, dispersal, and gene flow as the climate changes.

Question 3 The Conservation Status and Land Management of the PCT and CDT

To understand the conservation status and land management of the trails I queried the datasets for the conservation reserves and land managers for each square kilometer of trail and PCT and CDT buffer. Additionally, I assessed the number of protected areas that the PCT and CDT intersects using the Protected Area Database (PAD) v 1.3 and calculated the percentage of GAP status lands alongside their land manager types using the tabulate intersection tool in ArcGIS. I was interested to know if the land within the PCT and CDT buffer is currently protected and who manages each land unit. I combined the protected areas (GAP Status 1 or 2), PCT and CDT, and a wildland value base map to model the current green infrastructure in the West.

Results

The total area assessed of the Pacific Crest Trail (PCT) and its buffer was 7,045 km^2 (704,500 hectares), while the total area and buffer of the Continental Divide Trail (CDT) was 8045 km^2 (804,500 hectares). The PCT buffer crossed three states, California, Oregon and Washington, 58 wilderness areas and seven national parks (Appendix 2). To the east of the PCT, the CDT buffer traversed five states: Colorado, Idaho, Montana, New Mexico and Wyoming. The CDT buffer intersected 27 wilderness areas and 3 national parks, including Yellowstone, Rocky Mountain and Grand Teton. Both the CDT and the PCT buffers stretch from the border of Mexico to Canada and follow major mountain ranges. Furthermore, both trails show evidence of holding a variety of important conservation values for now and in the future (Figure 9).

Question 1

The PCT buffer was composed of 11% national park and 44% wilderness area. As well, 87% of the trail was in the top 50th percentile of the most valuable wildlands in the U.S. (Table 9, Figure 10). Secondly, eighteen percent of the trail was in the top 5% of wildland conservation value in the country and fifty percent of the trail is in the top 25%. The buffer around the trail contained high wildness value (23% is in the top 95th percentile) and high corridor value (25% is in the top 95th percentile). Sequoia-Kings Canyon Wilderness (29,845 hectares), Yosemite National Park and Wilderness (46,046 hectares), and Kings Canyon National Park (21,379 hectares) total 13.18% of the trail and since their ecosystems are protected as GAP Status 1 and 2 lands their ecological footprint positively contributed to the PCT's wildness and corridor values.

The San Bernardino and the Los Angeles Mountain ranges both had high biodiversity along the PCT, despite their close proximity to the human matrix in Southern California. Over 34% of the trail was in the top 50% of most species-rich places in the contiguous U.S. Though the majority of rare species are in the East, numerous locations in California are of high biodiversity priority. Over half of the PCT buffer was in the top 20% of the landscapes to be conserved for biodiversity and 91% was in the top 50% of biodiverse landscapes. Locations in elevations over 3,000 ft in San Bernardino, Los Angeles, Kern, Sierra, and Klamath counties all showed high biodiversity value

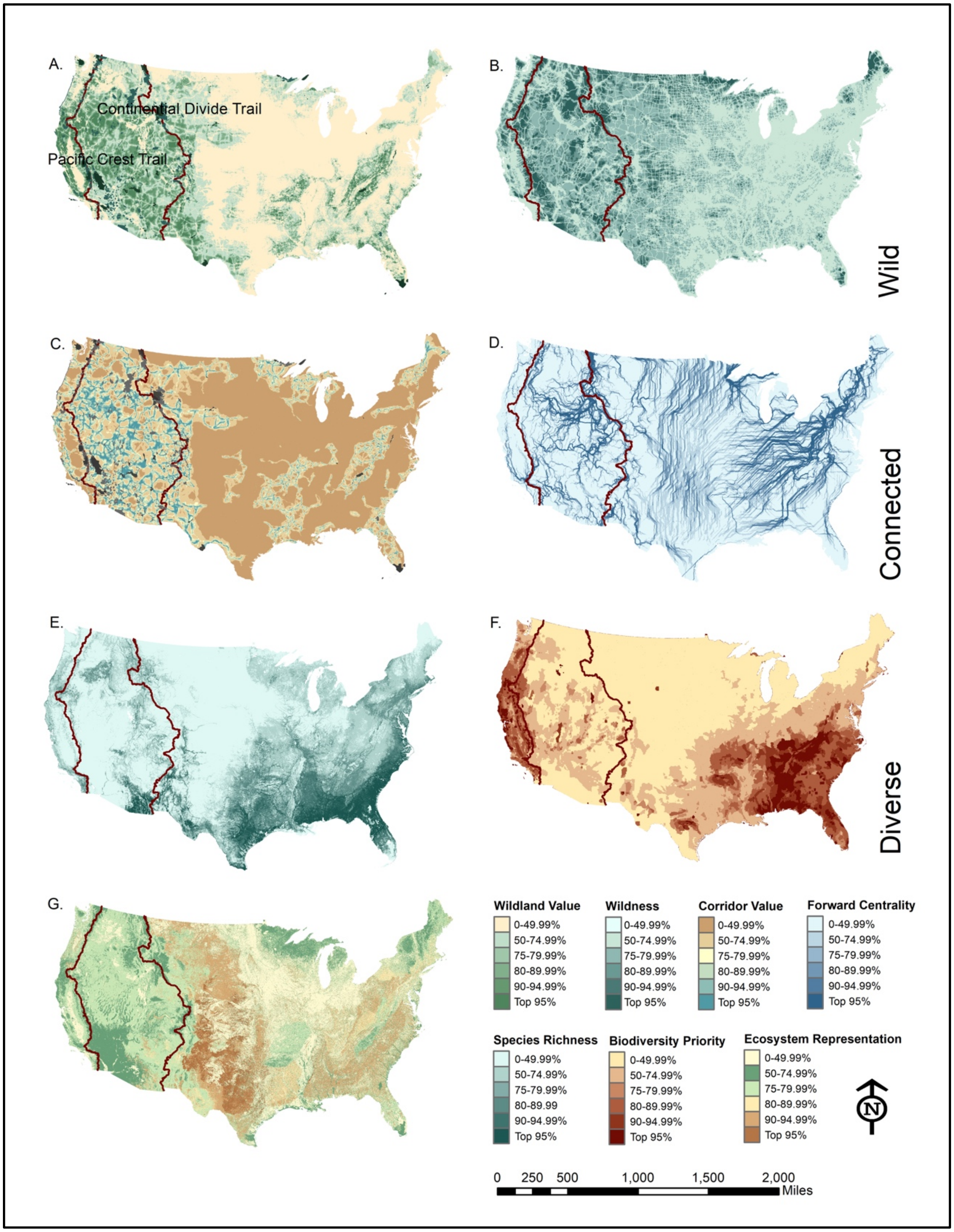

Figure 9. Recreational trails and the wild, connected and diverse U.S.

and were within the top 10% of most biodiverse places in the country (Appendix 2, Table 20). Despite its species richness and biodiversity priority, many of the ecosystems within the PCT buffer were already represented in protected areas.

Twenty-eight percent of the CDT buffer intersects a protected area (8% national park and 20% wilderness). While only 1.5% of the trail buffer was in the top 95th percentile, 38% was the top 75th percentile, and 87% was the top 50th percentile of the most valuable wildlands (Table 11, Figure 12). Similar to the PCT, the CDT had a high wildness value and 11% was in the top 95th percentile and 75% was in the top 50th percentile. The large footprints of Glacier National Park (4.21%, 35,473 hectares), Bob Marshall Wilderness (2.75%, 23,1370 hectares), Bridger Wilderness (2.53%, 21,346 hectares), Yellowstone National Park (2.52%, 21,224 hectares) and Weminuche Wilderness (2.46%, 20,764 hectares) along the CDT all contributed to its wildness value (Appendix 2, Table 21).

Ninety-five percent of the CDT was in the top 50 percent of the most valuable corridor lands (Table 12, Figure 12). Locations between 36.1841855 degrees and 45.5554753 degrees north had the highest corridor values and were in the top 10%. The CDT exhibits less biodiversity than the PCT and only 37% was in the 50th percentile of the most species rich places in the country (Table 13, Figure 13). In addition, only 22% of the CDT buffer was in the top 50% of the landscapes deemed a biodiversity priority. Similar to the PCT, many of the ecosystems on the CDT were already represented within protected areas and only 37% of the PCT is in the 50th percentile of ecosystems that are still in need of representation.

Table 9. The conservation value of the Pacific Crest Trail.

