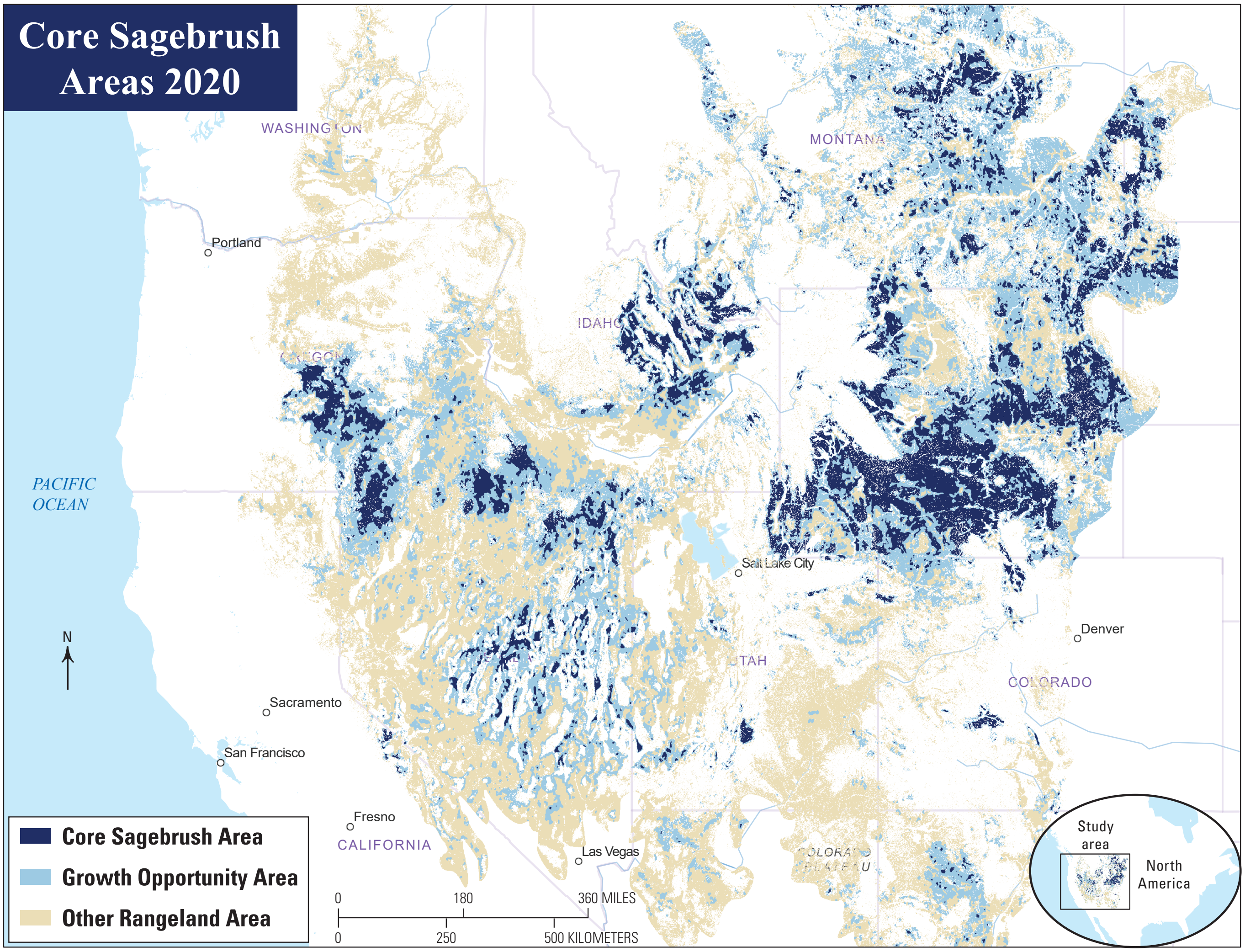
Prepared in cooperation with the Western Association of Fish and Wildlife Agencies and the U.S. Fish and Wildlife Service

A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome



Open-File Report 2022–1081

U.S. Department of the Interior
U.S. Geological Survey

Cover image: Map showing the size and extent of core sagebrush areas, growth opportunity areas, and other rangeland areas within the sagebrush biome of the United States in 2020.

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Conversion Factors

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
acre	0.4047	hectare (ha)
hectare (ha)	2.471	acre

Abbreviations

~	approximately
%	percent
BF	US Building Footprints
BLM	Bureau of Land Management
CSA	core sagebrush area
EIA	U.S. Energy Information Administration
GAP	Gap Analysis Project
GOA	growth opportunity area
HGL	hydrocarbon gas liquids
LCMAP	Land Change Monitoring, Assessment, and Projection
NA	not applicable
NAWMP	North American Waterfowl Management Plan
NCEI	National Centers for Environmental Information
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
ORA	other rangeland areas
PDF	portable document format
PHMA	Priority Habitat Management Area
R&R	resistance and resilience
RAP	Rangeland Analysis Platform
RCMAP	Rangeland Condition, Monitoring, Assessment, and Projection
RCP	representative concentration pathway
SEI	sagebrush ecological integrity
SHC	Strategic Habitat Conservation
TIGER	Topologically Integrated Geographic Encoding and Referencing
U.S.	United States
USDA	U.S. Department of Agriculture
USFS	U.S. Department of Agriculture Forest Service
USFWS	U.S. Fish & Wildlife Service
USGS	U.S. Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite
WGA	Western Governors' Association
WLFW	Working Lands for Wildlife

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By Kevin Doherty,[1] David M. Theobald,[2] John B. Bradford,[3] Lief A. Wiechman,[3]* Geoffrey Bedrosian,[1] Chad S. Boyd,[4] Matthew Cahill,[5] Peter S. Coates,[3] Megan K. Creutzburg,[6] Michele R. Crist,[7] Sean P. Finn,[1] Alexander V. Kumar,[1] Caitlin E. Littlefield,[8] Jeremy D. Maestas,[9] Karen L. Prentice,[7] Brian G. Prochazka,[3] Thomas E. Remington,[10] William D. Sparklin,[1] John C. Tull,[1] Zachary Wurtzebach,[11] and Katherine A. Zeller[12]

Executive Summary

A working group of experts with diverse backgrounds and disciplinary expertise was assembled to conceptualize a spatially explicit conservation design to support and inform the Sagebrush Conservation Strategy Part 2. The goal was to leverage recent advancements in remotely sensed landcover products to develop spatially and temporally explicit maps of sagebrush rangeland condition and landscape threats. In addition, the group sought to provide a common basis for understanding the state of sagebrush rangelands through time. First, the study team developed a spatially explicit model to assess geographic patterns in sagebrush ecological integrity and used this model to identify core sagebrush areas (CSAs), growth opportunity areas (GOAs), and other rangeland areas (ORAs) across the biome. Among the identified rangelands, 13.6 percent were classified as CSAs; 34.4 percent, as GOAs; and 51.9 percent, as ORAs. This equated to 33.4 million acres of CSAs and 84.3 million acres of GOAs, or 117.7 million acres of CSAs and GOAs combined as of 2020. Second, the team sought to demonstrate the ecological relevance of the identified CSAs and GOAs by comparing these data with independent datasets for sagebrush obligate species of conservation concern. Geographical patterns in sagebrush ecological integrity were strongly associated with high-priority species and displayed clear links to population performance for *Centrocercus urophasianus* (Bonaparte, 1827) (greater sage-grouse). The positive link to greater sage-grouse population trends in CSAs is important, as habitat management designations for this species have largely driven conservation actions across the sagebrush biome for the past several decades. Third, the team parsed out the type, location, and acres of primary threats within the different categories (CSAs, GOAs, and ORAs) to help focus active management by identifying places where multiagency and organization efforts can protect CSAs and GOAs that have higher levels of integrity with lower cumulative threats. The assessment of the condition of the sagebrush biome (that is, the location, amount, and conservation status) indicated that complex ecosystem function problems are driving ~73 percent of the demonstrated threats within the CSAs and GOAs (rather than point-source problems, such as human development). Fourth, the team developed trend estimates for the identified CSAs and GOAs and three selected primary threats (invasive annual grasses, conifer encroachment, and human modification) to the sagebrush biome from 2001 to 2020. Results showed that an average of 1.3 million acres per year have transitioned to ORAs at an annual rate of −1.34 percent. Fifth, the team developed an approach to integrate climate change effects into the threat-based landscape conservation design and conducted an initial assessment on the magnitude of near-term climate effects in the context of observed historical trends. The team's analysis suggests that climate change alone is unlikely to be the dominant threat to sagebrush ecological integrity in the next few decades, although interactions of climate with wildfire and invasive annual grasses may be an important threat, especially in the longer term.