Wild, Connected, and Diverse	Top 50%	Top 25%	Top 20%	Top 10%	Top 5%
Wildland Value					
Square km	6123	3490	2968	1939	1308
Percentage	86.74%	49.44%	42.05%	27.47%	18.53%
Wildness					
Square km	5448	4530	4015	2747	1600
Percentage	78.63%	65.38%	57.94%	39.64%	23.09%
Corridor Value					
Square km	7060	4951	4159	2433	1435
Percentage	99.96%	70.10%	58.88%	34.45%	20.32%
Forward Centrality					
Square km	4721	1961	1509	595	285
Percentage	66.79%	27.74%	21.35%	8.42%	4.03%
Gap Species Richness					
Square km	2430	977	650	101	10
Percentage	34.39%	13.83%	9.20%	1.43%	0.14%
Biodiversity Priority					
Square km	6408	4680	3773	993	453
Percentage	90.70%	66.24%	53.40%	14.06%	6.41%
Ecosystem Representation					
Square km	1310	93	86	0	0
Percentage	18.54%	1.32%	1.22%	0.00%	0.00%

Question 2

The PCT and the CDT exhibited valuable continental corridor values for today and over the next century. Twenty percent of the PCT and twenty five percent of the CDT was in the 95th percentile of the most valuable corridor landscapes. Additionally, as the climate changes, 66% of the PCT was in the top 50th percentile of the most important wildlife corridor routes and 82% of the CDT was in the top 50th percentile. Landscapes near Glacier and Yellowstone National Park as well as land units in Southern California and near Yakima, California in the North will be valuable anchors along the CDT and PCT over the next 100 years.

Table 10. The conservation value of the Continental Divide Trail.

Wild, Connected, and Diverse	Top 50%	Top 25%	Top 20%	Top 10%	Top 5%
Wildland Value					
Square km	7349	3187	2243	582	121
Percentage	87.09%	37.77%	26.58%	6.90%	1.43%
Wildness					
Square km	6192	5696	5140	3713	913
Percentage	74.78%	68.79%	62.08%	44.84%	11.03%
Corridor Value					
Square km	8015	6250	5367	3367	2078
Percentage	94.96%	74.05%	63.59%	39.89%	24.62%
Forward Centrality					
Square km	6942	5337	4912	3595	2567
Percentage	82.19%	63.19%	58.16%	42.56%	30.39%
Gap Species Richness					
Square km	3145	1025	658	301	185
Percentage	37.19%	12.12%	7.78%	3.56%	2.19%
Biodiversity Priority					
Square km	1925	30	12	10	10
Percentage	22.78%	0.35%	0.14%	0.12%	0.12%
Ecosystem Representation					
Square km	3145	229	47	9	7
Percentage	37.21%	2.71%	0.56%	0.11%	0.08%

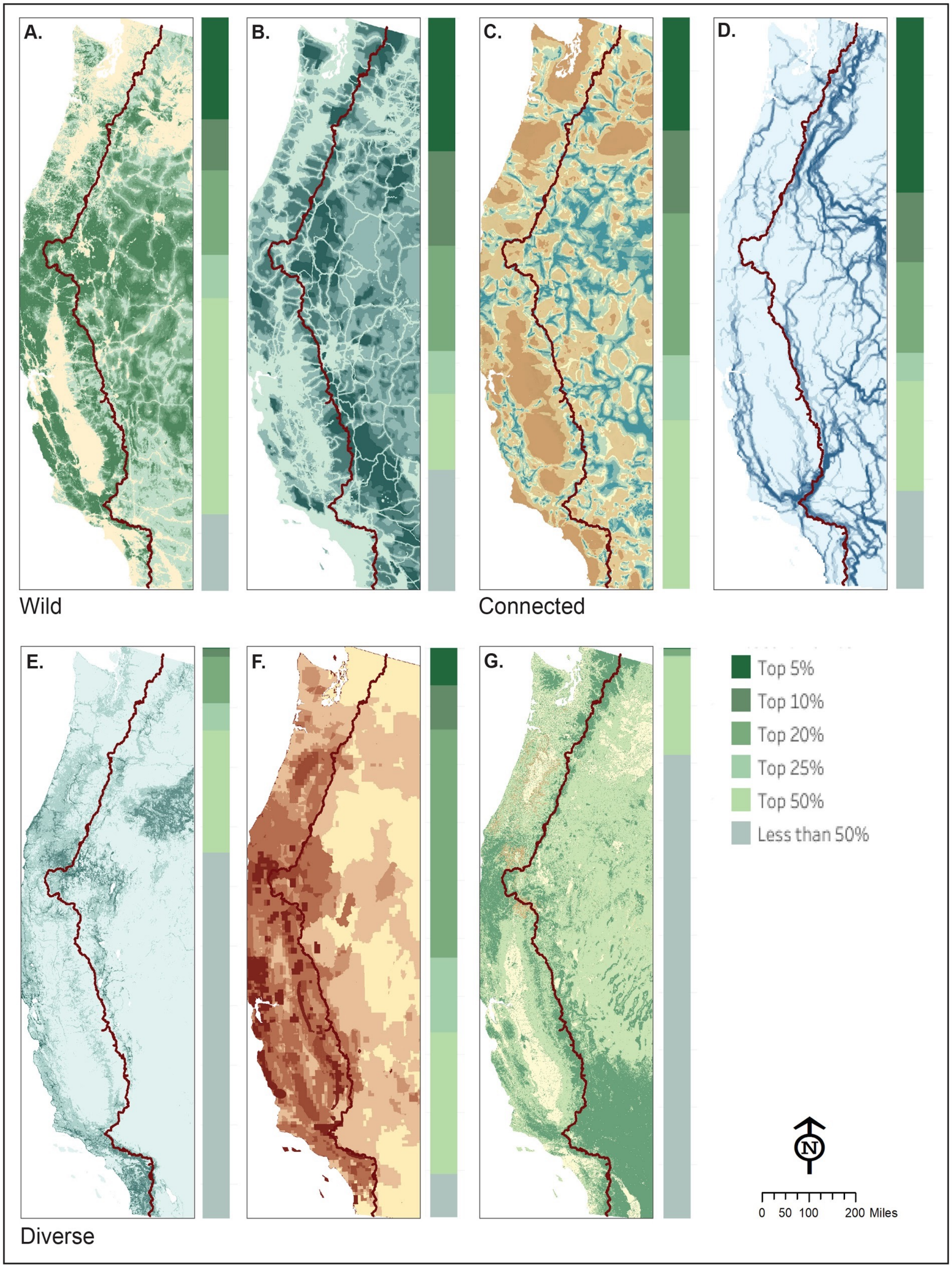

Figure 10. The conservation value of the Pacific Crest Trail.

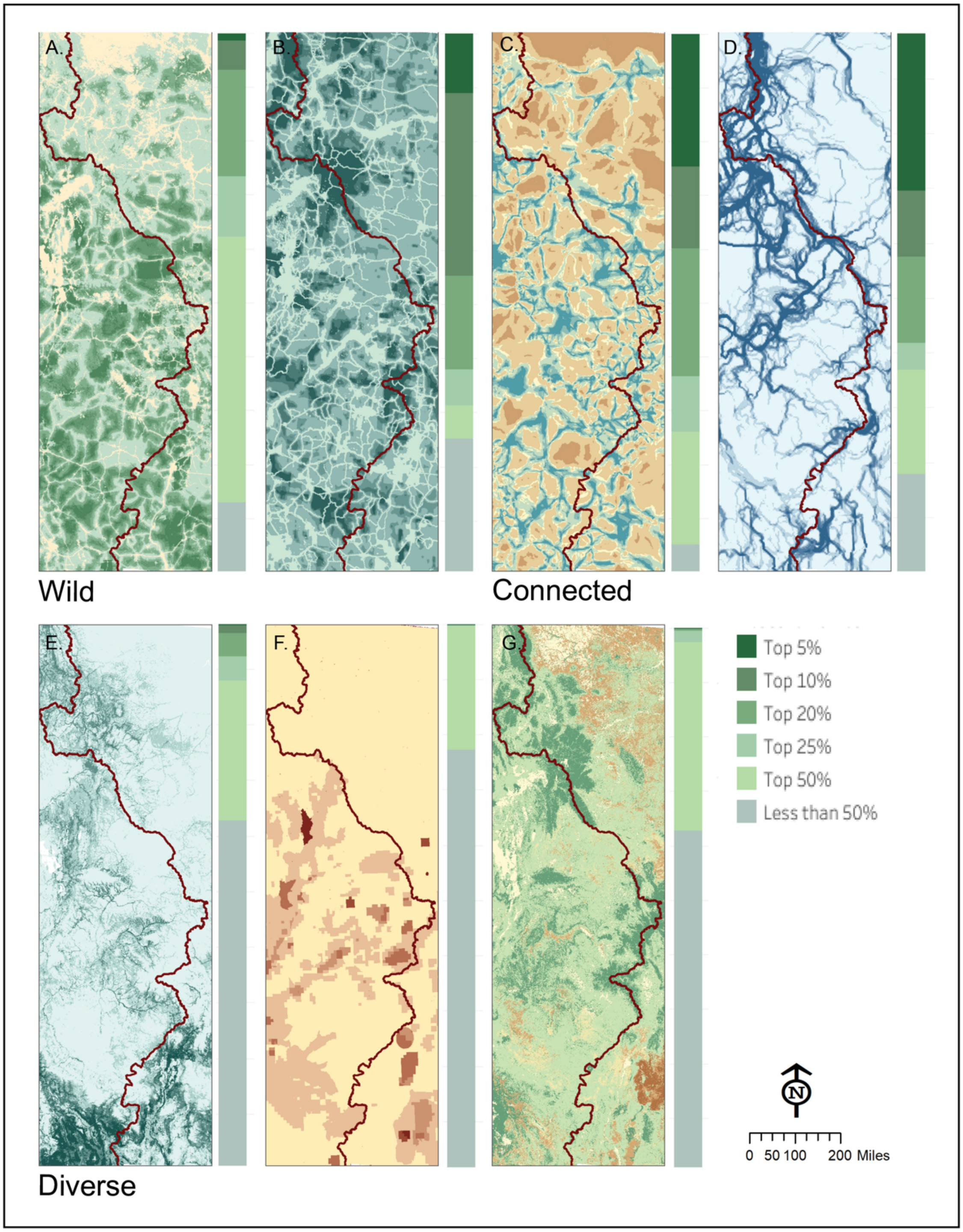

Figure 11. The conservation value of the Continental Divide Trail.