In total, this work indicates that significantly more attention and commitment to targeted restoration and management will be needed to halt ecosystem degradation at a biome-wide scale should threats continue as they have in past decades. A spatial overlap analysis was performed and

*Authors are listed in alphabetical order after Wiechman

[1]U.S. Fish and Wildlife Service, U.S. Department of the Interior

[2]Conservation Planning Technologies

[3]U.S. Geological Survey, U.S. Department of the Interior

[4]Agricultural Research Service, U.S. Department of Agriculture

[5]The Nature Conservancy

[6]Oregon State University

[7]Bureau of Land Management, U.S. Department of the Interior

[8]Conservation Science Partners

[9]Natural Resources Conservation Service, U.S. Department of Agriculture

[10]Western Association of Fish and Wildlife Agencies

[11]Center for Large Landscape Conservation

[12]Aldo Leopold Wilderness Research Institute, U.S. Forest Service Rocky Mountain Research Station, U.S. Department of Agriculture

highlighted 45.8 million acres of shared priorities among existing conservation frameworks to help anchor and guide collaborative landscape-scale conservation of areas that still have no to low threats. The team identified annual rates of loss to combat annually to stop losses to the ecosystem and broadly identified how much and where conservation actions could be implemented. This information is critical to provide context for decisions about the volume and nature of conservation actions and funding requirements.

The scale of conservation called for in the sagebrush biome is daunting; however, there is clear precedence for successful conservation at tens of millions of acres and billions of dollars within North America through the North American Waterfowl Management Plan (U.S. Fish and Wildlife Service and the Canadian Wildlife Service, 1986; USFWS, 2022a). Regardless of the final form of coordination leaders in the Western United States agree upon, what is clear is that a comparable collaborative effort into durable conservation approaches that bring people together across geographies and cultures could benefit restoration of the sagebrush biome.

Introduction

Wildland systems around the world, particularly drylands, are experiencing degradation and changes in ecological integrity at unprecedented rates in modern history (Millennium Ecosystem Assessment, 2005; Reynolds and others, 2007). Managing large-scale ecosystem degradation is a primary conservation challenge that requires a shift from traditional species-specific interventions to planning frameworks that simplify complex causes of degradation into discrete and comparable categories of ecosystem condition (Salafsky and others, 2008). Regulatory intervention may not be effective at controlling complex problems that involve disruption of ecosystem processes, such as invasive annual grasses, altered wildfire regimes, and drought (Boyd and others, 2014). When these threats interact at a landscape-scale and are further compounded by a changing climate, new and more holistic approaches may be beneficial in preventing further degradation. Addressing persistent, complex, and large-scale ecosystem degradation likely requires sustained and adaptive management actions to direct limited resource capacity, funding, and tools as effectively and strategically as possible (Walker and others, 2004).

Landscape conservation frameworks that provide a common strategic approach for reducing ecosystem threats can help to unify diverse stakeholders around a shared vision despite multiple types of land ownership, land use, and community values (Boyd and others, 2014; Natural Resources Conservation Service [NRCS], 2021b). For example, a multistakeholder framework was used in the 1980s to create the North American Waterfowl Management Plan (NAWMP)—a large-scale conservation plan that focused on the primary factors driving wetland and associated habitat loss for waterfowl (U.S. Fish and Wildlife Service and the Canadian Wildlife Service, 1986). The original NAWMP outlined conservation actions guided by expert-drawn maps that identified places and practices for wetland conservation with broad stakeholder appeal and actionable goals (U.S. Fish and Wildlife Service and the Canadian Wildlife Service, 1986). This simple, unifying vision led to the establishment of Migratory Bird Joint Ventures in 1986 that have conserved 27 million acres as well as the passage of the North American Wetland Conservation Act (Public Law 101–233) in 1989, which raised $5.8 billion in funding ($1.9 billion in grants and $3.9 billion in matching funds) that has been used to restore an additional 31.5 million acres of waterfowl habitats (U.S. Fish and Wildlife Service [USFWS], 2022a; USFWS, 2022b). The NAWMP highlights the value of establishing a broad partnership and producing a framework with a landscape-scale vision that can unify stakeholders and help to focus complex ecological issues into clear, well-aligned goals and actions to work towards reversing declines in ecological integrity.

Within the shrubland biome of western North America, the spatial extent of *Artemisia* L. spp. (sagebrush) rangelands has declined by approximately 50 percent since the arrival of European settlers in the 1800s (Schroeder and others, 2004; Homer and others, 2015). This decline is associated primarily with biome-level threats, such as altered wildfire regimes, invasive annual grasses, conifer expansion, and human land use and land modification (USFWS, 2010; Davies and others, 2011). These factors are threatening a wide range of interests and values, including native plant conservation, wildlife and their habitats, wilderness preservation, health and human safety, rangeland agriculture, and the economic stability of rural communities. Given the pace and scale of the biome-level threats, sustaining the diverse ecosystem services associated with the sagebrush biome involves moving beyond species-level and value-specific management practices and into the realm of proactive ecosystem management focused on lessening factors that are driving biome-wide collapse (Boyd and others, 2014).

In the sagebrush biome, *Centrocercus urophasianus* (Bonaparte, 1827) (greater sage-grouse) has been a primary driver of sagebrush conservation for more than a decade, resulting in strong collaboration, restoration, and land-use policy changes (USFWS, 2010; Bureau of Land Management, 2015). Initially motivated by species-specific concerns, the sagebrush conservation partnership is shifting to an ecosystem-based approach to address landscape threats. In the Northern Great Basin, a diverse group of partners piloted the use of threat-based state and transition models to fight invasive annual grass invasion, encroaching conifer woodlands, and altered wildfire regimes (Johnson and others, 2019). These threat-based models seek to facilitate management of multiple complex, landscape-level threats through easily communicated and actionable steps. These models promote communication and align the conservation efforts of diverse stakeholders towards preserving and creating sagebrush-dominated stands with a perennial grass understory

(Johnson and others, 2019). Further, recent work quantitatively linked greater sage-grouse to these threat-based models and demonstrated the utility of this approach in benefiting species of conservation concern (Doherty and others, 2021).

A growing recognition of the need to effectively curtail large-scale threats has also led to the emergence of a new proactive strategy for sagebrush rangeland conservation titled "Defend the Core, Grow the Core, Mitigate Impacts" (NRCS, 2020, 2021b; Western Governors' Association [WGA], 2020). This broad strategy focuses on first protecting intact and functioning sagebrush ecosystems ("cores") and then working outward to improve the management and restoration of more degraded landscapes rather than initially starting with the most degraded areas (NRCS, 2021b). The "defend the core" strategy is now being used to direct resources to address a variety of rangeland threats, from invasive species to land-use conversion (NRCS, 2021b; Maestas and others, 2022). This strategy, focused on the threat of invasive annual grasses, has been particularly helpful in providing a path forward for addressing previously intractable problems (NRCS, 2020; WGA, 2020; Creutzburg and others, 2022).

In preparing the sagebrush conservation design, the study team leveraged recent advancements in remotely sensed landcover products to develop spatially and temporally explicit maps of sagebrush rangeland condition and landscape threats. The goal was to provide a common basis for understanding the state of sagebrush rangelands through time across the entire biome to help conservation partners more fully incorporate a holistic, ecosystem- and threat-based approach. The team had five main objectives: (1) Develop a spatially explicit model to assess geographic patterns in sagebrush ecological integrity and use these results to identify core sagebrush areas (CSAs), growth opportunity areas (GOAs), and other rangeland areas (ORAs). (2) Evaluate the temporal and spatial predictions of CSAs and GOAs to understand the congruence of these model-defined areas with other existing models for the following priority species: greater sage-grouse, three sagebrush obligate songbirds—*Spizella breweri* (Cassin, 1856) (Brewer's sparrow), *Artemisiospiza nevadensis* (Ridgway, 1874) (sagebrush sparrow), and *Oreoscoptes montanus* (J.K. Townsend, 1837) (sage thrasher)—and *Brachylagus idahoensis* (Merriam, 1891) (pygmy rabbit). The team also evaluated predictions against existing Federal and State agency-led conservation prioritization efforts in the sagebrush biome. (3) Provide context to the scale of conservation needed by calculating where and how many acres of invasive annual grasses, conifers, and human modification exist within CSAs and GOAs. (4) Provide trend estimates for CSAs and GOAs and summarize the amount of invasive annual grasses, conifer encroachment, and human modification within the sagebrush biome from 2001 to 2020. (5) Develop an approach to integrate climate change effects into a threat-based landscape conservation design and conduct an initial assessment on the magnitude of near-term climate effects (over the next ~25 years) in the context of observed historical trends.