Table 11. Locations in the top 90th percentile of wildlands along the Pacific Crest Trail and Continental Divide Trail.

Conservation Value	#	Name	County	State	Latitude	Longitude	Elevation (Ft)
			Wildland Value				
Pacific Crest Trail	1	Scotland	San Bernardino	CA	34.242229	-117.4981066	3015
	2	Lytle Creek	San Bernardino	CA	34.2591728	-117.5000512	3419
	3	Lake Hughes	Los Angeles	CA	34.6769294	-118.4453598	3228
	4	Monolith	Kern	CA	35.1199664	-118.3742489	3966
	5	La Porte	Plumas	CA	39.6821146	-120.9841206	4980
	6	Dunsmuir	Siskiyou	CA	41.2082089	-122.2719529	2290
	7	Sawyers Bar	Siskiyou	CA	41.2973587	-123.1303203	2241
	8	N. Bonneville	Skamania	WA	45.6373393	-121.9711934	66
Continental Divide Trail	1	Pinehill	Cibola	NM	34.9992044	-108.4111819	7119
	2	San Luis	Sandoval	NM	35.6825261	-107.0505975	6243
	3	Cathedral	Hinsdale	CO	38.0958289	-107.0339372	8914
	4	Riner	Sweetwater	WY	41.7352375	-107.5506201	6755
	5	Atlantic City	Fremont	WY	42.4966221	-108.7306677	7690
	6	Lakeview	Beaverhead	MT	44.5993607	-111.8105246	6706
			Wildness				
Pacific Crest Trail	1	Cartago	Inyo	CA	36.3207709	-118.0264725	3629
	2	Olancha	Inyo	CA	36.2818827	-118.0064718	3658
	3	Johnsville	Plumas	CA	39.7607303	-120.6954985	5180
	4	Twain	Plumas	CA	40.0201673	-121.0719031	2858
	5	Etna	Siskiyou	CA	41.4568065	-122.8947551	2936
	6	Fort Klamath	Klamath	OR	42.7045782	-121.9958544	4183
	7	Trout Lake	Klickitat	WA	45.9973427	-121.528137	1893
Continental Divide Trail	1	Chloride	Sierra	NM	33.338681	-107.6778146	6181
	2	Winston	Sierra	NM	33.3467365	-107.6472591	6158
	3	Creede	Mineral	CO	37.8491662	-106.9264345	8799
	4	Dubois	Fremont	WY	43.533565	-109.6304335	6945

5	West Thumb	Teton	WY	44.4154952	-110.5754846	7795
6	Gibbonsville	Lemhi	ID	45.5554753	-113.9231305	4570
7	Kiowa	Glacier	MT	48.5477483	-113.2709306	5075

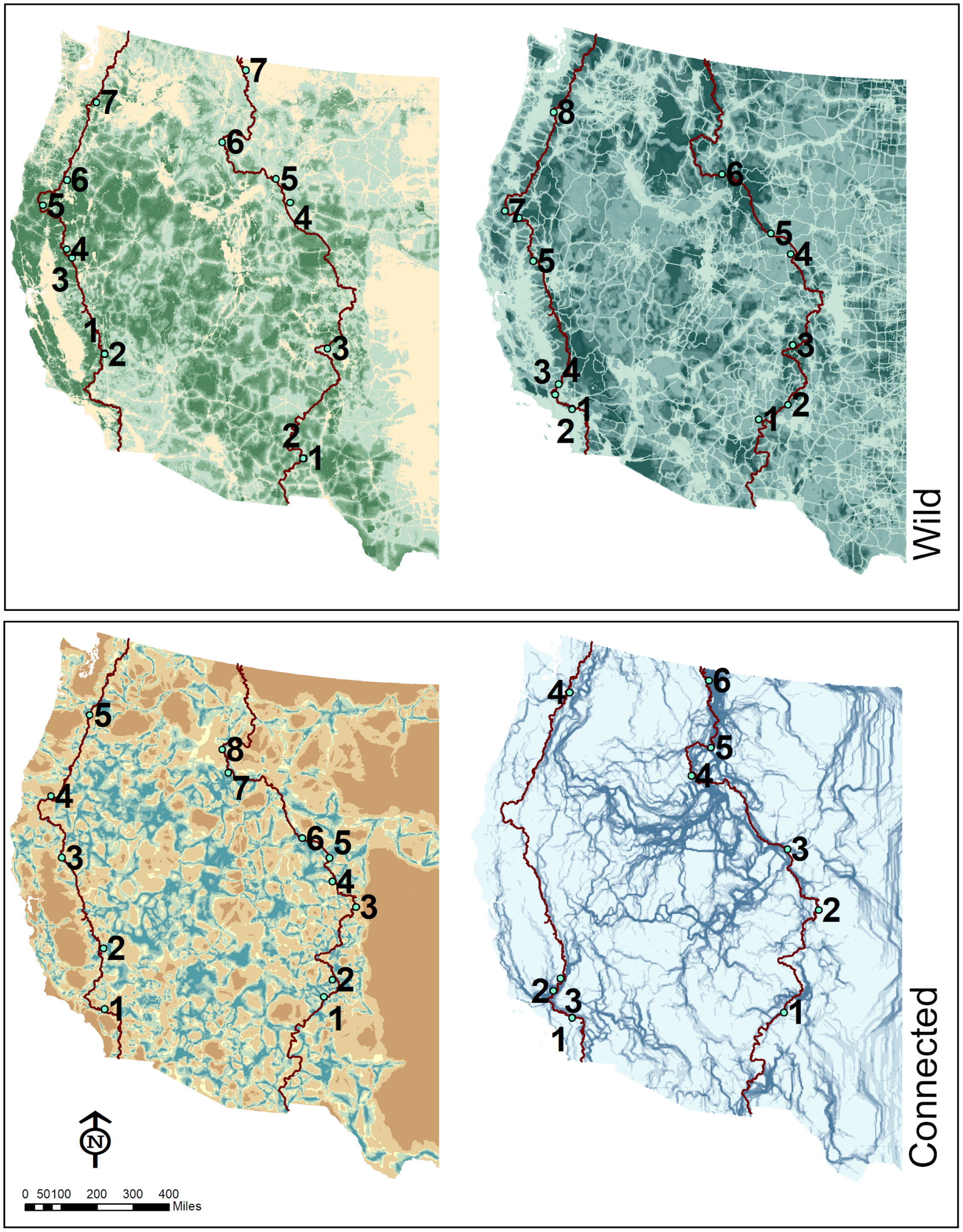

Figure 12. Wild and connected along the Pacific Crest Trail and Continental Divide Trail. Locations represent land units with (A) wildland value, (B) wildness, (C) corridor value, or (D) forward centrality.

Table 12. Locations in the 90th percentile of connected lands along the Pacific Crest Trail and Continental Divide Trail.

Conservation Value	#	Name	County	State	Latitude	Longitude	Elev. (Ft)
			Corridor Value				
Pacific Crest Trail	1	Phelan	San Bernardino	CA	34.4261089	-117.572275	4121
	2	Independence	Inyo	CA	36.8027102	-118.2000951	3930
	3	Tobin	Plumas	CA	39.9379409	-121.3085769	2064
	4	Ashland	Jackson	OR	42.1945759	-122.7094767	1949
	5	Carson	Skamania	WA	45.7253947	-121.8192443	469
Continental Divide Trail	1	Regina	Sandoval	NM	36.1841855	-106.9567082	7480
	2	Chama	Rio Arriba	NM	36.9030679	-106.5794793	7871
	3	East Portal	Gilpin	CO	39.9033204	-105.6444469	9242
	4	Columbine	Routt	CO	40.8541365	-106.9658839	8701
	5	Rawlins	Carbon	WY	41.7910697	-107.2386627	6798
	6	South Pass City	Fremont	WY	42.4682883	-108.799836	7808
	7	Leadore	Lemhi	ID	44.6802005	-113.358091	5971
	8	Gibbonsville	Lemhi	ID	45.5554753	-113.9231305	4570
			Forward Centrality				
Pacific Crest Trail	1	Crestline	San Bernardino	CA	34.2419509	-117.2855993	4613
	3	Onyx	Kern	CA	35.6902305	-118.220634	2795
	2	Tehachapi	Kern	CA	35.1321878	-118.4489739	3970
	4	Goose Prairie	Yakima	WA	46.8951142	-121.2670304	3248
Continental Divide Trail	1	San Luis	Sandoval	NM	35.6825261	-107.0505975	6243
	2	East Portal	Gilpin	CO	39.9033204	-105.6444469	9242
	3	Bairoil	Sweetwater	WY	42.244401	-107.5595141	6857
	4	Leadore	Lemhi	ID	44.6802005	-113.358091	5971
	5	Janney	Silver Bow	MT	45.9093709	-112.4952965	5889
	6	Kiowa	Glacier	MT	48.5477483	-113.2709306	5075