Study Area

This project encompassed the full geographic extent of the sagebrush biome in the United States, which is found in 13 States in the western conterminous United States (Jeffries and Finn, 2019). Three small sagebrush landscapes within Canada along the border were not included in these analyses because of the lack of directly comparable spatial data. Within the U.S. sagebrush extent, nonrangelands, such as forests, lakes, urban areas, and cropland, were removed using a previously developed mask layer described in Maestas and others (2020). Alpine tundra grasslands were removed using the U.S. Geological Survey Gap Analysis Project (GAP) landcover dataset (U.S. Geological Survey Gap Analysis Project, 2016). The remaining unmasked areas were defined as sagebrush rangelands and represent the area modeled.

The U.S. Environmental Protection Agency level III dataset (Omernik and Griffith, 2014) ecoregions were used to form three regional groupings. Within these groupings, specific model parameters were used to account for biotic and abiotic differences (fig. 1) and differences in threat levels (section 1 of appendix 1) that occur across the biome. These regions (grouped from the level III ecoregions) are as follows:

Southern Great Basin. The Southern Great Basin region includes the Central Basin and Range, the Mojave Basin and Range, and the Sonoran Basin and Range level III ecoregions. This region represents the most southern and western portions of the sagebrush biome. This area was modeled separately because it is warmer and dryer, which results in naturally occurring lower amounts of perennial vegetation along with increased bare ground between vegetation (fig. 1). The differences in perennial vegetation are particularly pronounced compared with the vegetation of the Great Plains region (fig. 1).

Great Plains. The Great Plains region includes the High Plains, the Southwestern Tablelands, the Northwestern Glaciated Plains, and the Northwestern Great Plains level III ecoregions. The Great Plains region in the northeastern part of the sagebrush biome represents some of the largest remaining intact sagebrush and grassland rangelands in the conterminous United States. Ecologically, this area is characterized by a lower percent of sagebrush cover and higher levels of perennial grass both within and between the sagebrush stands (fig. 1). Compared with the other two regions, the Great Plains region receives the highest amount of precipitation per year and more precipitation during the warm growing season than the other regions studied.

Intermountain West. The Intermountain West region is typified by landscapes that transition from montane woody communities to sagebrush-dominated stands in areas of lower elevation or in rain shadows of mountain ranges. This region makes up the rest of the biome and includes the Cascades, the Sierra Nevada, the Eastern Cascades Slopes and Foothills, the Columbia Plateau, the Blue Mountains, the Snake River Plain, the Northern Rockies, the Idaho Batholith, the Middle Rockies, the Wyoming Basin, the Wasatch and

Uinta Mountains, the Colorado Plateaus, the Southern Rockies, the Arizona/New Mexico Plateau, the Arizona/New Mexico Mountains, and the Northern Basin and Range level III ecoregions. This region is typified by a relatively high percent of sagebrush cover and moderate levels of perennial grasses in the understory (fig. 1).

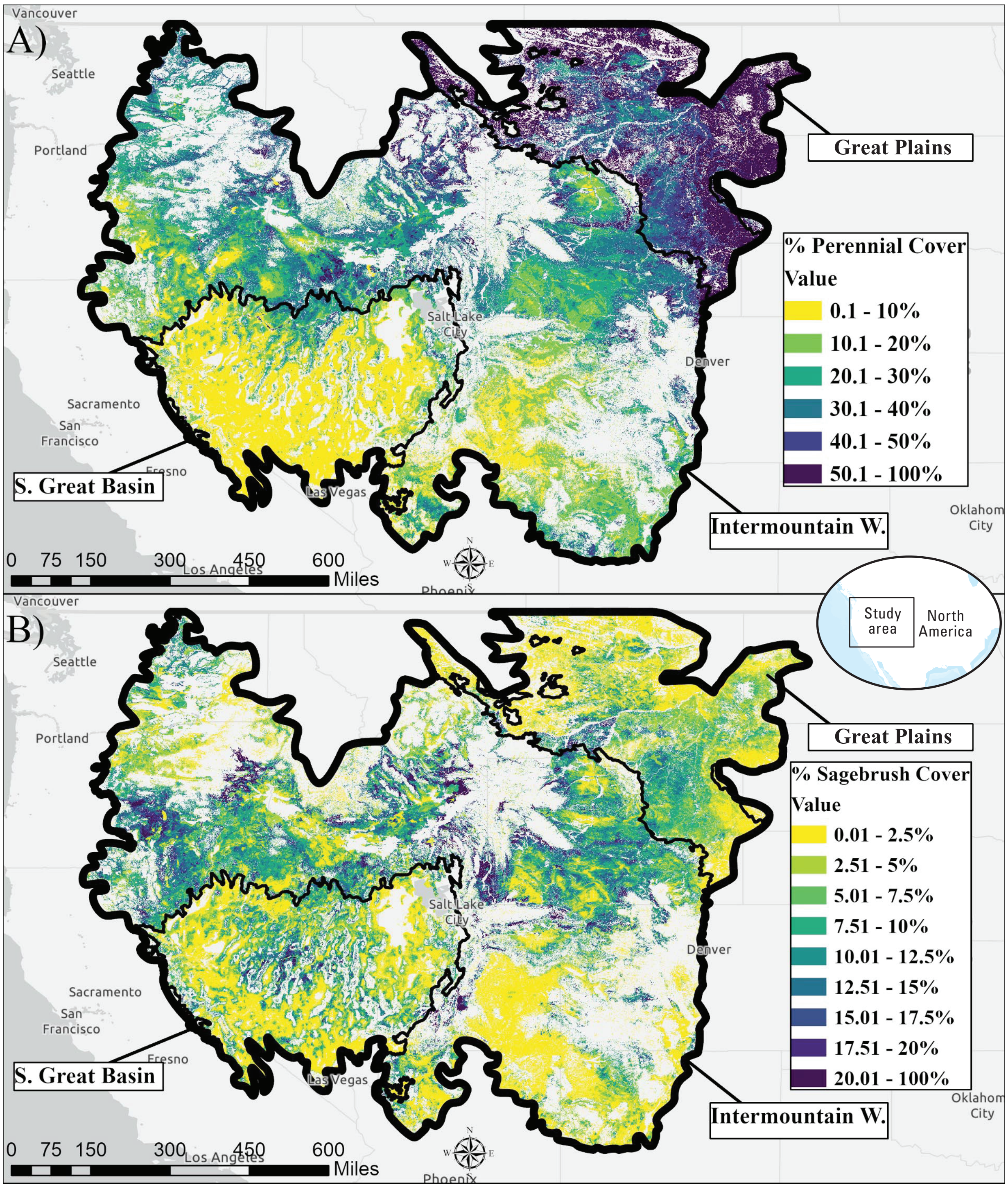

Figure 1. Differences in the amount of *A*, perennial grassland cover, and *B*, sagebrush cover across the three ecological regions (Southern Great Basin, Great Plains, and Intermountain West) used to model sagebrush ecological integrity in the sagebrush biome of the United States for 2020. Labels provided within the figure are names of cities. %, percent

Methods

A working group with diverse disciplinary expertise was assembled to conceptualize a spatially explicit conservation design. Specifically, this group was convened to develop a landscape conservation design that could provide a foundation for a common strategic approach for addressing biome-wide threats to the sagebrush ecosystem. The intent of the effort was to help unify conservation delivery efforts, facilitate and promote discussion among stakeholders to set ecosystem-level objectives, and be a foundation for part of a comprehensive and strategic adaptive management framework. This expert group represented a diverse set of disciplines, including climatology, conservation biology, fire ecology, landscape ecology, rangeland ecology, spatial ecology, and wildlife biology. Collectively, the working group had experience that spanned different regions within the sagebrush biome and accounted for regional variability across the biome. All phases of the development of the threat-based conservation design, including spatial products, were vetted within the networks of the agency and organizations represented within the expert working group. Lastly, many members of the working group had been or were involved in various interagency and multiorganizational collaboratives for the sagebrush biome, which helped the group develop a product that is complementary to existing conservation plans and frameworks (for example, the Sagebrush Conservation Strategy Part 1 [Remington and others, 2021] and the Integrated Rangeland and Fire Management Strategy Science Frameworks Part 1 [Chambers, Beck, and others, 2017] and Part 2 [Crist and others, 2019]).

The spatially explicit conservation design expands upon two recent broad-scale interagency and organization collaborative conservation initiatives. One recent initiative is the conceptual model of “Defend the Core, Grow the Core, Mitigate Impacts” (NRCS, 2020, 2021b; WGA, 2020), which has helped change the conservation narrative into one that begins with healthy anchor landscapes that have no threats or low-level threats and expands outwards towards the more threatened areas. The second recent initiative is the threat-based state and transition models developed in Oregon to fight invasive annual grass invasion, encroaching conifer woodlands, and altered wildfire regimes (Johnson and others, 2019); these models are critical to simplifying the complex ecology so that the science is actionable to managers, policymakers, and stakeholders charged with supporting and implementing landscape-level conservation. These two approaches were expanded on to model sagebrush conservation from regional landscapes to the biome-wide distribution of sagebrush.

Objective 1: Model the Integrity of the Sagebrush Ecosystem

In preparing the model of integrity, the study team followed the concepts of ecosystem degradation, which are changes to an ecosystem that directly impair the biotic and (or) abiotic components of biological integrity for that ecosystem (Salafsky and others, 2008). The term integrity, which is the inverse of degradation, is used because it places the focus on quality rather than on dysfunction. The determination of core sagebrush areas included two steps: first, patches of high sagebrush ecological integrity (SEI) were defined as being those with abundant sagebrush, native understories, and minimal threats (that is, invasive annual grasses, expanding conifers, and human modification). Second, the places where these patches converged to create large and intact sagebrush landscapes were identified.

In step 1, SEI for the biome was modeled with a focus on five patch-level indicators (or variables). Two of the five indicators (percent sagebrush cover and percent perennial grass cover) contribute to integrity, whereas three variables (percent annual grass cover, percent tree [conifer] cover, and an index of human modification) represent “threats” that detract from integrity. Taken together, these indicators characterize sagebrush ecosystem integrity (table 1). Each of the five indicators used are well-supported in the literature and can be mapped and tracked through time using remotely sensed and web-based datasets (Theobald and others, 2020; Allred and others, 2021; Rigge, Homer, and others, 2021), which allows for range-wide assessment, setting objectives at multiple scales, and frequent evaluation of the cumulative effectiveness of management actions at slowing or reducing threats at landscape scales. All data processing and modeling of SEI was conducted using Google Earth Engine (Gorelick and others, 2017).

Ecology of Factors Contributing to Sagebrush Ecological Integrity

Sagebrush foliage percent cover is a definitive characteristic of the ecosystem and relevant to persistence of most sagebrush-associated animal species studied, such as greater sage-grouse (Connelly and others, 2011), sagebrush-obligate songbirds (Knick and Rotenberry, 1995; Earnst and Holmes, 2012; Carlisle and others, 2018), and pygmy rabbits (Smith and others, 2019). Fragmentation and loss of formerly large and contiguous sagebrush patches are primarily the result of altered fire regimes, annual grass invasion, conifer woodlands expansion, and various human land uses—trends that profoundly alter the composition, structure, and function of the ecosystem (table 2; Knick, 1999). Therefore, extant stands of sagebrush are a good representation of ecological function relative to lack of degradation-causing threats. The sagebrush cover was measured using the U.S. Geological Survey (USGS) Rangeland Condition, Monitoring, Assessment, and Projection (RCMAP) dataset (table 1; Rigge, Homer, and others, 2021).

The effects of fire on SEI were modeled by measuring the changes in percent cover of sagebrush, perennial herbaceous (grass and forb) cover, invasive annual grass cover, and tree (conifer woodlands) cover from remotely sensed platforms (table 1). Therefore, the effects of fire are captured by the measured changes in cover of the indicators that make up SEI (see the Sagebrush Ecological Integrity Functional Relationships section below). Fires were explicitly accounted for by excluding cover data in table 1 in years prior to each given fire. For example, if a fire burned in 2018, landcover in only 2019 and 2020 was used to calculate the SEI. This method ensured that the effects of fire were not diluted because of the multiyear averaging process used. This process also ensured that landscape-level changes that result from wildfire are incorporated in the estimates of SEI and trends in SEI through time.

Perennial herbaceous (grass and forb) cover is a second key component of a high-functioning sagebrush system as measured by the SEI approach. Prior to European settlement in the 1800s, sagebrush vegetation communities consisted predominantly of native perennial plants, including grasses, forbs, sagebrush, and other shrubs. Much of that native vegetation mosaic has been affected by human settlement and land-use change (Remington and others, 2021). Especially during the 20th century, the distribution of invasive annual grasses has greatly expanded (Germino and others, 2016; Smith and others, 2022), which has increased the flammability and frequency of fires in areas where the invasive annual grasses are present (Balch and others, 2013; Bradley and others, 2018). Intact perennial understories provide biotic resistance to invasive annual grass expansion (Davies, 2008; Chambers and others, 2014; Davies and Johnson, 2017). Additionally, persistent native herbaceous communities provide critical ecosystem services, including stabilizing soil, enhancing soil water availability (Roundy and others, 2014), supporting food webs important to wildlife (Goosey and others, 2019), and supplying desirable forage for domestic livestock grazing (Davies and Svejcar, 2008). Perennial herbaceous cover was measured using the Rangeland Analysis Platform, version 2 (RAP v2) (table 1; Allred and others, 2021).

Table 1. Landcover variables that were used to define sagebrush ecological integrity within the sagebrush biome of the United States from 1998 to 2020.

[Where wildfires occurred during the sampled time interval, values for the fire year and previous years were removed for sagebrush, perennial grass cover, annual grass cover, and tree cover. For each year the Core Sagebrush Area Model was built (2001, 2006, 2011, 2016, and 2020), data were averaged over the 4 years to reduce interannual variability. For example, the 2020 model was an average of 2017, 2018, 2019, and 2020 data. USGS, U.S. Geological Survey; %, percent]

Name of variable	Source	Native resolution (meters)	Timeframe	Update frequency	Description
Mean sagebrush cover	USGS Rangeland Condition, Monitoring, Assessment, and Projection (RCMAP) (Rigge, Homer, and others, 2021)	30	1998 to 2020	Annually	Sagebrush cover (%) estimated as canopy cover of sagebrush shrub species (*Artemisia* spp.) using Landsat satellite imagery.
Mean perennial grass cover	Rangeland Analysis Platform, version 2 (RAP v2) (Allred and others, 2021)	30	1998 to 2020	Annually	Perennial grass cover (%) estimated using Landsat satellite imagery. Note that current satellite platforms cannot distinguish between native and nonnative perennial herbaceous cover.
Mean annual grass cover	Rangeland Analysis Platform, version 2 (RAP v2) (Allred and others, 2021)	30	1998 to 2020	Annually	Annual grass and forb cover (%) estimated using Landsat satellite imagery. Note that current satellite platforms cannot distinguish between native and nonnative annual herbaceous cover.
Mean tree cover	Rangeland Analysis Platform, version 2 (RAP v2) (Allred and others, 2021)	30	1998 to 2020	Annually	Tree cover (%) estimated using Landsat satellite imagery. This dataset is used as a surrogate for expanding conifer woodlands, but expansion was not directly modeled.
Mean human modification	Theobald and others, 2020	560	2001–2020	2001, 2006, 2011, 2016, 2019, and 2020	Value of human modification (0.0 to 1.0) is an integration of human land uses and threats. (See table 2 for full list.) Data were smoothed in the same manner as for sagebrush cover.

Invasive annual grasses (for example, *Bromus tectorum* L. [cheatgrass] and *Taeniatherum caput-medusae* L. [medusahead]) have profound and well-documented effects on the ecological function of sagebrush plant communities, including increased fire frequency and loss of native perennial species (Germino and others, 2016; Davies and others, 2021). Further, increases in invasive annual grasses and associated increases in wildfire frequency and extent (D'Antonio and Vitousek, 1992; Balch and others, 2013; Crist and others, 2021) are the most pervasive change agents leading to loss of SEI in the Southern Great Basin and Intermountain West regions (Smith and others, 2022). The invasive grass fire cycle and associated effects on sagebrush-dominated communities are well-documented ecologically (Bradley, 2009) and spatially (Jones and others, 2018; Boyte and others, 2019). Owing to the slow rate of sagebrush recovery in these ecoregions, large and frequent fires that lead to extensive loss of sagebrush cover will likely have negative effects on wildlife populations over long periods of time (decades) (Longland and Bateman, 2002; Coates and others, 2016). Further, certain areas that have lower resistance and resilience to disturbance may experience state changes to invasive annual grasses (Chambers and others, 2014; Chambers, Beck, and others, 2017; Chambers, Maestas, and others, 2017).