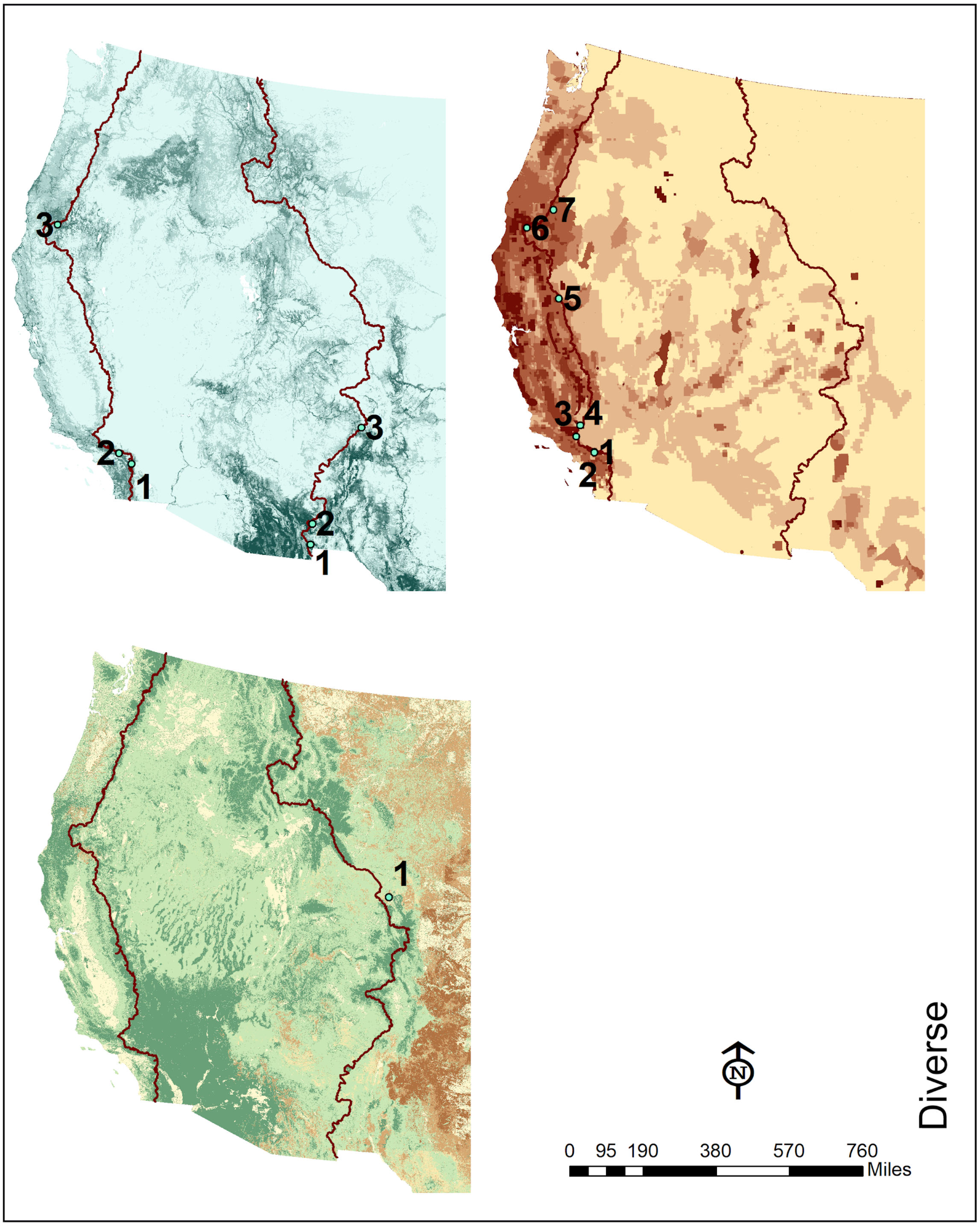

Figure 13. Diversity along the Pacific Crest Trail and Continental Divide Trail. Locations represent land units with (D) GAP species richness, (E) biodiversity priority, (F) ecosystem representation.

Table 13. Locations in the 90th percentile of biodiverse lands along the Pacific Crest Trail and Continental Divide Trail.

Conservation Value	#	Name	County	State	Latitude	Longitude	Elevation (Ft)
			Gap Richness				
Pacific Crest Trail	1	Whitewater	Riverside	CA	33.9355876	-116.687212	1834
	2	Cedarpines Park	San Bernardino	CA	34.2500062	-117.3258786	4734
	3	Hilt	Siskiyou	CA	41.994859	-122.6233613	2907
Continental Divide Trail	1	Hachita	Grant	NM	31.9181501	-108.3203211	4521
	2	Tyrone	Grant	NM	32.7097986	-108.3019925	5745
	3	Canjilon	Rio Arriba	NM	36.4794611	-106.4378091	7785
			Biodiversity Priority				
Pacific Crest Trail	1	Scotland	San Bernardino	CA	34.242229	-117.4981066	3015
	2	Lytle Creek	San Bernardino	CA	34.2591728	-117.5000512	3419
	3	Lake Hughes	Los Angeles	CA	34.6769294	-118.4453598	3228
	4	Monolith	Kern	CA	35.1199664	-118.3742489	3966
	5	Sierra City	Sierra	CA	39.5657329	-120.6338273	4176
	6	Hamburg	Siskiyou	CA	41.7829093	-123.0603186	1617
	7	Fort Klamath	Klamath	OR	42.7045782	-121.9958544	4183
			Ecosystem Representation				
Continental Divide Trail	1	Saratoga	Carbon	WY	41.4549621	-106.8064263	6785

Question 3

Many of the ecosystems on the Pacific Crest Trail and CDT are already represented within protected areas. Fifty percent of the PCT is preserved as GAP Status

1 and 2 lands (Table 14, Figure 14) and 34% CDT is preserved (Table 15, Figure 14). The rest of the PCT trail and surrounding buffer is primarily managed by the U.S. Forest as GAP Status 3 which allows extractive use. Approximately another 2% is managed by the BLM, and a handful of state agencies and regional agencies. In addition, 12% is either known to be GAP Status 4 and be unmanaged or is uncategorized.

Table 14. GAP status and land managers of the Pacific Crest Trail.

	GAP Status (square km and percentage of trail)					
Manager	1	2	3	4	Null	Total
U.S. Forest Service	2344.28	84.59	2453.58			4882.46
	33.16%	1.20%	34.70%			69.06%
Bureau of Land Management	152.63	209.01	89.91			451.55
	2.16%	2.96%	1.27%			6.39%
State Lands		87.85	25.20	65.26		178.31
		1.24%	0.36%	0.92%		2.52%
Regional (City, County, Water)		2.26	0.58	38.65		41.49
		0.03%	0.01%	0.55%		0.59%
Other			2.11	2.18		4.29
		0.00%	0.03%	0.03%		0.06%
Non-governmental Organization		3.38		0.75		4.12
		0.05%		0.01%		0.06%
National Park Service	770.13	0.99				771.12
	10.89%	0.01%				10.91%
Unknown					736.99	736.99
					10.42%	10.42%
Total Square Km	3267.05	388.08	2571.37	106.83	736.99	7070.32
	46.21%	5.49%	36.37%	1.51%	10.42%	100.00%

GAP status of the PCT buffer (sq km). Rank ordered by GAP 3 and 4 values to visualize areas of conservation priority.

The land units that the CDT buffer crosses that are not in protected areas totals over 66%. Of that non-permanently protected land, much of it is GAP Status 3 (56%) which is owned by three primary entities, the USFS (47%), BLM (8%), and State lands (1%) (Figure 15). Another 12% is either GAP Status 4 or unclassified and none of the land that crosses the trail is owned or managed by a non-governmental conservation organization.

Table 15. GAP status and land managers of the Continental Divide Trail.

	GAP Status (square km)					
Manager	1	2	3	4	Null	Total
U.S. Forest Service	1614.44	38.85	3967.47			5620.75
	19.09%	0.46%	46.92%			66.47%
Bureau of Land Management	21.47	462.03	675.88			1159.38
	0.25%	5.46%	7.99%			13.71%
State Lands		19.85	96.19	148.05		264.09
		0.23%	1.14%	1.75%		3.12%
Regional (City, County, Water)		0.0477		1.935		1.9827
		0.00%		0.02%		0.02%
National Park Service	624.11	61.62	22.65			708.39
	7.38%	0.73%	0.27%			8.38%
U.S. Fish and Wildlife		0.09				0.09
		0.00%				0.00%
Unknown					701.07	701.07
					8.29%	8.29%
Total Square Km	2260.02	582.49	4762.20	149.99	701.07	8455.77
	26.73%	6.89%	56.32%	1.77%	8.29%	100.00%

GAP status of the PCT buffer (sq km). Rank ordered by GAP 3 and 4 values to visualize areas of conservation priority.