The relationship between invasive annual grass and wildfire observed in the Southern Great Basin and Intermountain West regions likely differs in the Great Plains. The Great Plains region has higher amounts of perennial grass cover both within and between sagebrush stands (fig. 1), more summer precipitation (Porensky and Blumenthal, 2016; Porensky, 2021), and native plants with a higher tolerance for disturbances, such as fire and herbivory (Porensky and Blumenthal, 2016; Porensky and others, 2020; Porensky, 2021). These differences may help explain why in this region wildfires (Porensky and Blumenthal, 2016) and prescribed fire burns (Symstad and others, 2021) can reduce the presence of invasive annual grasses, which is not the case the Intermountain West and the Southern Great Basin regions. Invasive annual grass cover was measured using the RAP v2 (table 1; Allred and others, 2021)

Conifer woodlands [that is, *Pinus edulis* (Engelm) (piñon pine) and *Juniperus* L. spp. (juniper)] have expanded their range in parts of the sagebrush biome, particularly in the Southern Great Basin region (Miller and Rose, 1995; Miller and others, 2000) and the Colorado Plateau ecoregion (Romme and others, 2009; Miller and others, 2019). These shifts are known to have negative effects on greater sage-grouse (Baruch-Mordo and others, 2013; Coates and others, 2017; Severson and others, 2017b) and other sagebrush-associated wildlife populations (Miller and others, 2017; Maestas and others, 2021). Increases in conifer canopy cover result in nonlinear declines in sagebrush cover (Roundy and others, 2014; Miller and others, 2000), which directly reduces the amount of available food and cover for sagebrush-dependent species and thereby increases its relative threat (Maestas and others, 2021). Climate patterns influence natural disturbance, such as: drought, insects, disease, and wildfire, which all have a strong influence on the expansion and contraction of conifer woodlands. In the 20th century, a climatic period of higher levels of precipitation combined with past over-grazing and fire suppression promoted woodland expansion into more sagebrush-dominated areas (Miller and others, 2008). Tree-ring analyses in the Great Basin region suggest a twofold to sixfold increase in woodlands prior to the arrival of European settlers in the 1800s (Miller and others, 2008), but the overall extent of pinyon-juniper increase varies across its range; expansion is more localized in some areas, such as the Colorado Plateau ecoregion, whereas other areas are experiencing contractions (Romme and others, 2009). In most areas, conversion from sagebrush to conifer dominance decreases perennial grass and forb cover, productivity, and species richness; influences soil water infiltration, runoff, erosion, and sediment loads; and changes carbon cycles (Miller and others, 2000; Maestas and others, 2021). These alterations can reduce sagebrush ecosystem resilience to disturbances and resistance to invasive plants (Miller and others, 2013; Chambers and others, 2014; Chambers, Beck, and others, 2017; Chambers, Maestas, and others, 2017). Conifer cover was measured using the RAP v2 (table 1; Allred and others, 2021)

Human modifications to natural ecosystems, including landcover conversion for urban, agricultural, and energy development, also reduce SEI at local and landscape scales. Human modification to and land-use change of sagebrush ecosystems have altered or removed native vegetation cover over millions of acres (Reeves and others, 2018). Landcover conversion and modification of natural ecological processes across the ecosystem vary in extent and severity and include agriculture, urban development, resource extraction and energy development (for example, hard rock mining, and oil and gas drilling), and residential and industrial infrastructure (roads, transmission lines, railroads, and pipelines; table 2). Conversion of native sagebrush to other landcover types results in direct habitat loss for sagebrush-obligate wildlife species, such as greater sage-grouse and *Centrocercus minimus* (J.R. Young, C.E. Braun, S.J. Oyler-McCance, J.R. Hupp & T.W. Quinn, 2000) (Gunnison sage-grouse) and Brewer's sparrow (Monroe and others, 2021). Similarly, pygmy rabbits avoid roadsides with reduced sagebrush cover (Pierce and others, 2011). Additionally, roads and other human modifications to sagebrush communities serve as vectors for exotic plant invasion and establishment (Gelbard and Belnap, 2003; Manier and others, 2011; Barlow and others, 2017). Mean human modification of the sagebrush biome was measured using the methods of Theobald and others (2020, table 2).

Sagebrush Ecological Integrity Functional Relationships

Continuous functional relationship curves were created by experts to quantify the relationship between the percent of each variable within a patch-scale (560 meter [m]) and the component SEI values (Q; roughly interpreted as "quality"), resulting in values that ranged from zero to one (figs. 2 and 3). This analysis was conducted using 30-m-resolution data averaged by a 560-m-radius window because this has been shown to be a strong predictor scale for greater sage-grouse habitat selection when using a threat-based framework (Doherty and others, 2021). This scale also made it possible to identify patches of relatively intact sagebrush with perennial understories. Monte Carlo simulations were used to assess the sensitivity of overall SEI estimates to uncertainty in expert-based relationships between individual Q curves in figures 2 and 3. This sensitivity analysis demonstrated that the SEI estimates were stable up to variation of 1 standard deviation (see section 2 of appendix 1). Consequently, the results discussed in the main body of this report are, at a biome-wide extent, largely robust to the estimated relationships specified in the SEI model (see section 2 of appendix 1).

Continuous relationships representing how SEI is influenced by each of the five indicators were defined. SEI is decreased at low levels of sagebrush or perennial grass cover, and decreased at high levels of annual grasses, conifers, and human modification (figs. 2 and 3). Thus, for each location, these relationships generated five Q values that combine to estimate SEI values that can range from zero to one (eq. 1).

$$SEI_{560} = Q_{sage} \times Q_{perennial\ grass} \times Q_{annual\ grass} \times Q_{conifer} \times Q_{human\ modification} \quad (1)$$

where SEI_{560} denotes the multiplicative SEI score for each 30m x 30m pixel and Q values are derived from the relationships for each remotely-sensed indicator (figs. 2 and 3). A rangeland mask was applied to remove locations that are dominated by nonrangeland land-cover types (for example, urban areas, croplands, roads, and so forth; Maestas and others, 2020). Locations typically above timberline that were identified as tundra ecological systems from the USGS GAP landcover dataset (U.S. Geological Survey Gap Analysis Project, 2016) were removed as well. The percent cover of all five variables was calculated for each pixel using a Gaussian kernel within a 560-m radius (Gorelick and others, 2017).

Defining Core Sagebrush Areas, Growth Opportunity Areas, and Other Rangeland Areas

The average SEI_{560} value within a 2-km radius Gaussian kernel was calculated (to obtain SEI_{2000} values) to reflect a broader, management-relevant scale. This calculation was done to identify the patches of sagebrush that had sufficient perennial herbaceous understories and low levels of the three threats, as defined by the Q curves, to create large and intact landscapes. SEI_{2000} was then used as the continuous values to define CSAs, GOAs, and ORAs.

To define these three classes, outliers in the distribution were removed by finding the bottom and top 1 percent of the SEI_{2000} values (0.002 and 0.7988), respectively. The SEI_{2000} values were then normalized so that the minimum (0.002) and maximum (0.7988) values would equal 0.0 and 1.0 (that is, a unit scale normalization). The normalized SEI_{2000} values were then binned into equal intervals that ranged from 1 to 10 and where values greater than or equal to 9 represent the top ~10 percent of possible normalized values. The normalized SEI_{2000} values were found to be coincident with the decile breaks, which were 0.002, 0.009, 0.068, 0.115, 0.173, 0.244, 0.326, 0.431, 0.565.

The equal interval classification methodology was used because it ensures that values with similar SEI_{2000} scores are contained within the same bins and because it is easy to interpret and explain. The outliers of the distribution were removed before the SEI_{2000} values were normalized into equal interval break values to create a better distribution of values within each class. Quantile classification was not used because it would have resulted both in large differences in SEI_{2000} scores contained within a single bin and in multiple bins differing by very small amounts. This is because the SEI_{2000} values were not uniformly distributed, and a large proportion of the study area had low values.

Note that during the review of the Great Plains region, the experts on the team made minor adjustments to the response curves (Q values) to generate the final SEI_{2000} values. The 99 percent threshold used to remove outliers (see the text above on defining the three classes) was adjusted slightly to 0.767 from the original value of 0.798. Because the class breaks from the previous decile calculations were reviewed in detail by the advisory group, the study team retained the original class breaks after reviewing the choropleth-maps in detail and observing no significant differences. The team also reviewed the distribution of the class breaks for obvious breaks in slope as another line of evidence in grouping the decile bins. Based upon these reviews, the CSAs were then defined as those areas representing the top ~20 percent of normalized SEI_{2000} scores. Growth opportunity areas were defined in the next highest ~50 percent of normalized SEI_{2000} scores. Lastly, ORAs were defined as the lowest ~30 percent of normalized SEI_{2000} scores.

Table 2. Threats and datasets used to estimate the degree of human modification in the sagebrush biome.