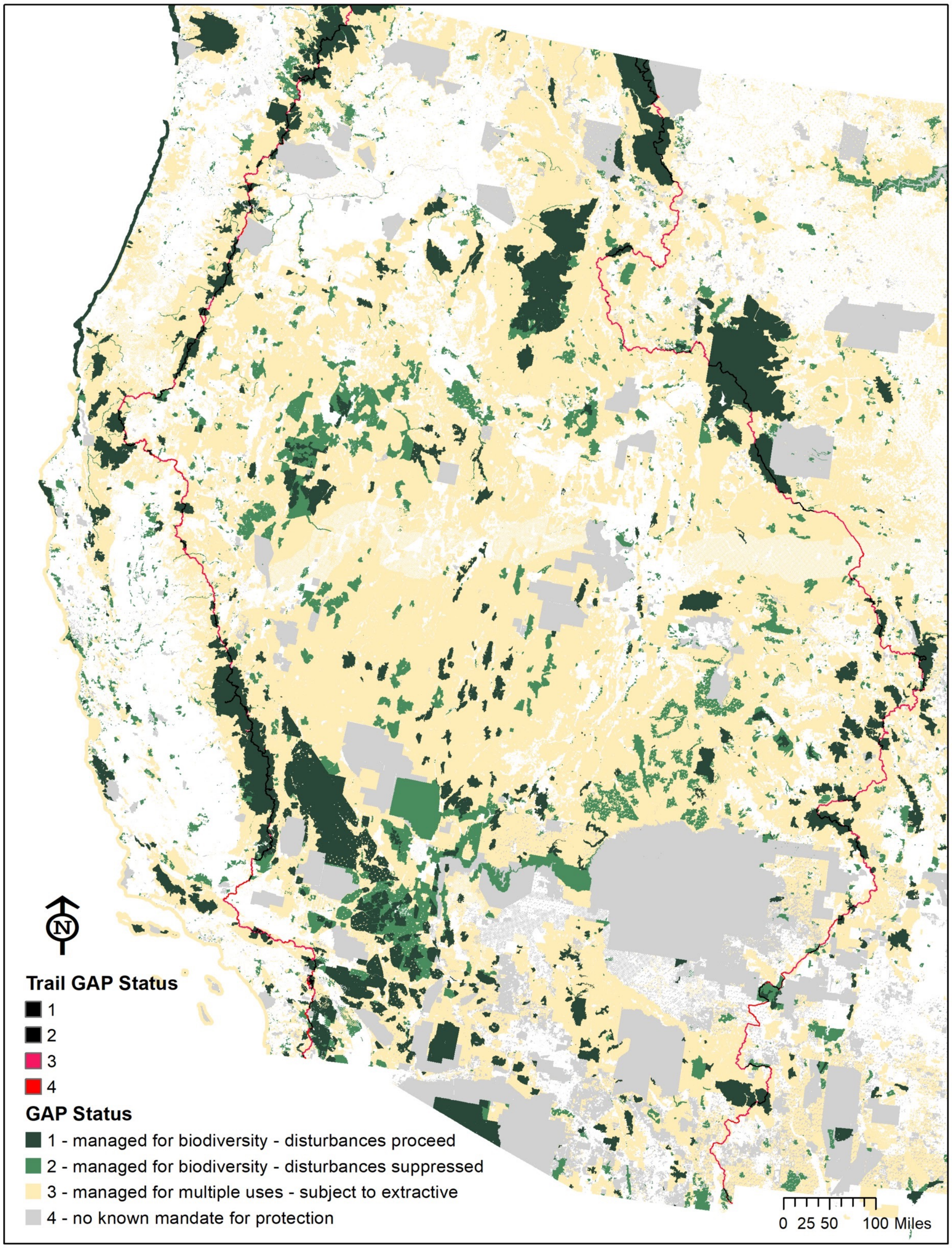

Figure 14. GAP status of the Pacific Crest Trail and the Continental Divide Trail.

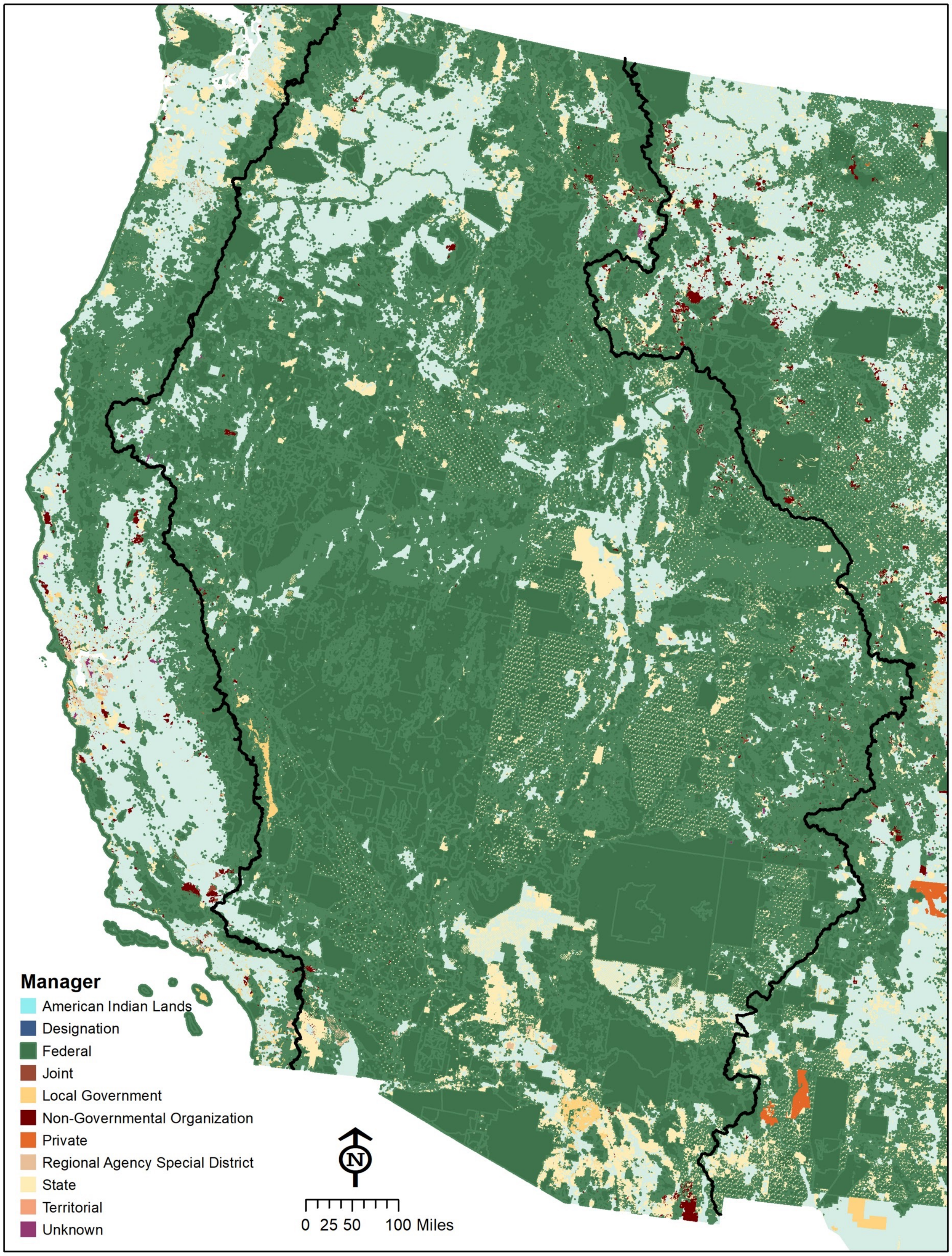

Figure 15. Land managers of the Pacific Crest Trail and the Continental Divide Trail.

Discussion

The green infrastructure that both the Pacific Crest Trail (PCT) and Continental Divide Trail (CDT) provide for the American West is quite remarkable (Figure 16). Whether it is their composite wildland value, or singular wildness, corridor, or forward centrality values, both the PCT and the CDT traverse highly wild and connected landscapes in the West. Multiple governmental agencies and major non-governmental organizations (NGOs) have done extensive work to plan and map potential corridors throughout the country. However, it seems that the first conservationists, local hiking clubs, might have left us a gem. Like Olmsted's Emerald Necklace in Boston, which sought to connect land to land and people to land, the PCT and CDT hold additional conservation values beyond human recreation. Set aside to be the best hiking lands in West (due to their elevational gradients, biodiversity, and routes from Mexico to Canada) these two scenic trails continue to protect ecological riches.

Despite their wildness and connectedness, many of the ecosystems along the PCT and CDT are already highly represented in the American conservation reserve. This is probably due to three reasons. 1) They are at high elevations and therefore less cultivated and used and influenced by the human matrix. 2) Hiking clubs, the first non-governmental organization (NGOs) to practice conservation, fought to conserve these trails for personal and community recreation before heavy human expansions. 3) Since hiking clubs established their routes first, protected areas and public lands popped up along the trails conserving high elevation trail landscapes before lower lying landscapes. Early recreationists' insight and effort to preserve these places created a valuable ecological anchor in the Anthropocene. Additionally, landscapes that were once primarily preserved for their recreational value, now hold important ecological values.