[Methods follow Theobald and others (2020). Threat (stressor) classification levels in parentheses correspond to those within the Direct Threats Classification v2 (Salafsky and others, 2008). Scale (or ratio) refers to the resolution of the dataset, and year represents the time for which the data were collected. BF, US Building Footprints; BLM, Bureau of Land Management; EIA, U.S. Energy Information Administration; HGL, hydrocarbon gas liquids; LCMAP, Land Change Monitoring, Assessment, and Projection; NCEI, National Centers for Environmental Information; NLCD, National Land Cover Dataset; NOAA, National Oceanic and Atmospheric Administration; TIGER, Topologically Integrated Geographic Encoding and Referencing; U.S. Census, U.S. Bureau of the Census; USDA, U.S. Department of Agriculture; USFS, U.S. Department of Agriculture Forest Service; USGS, U.S. Geological Survey; VIIRS, Visible Infrared Imaging Radiometer Suite; WRI, World Resources Institute; km, kilometer; m, meter; *n*, number; No_x, nitrous oxides; So_x sulfuric oxides; ~, approximately]

Class	Threat (stressor)*	Source	Scale (m or ratio)	Year
Urban and built-up (1)	Built-up (1.1, 1.2)	NLCD (www.mrlc.gov; Jin and others, 2019)	30 m	2016
		Low-density residential (approx. <1 unit per 2 acres; BF [Microsoft Corp., 2019])	30 m	2015
Agriculture (2)	Croplands and pasturelands (2.1)	NLCD	30 m	2019
		USDA Cropland Data Layer (Boryan and others, 2011; Lark and others, 2017)	30 m	2017–19
	Grazing (2.3)	Active grazing allotments on BLM or USFS public lands (Bureau of Land Management, 2019; U.S. Department of Agriculture Forest Service, 2020a)	30 m	~2017
Energy production and mining (3)	Oil and gas production (3.1)	Oil and gas wells: FracTracker (www.fractracker.org; *n*=1,193,570 [Homer and others, 2020]), and from NLCD impervious description	30 m	2016
		Petroleum refineries (EIA; *n*=129)	30 m	2020
	Mining and quarrying (3.2)	Surface mine footprints (Maus and others, 2020)	1 km 30 m	2018 2019
	Renewable (3.3) and nonrenewable power (1.2) generation	World Resources Institute powerplants (World Resources Institute, 2019)	~1:100,000	2019
		NLCD impervious descriptor	30 m	2016
Transportation and service corridors (4)	Roads (4.1)	U.S. Census TIGER Roads	~1:10–25,000	2019
	Railways (4.1)	U.S. Census TIGER Railways	~1:10–25,000	2019
	Powerlines and pipelines (4.2)	Powerlines, and pipelines for HGL, natural gas, petroleum products from the EIA;	~1:10–25,000	2019
	Electrical infrastructure (4.2)	Nighttime lights from VIIRS; Earth Observation Group, NOAA/NCEI (Elvidge and others, 2013; https://eogdata.mines.edu)	375 m	2019
Biological harvesting (5)	Logging and wood harvesting (5.3)	Timber harvest (U.S. Department of Agriculture Forest Service, 2020c) Forest change using USGS LCMAP (Zhou and others, 2020) and wildfire perimeters (Monitoring Trends in Burn Severity Project, 2021)	30 m	2020
Human intrusions (6)	Human intrusion (1.3, 5.1, 5.2, 6.1)	Ski resorts (U.S. Department of Agriculture Forest Service, 2020b)	30 m	2019
Natural system modifications (7)	Reservoirs (7.2)	National Inventory of Dams (U.S. Army Corps of Engineers, 2020)	~1:25,000	2019
Pollution (9)	Air pollution (9.5)	Deposition for NO_x and SO_x (Wisconsin State Laboratory of Hygiene, 2020)	3,000 m	2019

*Based on interpolation.

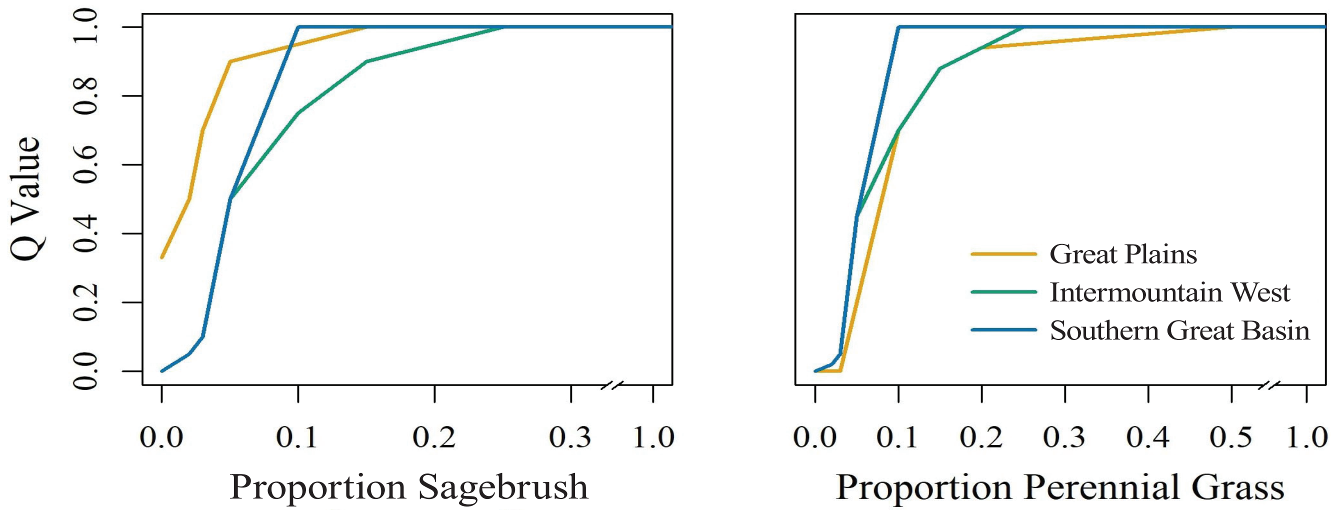

Figure 2. The functional relationship between the proportion of *A*, sagebrush and *B*, perennial grass within a 560-meter (m) Gaussian kernel to relative sagebrush ecological integrity (*Q* values), which allows a comparison of each 30-m pixel in the entire sagebrush biome of the United States. Expert opinions were used to define *Q* values as a relative ranking system for components of sagebrush ecological integrity.

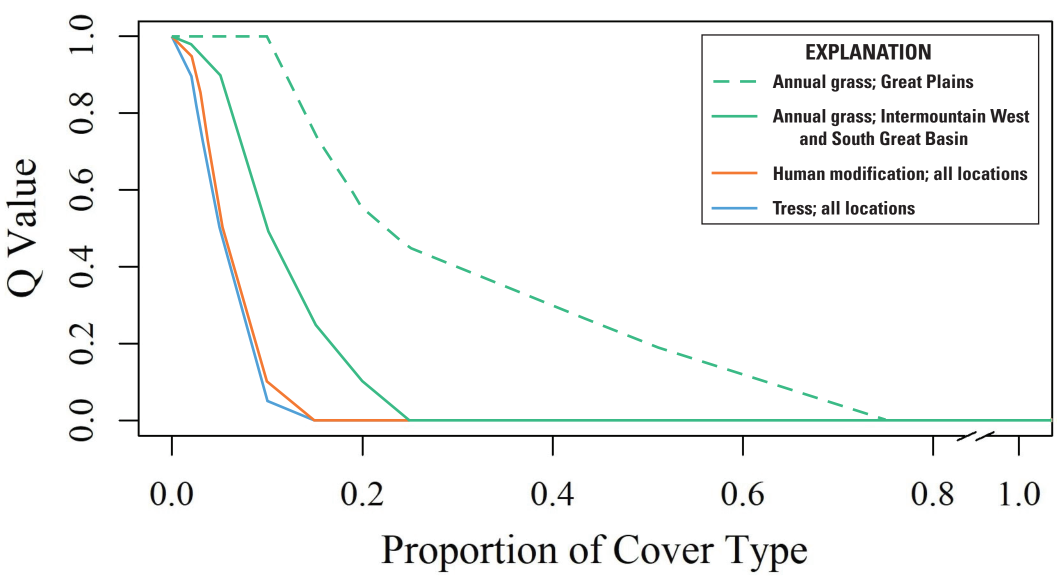

Figure 3. The functional relationship between the proportion of three primary threats to the sagebrush biome—invasive annual grasses, human modification, and tree (conifer) expansion—within a 560-meter (m) Gaussian kernel to relative sagebrush ecological integrity (*Q* values), which allows a comparison of each 30-m pixel in the entire sagebrush biome of the United States. Expert opinions were used to define *Q* values as a relative ranking system for components of sagebrush ecological integrity.

Objective 2: Evaluate Spatial Congruence With Single-Species Populations and Agency Priority Areas

For this analysis, areas designated as CSA and GOA were compared with priority habitat areas defined for single species that spanned the biome (that is, greater sage-grouse [Doherty and others, 2016], sagebrush obligate songbirds [USFWS, 2022b], and pygmy rabbits [Smith and others, 2019]). Also, the CSA and GOA areas were compared with existing agency and organization prioritizations; that is, those of States, the Bureau of Land Management (BLM), the U.S. Department of Agriculture Forest Service (USFS), the NRCS, and the USFWS.