Protected areas in the West and the East are to be the lynchpin for thousands of species as the climate changes (Majka, 2016). Many have stated that without national parks and wilderness areas we would experience a cascade of species losses (McGuire et al., 2016). Interestingly, according to corridor value and forward centrality maps (Figure 10) the routes that many species will take from protected area to protected area in the West follows either the PCT or the CDT. This means that not only are these scenic trails important to species movements now, they will be essential for species movements over the next 100 years. Terrestrial taxa will use these trails to migrate, disperse, and relocate in the Anthropocene. The PCT and CDT will become corridors of refugia and a wide variety of species will travel their high elevations to find suitable habitats. Additionally, due to extreme elevational changes microclimates along the trail will potentially be present. Therefore, the PCT and CDT original U.S. Congress designation as "scenic trails" could now be reclassified as "critical continental corridor" in the new millennia.

One of the biggest hindrances to creating a continental corridor, is the interagency collaboration and the procurement of additional land units. Fortunately, in this case the public already owns ninety percent of the land. By using Beier et al.'s (2018) recommendation of a 2 km buffer (1 km on either side of the centerline of the trail) a continental corridor for a diverse set of terrestrial species including megafauna could be set aside on public land.

The majority of the unprotected land on both trails is managed by the U.S. Forest Service and BLM (Appendix 2, Table 22). Therefore, they would need to re-designate 2 km wide swaths of land that intersect the PCT and CDT. For the U.S. Forest Service this means re-designating 2,456 sq km (245,600 hectares) along the PCT and 3,967 sq km (396,700 hectares) on the CDT (Appendix 2, Table 22). In addition, the BLM would re-designate 90 sq km (9,000 hectares) for the PCT buffer and 676 sq km (67,600 hectares) for the CDT buffer. To put this in perspective the U.S. Forest Service owns 781,340 km^2 (193 million acres) and they would re-designate less than 1% of their current reserve (0.31% on the PCT and 0.51% on the CDT). Meanwhile, the BLM owns 243 million acres and would re-designate less than 0.08% for wildlife movements (.01% for the PCT buffer and 0.07% for the CDT buffer).

A few state and regional agencies would need to add additional land (134 sq km around the PCT and 246 sq km around the CDT). Secondly, the conservation status and land managers of the additional unknown 10-12% of each trail would need to be researched. These landscapes could be pursued as conservation easements or purchased by conservation NGOs. Organizations such as the Pacific Crest Trail Association or the Continental Divide Trail Coalition could rally around areas that are currently unprotected like the first hiking clubs.

Recreation and conservation values have long been considered compatible (Larson et al., 2016). In fact, most protected areas have a twofold mission: to preserve and to provide enjoyment. A recent systematic global review states that human recreation can have a negative effect on a given species population and individual responses (Larson et al., 2016). In addition, approximately 40% of the 112 articles concluded that hiking and running, can have adverse effects on species. To understand the complexities of human-nature interactions, experimental studies specific to species along the PCT and CDT and their population and individual responses are warranted.

Conclusions

The time is now to set aside land for other species and for ourselves. The International Panel on Climate Change Report (UNEP, 2018), stated that climate instability is teetering radically and faster than projected. Wildlands are a natural carbon sinks that aid in slowing greenhouse gas accumulation. By buffering scenic trails and creating a continental corridor an anchor for further wild infrastructure is created. A wild, connected, and diverse green infrastructure could save the American reserve system (both wildlands and working lands) from continued loss of species and wild places in the Anthropocene.

Furthermore, a continental corridor could provide the necessary vision for Wilson's half-earth in the U.S. (2017). Currently, the United States government owns 47 percent of all land in the West (Bui & Sanger-Katz, 2016). While, not all of that land is set aside in a protected area, it is wilder and more connected than land in the East. As well, there are more forward centrality routes in the West due to the large tracts of public land and a concentrated human matrix. If we are to preserve half of all land masses in the world for biodiversity (Wilson, 2016), the West is the rationale place to start.

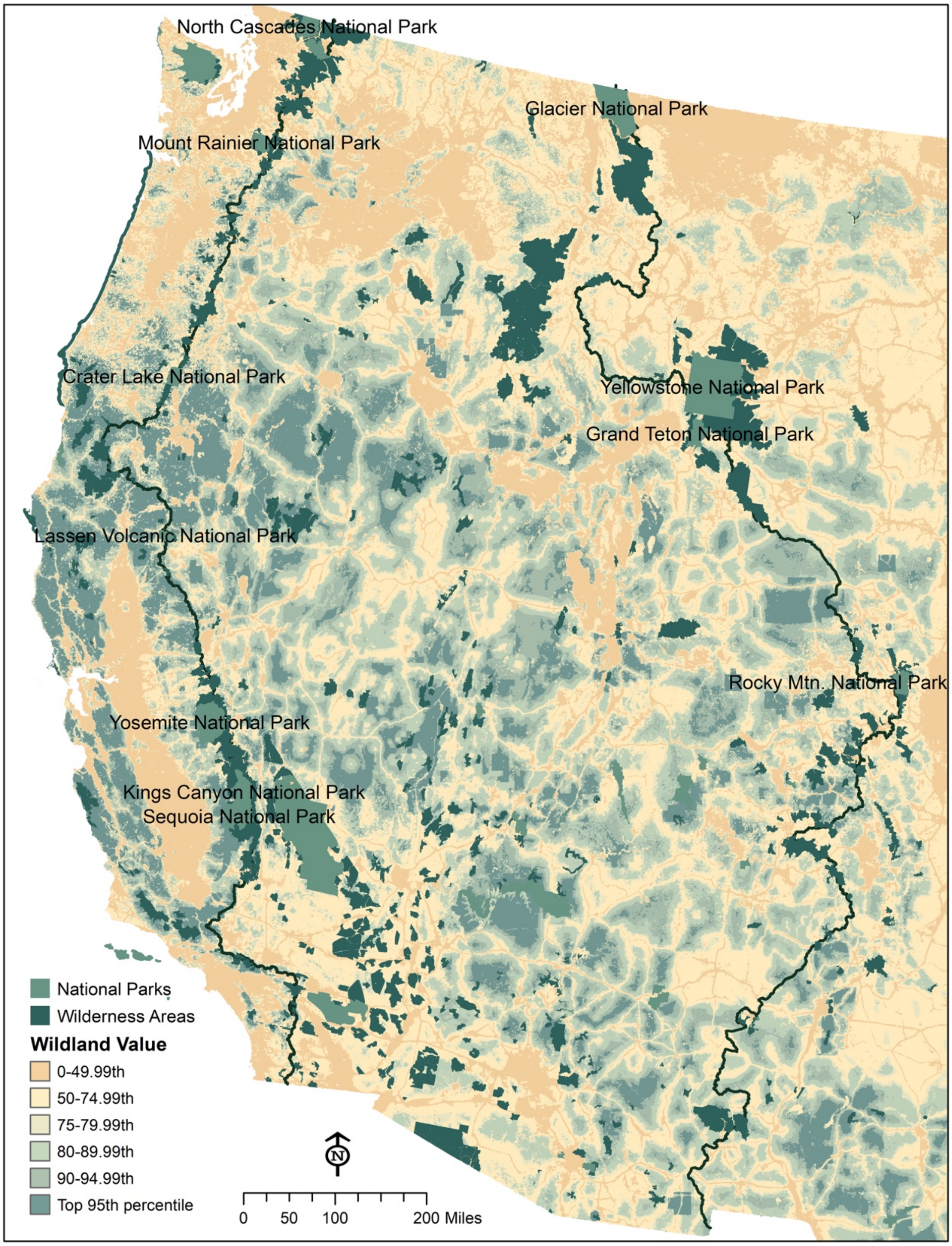

Figure 16. Potential protected area network.

Appendix 1

Greater Ecosystem Model (GEM)

Table 16. Ecosystem diversity surrounding Grand Canyon National Park.

Number of Ecosystems	Current Ecosystems Present	Current Hectares	Hectares Added	Represented in GAP 1/2 Reserves (%)
1	Great Plains Floodplain Forest	0	0	4
2	Southern Rocky Mountain Montane Shrubland	25	1469	6
3	Great Basin-Intermountain Dwarf Sagebrush Steppe & Shrubland	0	80	12
4	Warm Interior Chaparral	34	374	16
5	Great Basin Saltbush Scrub	38	5351	24
6	North America Warm-Desert Xeric-Riparian Scrub	15	19	26
7	Arid West Interior Freshwater Marsh	1	13	28
8	Introduced & Semi Natural Vegetation	29	514	33
9	Warm Desert Lowland Freshwater Marsh, Wet Meadow & Shrubland	0	13	34
10	Cool Interior Chaparral	0	0	34
11	Rocky Mountain-Vancouverian Subalpine-High Montane Mesic Meadow	17	142	34
12	Great Basin-Intermountain Tall Sagebrush Steppe & Shrubland	244	8907	38
13	Southern Rocky Mountain Lower Montane Forest	638	4105	41
14	Recently Disturbed or Modified	23	481	41
15	Southern Rocky Mountain & Colorado Plateau Two-needle Pinyon - One-seed Juniper Woodland	1319	20879	45
16	Mojave-Sonoran Semi-Desert Scrub	404	2769	54
17	Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland	3	474	55
18	Intermountain Singleleaf Pinyon - Utah Juniper - Western Juniper Woodland	409	3127	56

19	Great Basin-Intermountain Dry Shrubland & Grassland	1592	17959	85
20	Rocky Mountain Subalpine-High Montane Conifer Forest	44	2775	96
21	Intermountain Basins Cliff, Scree & Badlands Sparse Vegetation	1085	11440	132
22	North American Warm Semi-Desert Cliff, Scree & Rock Vegetation	1	22	202
	GEM Ecosystems			
1	North American Warm Desert Ruderal Scrub & Grassland		17	3
2	Chihuahuan Semi-Desert Grassland		1	6
3	Rocky Mountain-Great Basin Montane Riparian Forest		141	7
4	Central Rocky Mountain Montane-Foothill Grassland & Shrubland		0	10
5	Madrean Lowland Evergreen Woodland		0	16
6	Interior Warm & Cool Desert Riparian Forest		6	18
7	Western North American Temperate Cliff, Scree & Rock Vegetation		416	26
8	Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland		64	69
9	Rocky Mountain-Sierran Alpine Tundra		132	127
	Restoration Opportunities			
1	Quarries, Mines, Gravel Pits and Oil Wells		406	n/a
2	Barren		6	4
3	Herbaceous Agricultural Vegetation	0	125	n/a
4	Pasture & Hay Field Crop	0	10	n/a
	Other			
1	Developed & Urban	14	730	n/a
2	Open Water	33	482	n/a

Table 17. Ecosystem representation surrounding Yellowstone National Park.

Number of Ecosystems	Current Ecosystems Present	Current Hectares	Hectares Added	Represented in GAP 1/2 Reserves (%)
1	Great Plains Mixedgrass & Fescue Prairie	0	3556	4
2	Great Plains Saline Wet Meadow & Marsh	0	421	4
3	Central Rocky Mountain Mesic Lower Montane Forest	1	1175	5
4	Southern Rocky Mountain Montane Shrubland	0	14681	8
5	Great Plains Badlands Vegetation	9	11	14
6	Introduced & Semi Natural Vegetation	0	272	16
7	Great Plains Floodplain Forest	0	538	19
8	North American Boreal & Sub-Boreal Acidic Bog & Fen	0	185	19
9	Great Basin-Intermountain Dwarf Sagebrush Steppe & Shrubland	18	1335	19
10	Rocky Mountain-Vancouverian Subalpine-High Montane Mesic Meadow	1005	294	24
11	Western North American Temperate Cliff, Scree & Rock Vegetation	21	397	26
12	Arid West Interior Freshwater Marsh	6	96	28
13	Western North American Vernal Pool	9	18	31
14	Great Basin-Intermountain Tall Sagebrush Steppe & Shrubland	2845	518	38
15	Intermountain Singleleaf Pinyon - Utah Juniper - Western Juniper Woodland	255	1385	42
16	Rocky Mountain-Great Basin Montane Riparian Forest	184	1022	61
17	Central Rocky Mountain Dry Lower Montane-Foothill Forest	842	15034	63
18	Recently Disturbed or Modified	2131	1179	77
19	Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland	299	3082	79
20	Central Rocky Mountain Montane-Foothill Grassland & Shrubland	751	2042	88

21	Intermountain Basins Cliff, Scree &Badlands Sparse Vegetation	21	493	137
22	Rocky Mountain Subalpine-High Montane Conifer Forest	10819	14	231
23	Rocky Mountain-Sierran Alpine Tundra	4771	5	271
Ecosystems Added				
1	Great Plains Sand Grassland & Shrubland		170	1
2	Great Plains Forest & Woodland		27	3
3	Great Plains Cliff, Scree & Rock Vegetation		7	3
4	Great Basin Saltbush Scrub		23	10
5	Great Basin-Intermountain Dry Shrubland & Grassland		109	24
6	Great Plains Marsh, Wet Meadow, Shrubland & Playa		36	27
7	Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland		6	29
8	Southern Rocky Mountain Lower Montane Forest		137	32
Restoration Opportunities				
1	Quarries, Mines, Gravel Pits and Oil Wells		8	0
2	Herbaceous Agricultural Vegetation	0	12	0
3	Pasture & Hay Field Crop	14	2	0
1	Barren	1	1	93
Other				
1	Developed & Urban	43	83	0
2	Open Water	666	5321	0

Table 18. Ecosystem representation surrounding Yosemite-Sequoia National Park.

Number of Ecosystems	Current Ecosystems Present	Current Hectares	Hectares Added	Represented in GAP 1/2 Reserves (%)
1	Vancouverian Lowland Marsh, Wet Meadow & Shrubland	0	0	14
2	Californian Annual & Perennial Grassland	0	1573	18
3	Great Basin Saltbush Scrub	7	4453	24
4	North America Warm-Desert Xeric-Riparian Scrub	0	2556	26
5	Rocky Mountain-Vancouverian Subalpine-High Montane Mesic Meadow	0	5	30
6	Warm Desert Lowland Freshwater Marsh, Wet Meadow & Shrubland	0	232	34
7	Rocky Mountain-Sierran Alpine Tundra	7	0	34
8	Intermountain Basins Cliff, Scree & Badlands Sparse Vegetation	1	362	37
9	Great Basin-Intermountain Tall Sagebrush Steppe & Shrubland	701	7214	38
10	Interior Warm & Cool Desert Riparian Forest	467	891	44
11	Southern Rocky Mountain & Colorado Plateau Two-needle Pinyon - One-seed Juniper Woodland	0	14	45
12	Vancouverian Lowland & Montane Forest	8	15	48
13	Mojave-Sonoran Semi-Desert Scrub	1	29410	53
14	Californian Chaparral	33	487	53
15	Arid West Interior Freswater Marsh	0	111	54
16	Cool Interior Chaparral	9	31	56
17	Intermountain Singleleaf Pinyon - Utah Juniper - Western Juniper Woodland	734	6633	64
18	Great Basin-Intermountain Dry Shrubland & Grassland	133	8324	70
19	Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland	0	2821	76

20	Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland	14	59	84
21	Vancouverian Alpine Tundra	5661	1107	89
22	Californian Forest & Woodland	284	4939	101
23	Southern Vancouverian Montane-Foothill Forest	1639	5966	106
24	Western North American Temperate Cliff, Scree & Rock Vegetation	5	97	126
25	North American Warm Semi-Desert Cliff, Scree & Rock Vegetation	0	3954	170
26	Rocky Mountain Subalpine-High Montane Conifer Forest	249	568	171
27	Vancouverian Subalpine Forest	3816	2026	305
	New Ecosystems Added			
1	Great Plains Floodplain Forest		0	4
2	Southern Rocky Mountain Montane Shrubland		0	6
3	Central Rocky Mountain Montane-Foothill Grassland & Shrubland		0	10
4	Californian Coastal Scrub		5	12
5	Pacific Coastal Beach & Dune		0	23
6	Rocky Mountain-Great Basin Montane Riparian Forest		0	28
7	North American Coastal Salt Marsh		0	32
8	Southern Rocky Mountain Lower Montane Forest		3	32
9	Introduced & Semi Natural Vegetation		35	33
10	North Pacific Bog & Fen		0	43
11	Warm Interior Chaparral		2	52
	Restoration Opportunities			
1	Quarries, Mines, Gravel Pits and Oil Wells		2	0
2	Herbaceous Agricultural Vegetation	0	637	0
3	Pasture & Hay Field Crop	0	297	0
4	Recently Disturbed or Modified	2	191	77
5	Barren	10	17	21

Other				
1	Developed & Urban	28	1933	0
2	Open Water	127	922	0

Appendix 2

Conservation Value of Scenic Trails

Table 19. Raster values used to determine the most wild, diverse, and connected land in the contiguous United States (CONUS).

Wild, Connected, and Diverse	Top 25%	Top 20%	Top 10%	Top 5%
Wildland conservation value	2597	2665	2817	2917
Wildness (Human Footprint)	47	47.704	48.69	49
Corridor value	33	34	36	37
Forward velocity centrality	131.85	158.93	261.12	405.19
Biodiversity priority	0.2863	0.3506	0.5049	0.5972
Ecosystem representation priority	0.947	0.96	0.984	0.989
GAP species richness	237.20	243.84	265.64	285.89

Table 20. Pacific Crest Trail and protected areas.