These comparisons have three benefits. First, having different methodologies and paradigms highlight similar landscapes increases the scientific rigor of and confidence in the results of the analysis (Romesburg, 1981). Second, the comparisons make it possible to quantify the percent of focal species populations within the CSAs and GOAs and the spatial overlap between existing agency priority areas. For the purposes of this evaluation, “priority areas” were considered to include Priority Areas for Conservation (or PACs, as developed by States), the BLM and USFS Priority Habitat Management Areas (PHMAs), and the USFWS Sagebrush Strategic Habitat Conservation (SHC) 50% Wildlife Population Cores. This comparison was done to identify where priority areas aligned with the umbrella of CSAs and GOAs. Third, the comparisons highlight areas that are unique and would be missed by focusing solely on CSAs and GOAs.

To determine the percentage of a focal species population contained in CSAs and GOAs, the SEI results were compared with published spatial distribution models for the following five focal sagebrush species: greater sage-grouse (Doherty and others, 2016), Brewer’s sparrow, sagebrush sparrow, sage thrasher (USFWS, 2022b), and pygmy rabbit (Smith and others, 2019). For each focal species model, the summation of model values for pixels within the CSAs and GOAs was divided by the summation of model values for the entire SEI model area to obtain the percent of individual populations contained within the study extent. The difference in the amount of the population versus the area of CSAs and GOAs was calculated by dividing the percent of the population contained within the CSA or GOA by the percent area of the CSA or GOA relative to our modeled sagebrush rangelands. A percentage greater than 100 indicates that the CSAs and GOAs are identifying landscapes with higher densities of priority species than would be expected by their area alone.

To quantify the proportion of joint priority areas within the umbrella of CSAs and GOAs, a calculation of the percent overlap between agency specific conservation priority areas to nonrangelands, ORAs, CSAs, and GOAs was performed. A spatial representation of these analyses was prepared to visualize the congruence and divergence between the areas; this was done by identifying the percentage of area where CSAs and GOAs overlapped with one or more agency management designations, where CSAs and GOAs did not overlap with one or more agency management designations, and where no agency designations overlapped CSAs or GOAs. Anchor areas were defined and mapped as landscapes where CSAs and GOAs overlapped with one or more agency management designations and had no to low threats for all three of the modeled threats. These anchor landscapes represent places that are prioritized in multiple planning efforts and align with the “defend the core” strategy.

Long-term changes in greater sage-grouse population abundance were calculated in a separate study (Coates and others, 2021) and summarized within the categories of the conservation design (CSA, GOA, and ORA). This summarization was done to examine differences in range-wide population trends between categories. Trends in sage-grouse leks (breeding-grounds) in CSAs were expected to be higher than those in GOAs, and lek trends in GOAs were expected to be higher than those in ORAs. The leks were assigned categories (CSA, GOA, and ORA) based upon their location in 2019. Long-term changes in greater sage-grouse population abundance for all leks within each category were summarized. Once assigned to a category, posterior distributions of greater sage-grouse abundance and intrinsic rate of population change ($\hat{r}$) were summarized according to the parameter of interest ($\widehat{N}$ = summed, $\hat{r}$ = averaged) and converted to finite rate of change (λ) as $e^{\hat{r}}$. Long-term trends were calculated for each category based on the annual estimates from their constituent leks. Trends of greater sage-grouse abundance were summarized using the median estimates from the posterior probability distributions (highest probability value) of abundance at 4,478 leks, which spanned the species’ distribution within the sagebrush biome in 11 Western States.

The team evaluated differences in range-wide trends of greater sage-grouse population abundance over a recent 24-year period (1996 to 2019), which corresponds to the general duration of threat-based design for this study. The 1996 to 2019 period is a reasonable timeframe to summarize long-term changes in greater sage-grouse population abundance because (1) the start (1996) represented a population nadir (lowest points in oscillations of abundance), (2) 1996 represented the lowest point in range-wide abundance during the past 60 years, and (3) the time series was long enough to incorporate sufficient variability in the form of environmental and demographic stochasticity (Coates and others, 2021). The final year of the trend time-series (2019) from Coates and others (2021) represents the lowest population abundance (that is, nadir) in the most recent oscillation. If 2019 did not represent a nadir and populations continued to decline range-wide in 2020 and 2021, then overall trend estimates summarized within this report by CSA, GOA, and ORA may be conservative and change with updated data from 2020 and 2021. Regardless, the relative differences in trends between categories serve as an evaluation of the SEI concept.

Objective 3: Quantify Status of Sagebrush Rangelands Relative to Primary Threats in 2020

The type, location, and acres of threats within the different categories (CSAs, GOAs, and ORAs) were described for the following three threats: (1) annual grass cover; (2) conifer; and (3) human modification of the environment. A risk assessment framework (Connelly and others, 2018) was used where the potential risk of these threats was modeled across the sagebrush biome using the spatial overlap between the CSA and GOA models, and the hazard levels for each threat were defined using the most recent year of available data coverage (that is, 2019 for human modification and 2020 for invasive annual grass and conifer cover). The hazard levels—no to low, moderate, high, and very high—were set by thresholds of raw data values (for example, percent cover of annual grasses; table 3). These areas of overlap were expressed in risk matrixes, which were unique combinations of SEI classes by hazard level for each threat. These matrixes are intended to identify areas for potential targeting with the "defend the core," "grow the core," and "mitigate impacts" strategies (fig. 4).

Table 3. Levels of threat as measured by the percent cover for three of the largest threats to the sagebrush biome of the United States (invasive annual grasses, conifer woodlands expansion, and human modification).

[No to low threats represent a proactive and preventative care approach. Treatments within no to low threats often have higher success rates with lower costs. High and very high threats represent reactive and emergency care approaches within degraded states. Treatments within these areas have lower success rates and are more expensive. Moderate threats represent areas that are in transition. %, percent; NA, not applicable]

Threat	No to low	Moderate	High	Very high
Invasive annual grasses*	≥ 0 to ≤ 8%	> 8 to ≤ 15%	> 15%	NA
Conifer expansion	≥ 0 to ≤ 2%	> 2 to ≤ 10%	> 10 to ≤ 20%	> 20%
Human modification	≥ 0 to ≤ 3%	> 3 to ≤ 15%	> 15%	NA

*Breaks for the Great Plains region were 0% to 15% for no to low threat, 15% to 42% for moderate threat, and > 42% for high threat. This is because of a much higher ratio of perennial grasses to annual grasses within the ecoregion. Further, preliminary research suggests that fires in this ecoregion reset the area to perennial grass (Porensky and Blumenthal, 2016; Symstad and others, 2021), which will naturally transition to sagebrush through time (Johnson and others, 2019).

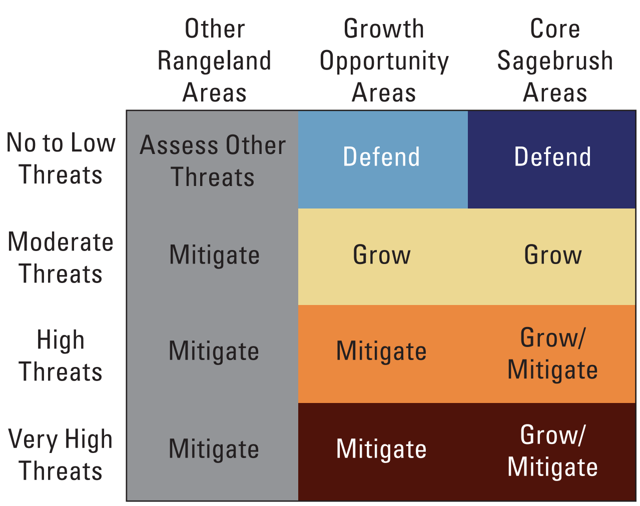

Figure 4. Conceptual threat matrix to align multithreat conservation strategies for core sagebrush areas and growth opportunity areas identified for the sagebrush biome of the United States with the conceptual classes (strategies) of "defend the core," "grow the core," and "mitigate impacts" (Natural Resources Conservation Service, 2020, 2021b; Western Governors' Association, 2020). The areas that align with the defend the core and grow the core strategy were spatially intersected and tabulated by conducting a matrix overlay using the classes defined in the figure. For each threat, the acres of treatment needed where "grow" is labeled in the matrix were summed. High and very high threats with "grow/mitigate" are labeled this way to highlight that treatment options may not be available for all areas that are subject to high or very high threats. Colors in the matrix correspond to colors on the maps in figures 8 through 11.