Name	State	Acres	Hectares	Area (sq km)	Percentage
Sequoia-Kings Canyon Wilderness	CA	768350.59	29,845.46	298.45	4.24%
Yosemite National Park	CA	745900.80	23,339.38	233.39	3.31%
Yosemite Wilderness	CA	704243.78	22,706.66	227.07	3.22%
Kings Canyon National Park	CA	458964.02	21,379.95	213.80	3.03%
Alpine Lakes Wilderness	WA	415578.08	17,813.63	178.14	2.53%
John Muir Wilderness	CA	653407.69	16,962.40	169.62	2.41%
Glacier Peak Wilderness	WA	566467.33	15,399.47	153.99	2.19%
Three Sisters Wilderness	OR	283769.65	13,661.26	136.61	1.94%
Crater Lake National Park	OR	182552.46	12,388.54	123.89	1.76%
Sky Lakes Wilderness	OR	113834.90	11,092.74	110.93	1.57%
Mount Jefferson Wilderness	OR	108963.60	9,272.84	92.73	1.32%
Marble Mountain Wilderness	CA	225300.80	9,209.61	92.10	1.31%
Sequoia National Park	CA	406805.66	8,466.06	84.66	1.20%
Ansel Adams Wilderness	CA	231020.99	8,409.84	84.10	1.19%
Golden Trout Wilderness	CA	305388.95	7,687.48	76.87	1.09%
Goat Rocks Wilderness	WA	108183.68	7,520.72	75.21	1.07%
Diamond Peak Wilderness	OR	52458.92	6,560.49	65.60	0.93%
Henry M. Jackson Wilderness	WA	103223.96	6,543.27	65.43	0.93%
Mount Thielsen Wilderness	OR	55150.65	6,442.74	64.43	0.91%
Pasayten Wilderness	WA	531274.19	6,396.14	63.96	0.91%
Mark O. Hatfield Wilderness	OR	65517.88	6,315.80	63.16	0.90%
Owens Peak Wilderness	CA	76969.74	6,094.96	60.95	0.87%
San Jacinto Wilderness	CA	33178.74	6,074.19	60.74	0.86%
Desolation Wilderness	CA	64054.74	5,497.62	54.98	0.78%
William O. Douglas Wilderness	WA	169201.66	5,495.62	54.96	0.78%
South Sierra Wilderness	CA	60319.19	5,415.78	54.16	0.77%
Carson-Iceberg Wilderness	CA	159344.30	5,253.54	52.54	0.75%
Pleasant View Ridge Wilderness	CA	26975.09	5,174.55	51.75	0.73%
Lassen Volcanic National Park	CA	107509.27	5,068.39	50.68	0.72%
Stephen Mather Wilderness	WA	641458.09	4,776.70	47.77	0.68%

Trinity Alps Wilderness	CA	540085.22	4,504.06	45.04	0.64%
Mount Adams Wilderness	WA	47123.27	4,401.73	44.02	0.62%
San Gorgonio Wilderness	CA	54706.77	4,384.77	43.85	0.62%
North Cascades National Park	WA	501379.64	4,324.54	43.25	0.61%
Mount Hood Wilderness	OR	64741.21	4,223.19	42.23	0.60%
Kiavah Wilderness	CA	45245.25	4,097.81	40.98	0.58%
Bucks Lake Wilderness	CA	23776.48	4,066.19	40.66	0.58%
Lassen Volcanic Wilderness	CA	78566.88	3,694.19	36.94	0.52%
Norse Peak Wilderness	WA	52297.33	3,554.98	35.55	0.50%
Mount Washington Wilderness	OR	54451.86	3,490.77	34.91	0.50%
Indian Heaven Wilderness	WA	20783.52	3,343.66	33.44	0.47%
Mokelumne Wilderness	CA	104380.22	3,339.33	33.39	0.47%
Hoover Wilderness	CA	128173.17	2,704.64	27.05	0.38%
Castle Crags Wilderness	CA	11079.38	2,431.50	24.32	0.35%
Sheep Mountain Wilderness	CA	43334.15	2,205.56	22.06	0.31%
Granite Chief Wilderness	CA	25260.46	1,954.89	19.55	0.28%
San Gorgonio Wilderness	CA	58636.44	1,951.19	19.51	0.28%
Russian Wilderness	CA	12653.13	1,926.37	19.26	0.27%
Domeland Wilderness	CA	94412.51	1,917.76	19.18	0.27%
Soda Mountain Wilderness	OR	24725.44	1,622.16	16.22	0.23%
Mount Rainier National Park	WA	236437.40	1,580.50	15.80	0.22%
Mount Rainier Wilderness	WA	227088.21	1,454.42	14.54	0.21%
Domeland Wilderness	CA	40115.43	1,452.78	14.53	0.21%
Emigrant Wilderness	CA	112844.64	1,110.98	11.11	0.16%
Chimney Peak Wilderness	CA	13243.39	803.44	8.03	0.11%
San Gabriel Wilderness	CA	35738.18	678.28	6.78	0.10%
Kiavah Wilderness	CA	42609.13	602.73	6.03	0.09%
Sawtooth Mountains Wilderness	CA	33654.13	278.83	2.79	0.04%
Red Buttes Wilderness	CA-OR	20175.27	183.62	1.84	0.03%
Salmon-Huckleberry Wilderness	OR	62135.89	136.47	1.36	0.02%
Hauser Wilderness	CA	7197.27	113.21	1.13	0.02%
Magic Mountain Wilderness	CA	12241.37	88.01	0.88	0.01%

Beauty Mountain Wilderness	CA	15709.88	12.61	0.13	0.00%
Owens River Headwaters Wilderness	CA	14725.22	4.27	0.04	0.00%
Bright Star Wilderness	CA	8763.28	0.37	0.00	0.00%
					55.20%

Hectares, acreage, and square km represents the total area that the proposed buffer currently crosses Gap status 1 and 2 lands.

Table 21. Continental Divide Trail and protected areas

Name	State	Acres	Hectares	Area (Sq km)	Percentage
Glacier National Park	MT	1,008,097.37	35,473.31	354.73	4.21%
Bob Marshall Wilderness	MT	1,014,477.05	23,137.09	231.37	2.75%
Bridger Wilderness	WY	426,751.45	21,346.46	213.46	2.53%
Yellowstone National Park	WY	2,199,453.66	21,224.34	212.24	2.52%
Weminuche Wilderness	CO	500,270.73	20,764.12	207.64	2.46%
Anaconda Pintler Wilderness	MT	158,753.49	13,129.24	131.29	1.56%
Teton Wilderness	WY	584,785.95	11,735.50	117.36	1.39%
Scapegoat Wilderness	MT	243,283.97	10,313.77	103.14	1.22%
Rocky Mountain National Park	CO	267,038.86	9,108.66	91.09	1.08%
South San Juan Wilderness	CO	160,955.09	9,082.22	90.82	1.08%
Rocky Mountain Wilderness	CO	249,268.31	8,593.90	85.94	1.02%
Aldo Leopold Wilderness	NM	203,533.97	7,260.60	72.61	0.86%
Mount Zirkel Wilderness	CO	160,504.09	6,719.58	67.20	0.80%
La Garita Wilderness	CO	126,486.49	5,725.88	57.26	0.68%
Collegiate Peaks Wilderness	CO	166,224.02	4,130.02	41.30	0.49%
Huston Park Wilderness	WY	30,974.61	3,416.90	34.17	0.41%
Indian Peaks Wilderness	CO	75,219.91	3,207.95	32.08	0.38%
San Pedro Parks Wilderness	NM	41,305.19	3,195.75	31.96	0.38%
Gila Wilderness	NM	559,314.75	3,165.58	31.66	0.38%
James Peak Wilderness	CO	17,080.37	2,668.20	26.68	0.32%
Chama River Canyon Wilderness	NM	46,052.56	2,428.04	24.28	0.29%
West Malpais Wilderness	NM	39,951.65	2,149.02	21.49	0.26%
Never Summer Wilderness	CO	20,830.49	1,994.71	19.95	0.24%
Mount Massive Wilderness	CO	23,936.43	1,978.66	19.79	0.23%
Holy Cross Wilderness	CO	122,939.31	1,223.91	12.24	0.15%
Vasquez Peak Wilderness	CO	13,000.32	1,009.83	10.10	0.12%
Cruces Basin Wilderness	NM	18,876.03	704.81	7.05	0.08%
Mount Massive Wilderness	CO	2,553.38	347.76	3.48	0.04%
Eagles Nest Wilderness	CO	135,218.29	29.79	0.30	0.00%

Indian Peaks Wilderness	CO	2,911.68	5.59	0.06	0.00%
					27.93%

Hectares, acreage, and square km represents the total area that the proposed buffer currently crosses Gap status 1 and 2 lands.

Table 22. Top 10 re-designations for the Pacific Crest Trail and Continental Divide Trails.

The Pacific Crest Trail	GAP Status 3 (Sqkm)
San Bernardino National Forest	251.85
Angeles National Forest	210.83
Lassen National Forest	204.52
Shasta-Trinity National Forest	121.00
Tahoe National Forest	104.00
Gifford Pinchot National Forest	101.02
Klamath National Forest	100.85
Mt. Hood National Forest	99.92
Plumas National Forest	92.56
Okanogan-Wenatchee National Forest	77.52
The Continental Divide Trail	
Gila National Forest	433.40
Beaverhead-Deerlodge National Forest	264.28
Carson National Forest	245.06
Medicine Bow-Routt National Forest	169.99
National Public Lands - Rawlins Field Office	168.83
West Big Hole Roadless Area	168.12
National Public Lands	167.99
Helena-Lewis and Clark National Forest	140.00
Italian Peak Roadless Area	136.84
White River National Forest	126.68
Cibola National Forest	118.07

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