Objective 4: Evaluate Spatial and Temporal Patterns of Change in Sagebrush Ecological Integrity

Trends were calculated for all components of SEI (that is, for each *Q* value) and in CSAs and GOAs for 2001 to 2020. Accounting for these dynamic changes through time is critical in determining potential net conservation uplift and the resources needed to generate that uplift during conservation planning, yet this accounting may be ignored when setting conservation goals (Doherty and others, 2013). SEI and its component values were modeled for 2001, 2006, 2011, 2016, and 2020, which coincided with National Land Cover Dataset data availability for human modification (table 2). Each time step label denotes the last of the 4 years during which values were averaged (that is, the label 2001 includes averaged values from 1998 to 2001). Wildfire effects were accounted for by removing the *Q* values for the component layers for years prior to the event, for pixels that sustained a fire event. This method made it possible to visually depict and calculate changes in area of CSAs and GOAs attributable to changes in sagebrush cover, perennial grass cover, annual grass invasion, conifer encroachment, and human modification. To delineate CSAs and GOAs prior to 2020, the class breaks identified using 2020 data (SEI_{2000}) were applied to the SEI model created for 2001, 2006, 2011, and 2016. The location and areas of CSAs and GOAs gained or lost were then calculated to determine the overall trends and spatial variation in SEI across time steps. To analyze trends in CSAs, GOAs, and ORAs, the areas of these three zones were extracted for each time step. Simple linear regression models were generated to characterize how the CSAs and the intersection of CSAs and GOAs (CSA+GOA) have changed over time. The rates were derived from a simple linear regression on area with time step as the only predictor variable. Simple linear regression does not account for temporal autocorrelation and may obscure fluctuations in time, but it is an appropriate approach for evaluating general trends in this context, particularly because the underlying data were averaged into multiyear time steps and because the assumption of a monotonic relationship (here, decreasing) largely holds upon visual inspection of the data. These models provide a generalized (that is, over 5-year time steps) rate of change of CSAs and CSAs+GOAs, which were then used to project the future year at which one-half of the areas have transitioned to lower classes. The models were generated and applied using R software version 4.1.2 (R Core Team, 2021).

Objective 5: First Look at Climatic Effects on Core Sagebrush Areas, Growth Opportunity Areas, and Other Rangeland Areas

To evaluate the potential effects of climate change, an estimate of how SEI would be altered by potential future shifts in the climate suitability for *Artemisia tridentata* Nutt. (big sagebrush), perennial grasses, and invasive annual grasses was made. To do this, the study team used recent results that quantify long-term climate-driven change in the biomass of these plant functional groups across the sagebrush biome (Palmquist and others, 2021). Briefly, changes in the biomass of each plant functional group are derived from an individual-based plant simulation model (STEPWAT2; Palmquist and others, 2018) that represents plant competition for water availability, which is estimated by a process-based soil water balance model (SOILWAT2; Schlaepfer and Murphy, 2018). Similar models have been used across the sagebrush biome (for example, Schlaepfer and others, 2012) operating under a range of future climate scenarios and models (for example, Bradford and others, 2020). Results presented here are based on an estimated change in biomass for recent climate (1980 to 2010) and near-term future climate (2030 to 2060) projections under representative concentration pathway 8.5 (RCP 8.5; which is the worst-case scenario) for the median value estimated from a representative set of 13 climate models (Palmquist and others, 2021). The representation of climate change for this initial assessment focused only on changing climatic suitability; subsequent analyses could expand to also represent the influence of climate change on wildfire and invasive species

Biomass changes were scaled to represent change as a percentage of maximum biomass under historical conditions, creating an index of change in potential suitability (*DeltaS*) to support the functional group that ranges from −1 (complete loss of suitability) to +1 (change from no suitability to maximum suitability). For each plant functional type, a calculation of the median *DeltaS* was made among the 13 climate models, and those factors were applied to estimate cover (C) under future conditions (C_{FUTURE}) from cover under current conditions (C_{CURRENT}) for each plant functional type as:

$$C_{\mathrm{FUTURE}} = C_{\mathrm{CURRENT}} \times (1+DeltaS) \tag{2}$$

Future ecological integrity was then calculated using the C_{FUTURE} values for sagebrush, perennial grasses, and invasive annual grass.

Results

Objective 1: Model Integrity of the Sagebrush Ecosystem

Within sagebrush rangelands identified in 2020, 13.6 percent (33.4 million acres) was classified as CSAs, 34.4 percent (84.3 million acres) as GOAs, and 51.9 percent (127.2 million acres) as ORAs. This equates to 117.7 million acres of CSAs and GOAs combined (fig. 5, time step 2020).

Objective 2: Evaluate Spatial Congruence With Single-Species Populations and Agency Priority Areas

Large spatial congruence was found between the priority area predicted for individual species and the 2020 CSAs and GOAs (table 4). The CSAs encompass up to 40 percent of focal species populations and, when combined with GSAs, encompass up to 84 percent (table 4). Combined, GOAs and CSAs were found to support up to 1.8 times more focal species than would be expected for a randomly selected area of similar size. CSAs were found to support up to 2.9 times more of the focal species than random areas (table 4). The CSAs and GOAs supported more of the populations of greater sage-grouse and pygmy rabbit than populations of Brewer's sparrow, sagebrush sparrow, and sage thrasher (table 4).

Using the 2020 data, CSAs and GOAs displayed a high degree of overlap with existing agency management designations. The CSAs and GOAs contained 71 percent of the BLM and USFS Priority Habitat Management Areas (PHMAs); 15 percent of the PHMAs were in ORAs and 14 percent were outside of sagebrush rangelands (table 5). For greater sage-grouse Priority Areas for Conservation (PACs) delineated by State wildlife agencies, 62 percent were contained within CSAs and GOAs (table 5). In addition, 19 percent of PACs were located in ORAs, and 19 percent were outside of the sagebrush rangelands modeled. Across all State and Federal agency prioritization efforts, the largest differences in spatial congruence occurred in the southern portion of the sagebrush biome, generally in areas outside the range of greater sage-grouse, and in the Great Plains ecoregion where sagebrush and grassland-dominated communities intermix (fig. 6).

CSAs and GOAs were found to encompass a large proportion of sage-grouse leks and successfully identified locations of sage-grouse population growth. Of the 4,478 greater sage-grouse leks used to evaluate trends within unique sagebrush areas, 1,785 (39.9 percent) were located within CSAs, 1,701 (38.0 percent) were located within GOAs, 647 (14.4 percent) were located within ORAs, and 345 (7.7 percent) were located outside all three. Summaries of abundance in 1996, using the median values of the posterior distributions, showed similar patterns for population size (CSAs contained 40.2 percent of the leks; GOAs, 36.5 percent; ORAs, 14.5 percent; outside all three areas, 8.8 percent). By 2019, the same summaries revealed that populations located in CSAs were the only ones to have exhibited net growth, having increased by 15.7 percent during the 24-year period and now representing 52.5 percent of the total population size (fig. 7). Conversely, populations from leks in GOAs declined by 24.8 percent relative to the 1996 values (fig. 7), accounting for 31.0 percent of the population in 2019; those in ORAs declined by 45.3 percent (fig. 7), accounting for 9.0 percent of the 2019 population); and those outside of these three areas declined by 24.1 percent, accounting for 7.5 percent of the 2019 population. Median estimates of λ of finite rate of population change were as follows: 1.006 for CSAs, 0.988 for GOAs, and 0.974 for ORAs. Areas classified as nonrangeland exhibited a finite rate of change similar to that of the GOAs.

Objective 3: Quantify Status of Sagebrush Rangelands Relative to Primary Threats in 2020

Within CSAs, 83.2 percent of the area had no to low levels for all three modeled threats, whereas 52.3 percent of the GOAs had no to low threats. Between the CSAs (33.4 million acres total) and GOAs (84.3 million acres total), there are 71.9 million acres of landscapes with no to low threats distributed across the entire sagebrush biome (fig. 8). Within ORAs, 26.5 percent (33.7 million acres) had no to low threats. Of the 95.6 million acres of CSAs and GOAs that co-occurred with ≥ 1 agency management designation, 45.8 million acres had no to low threats for all threats (fig. 6).

Invasive annual grasses accounted for 19.2 million of the 38 million acres (table 6) identified as "grow the core" treatment opportunity areas within the conceptual threat matrix to align multithreat conservation strategies for CSAs and GOAs (fig. 4). The analysis highlights the growing invasive annual grass challenge in the tri-State area of Oregon, Idaho, and Nevada (fig. 9). It also shows an increasing level of invasive annual grasses in the Great Plains region (fig. 9). A total of 8.9 million acres of conifer was identified as needing treatment in areas with moderate threats for both CSAs and GOAs and high or very high threats in CSAs (fig. 10, table 6). In addition, 10.3 million acres of human modification were within the moderate threat category for both CSAs and GOAs and the high threat category for CSAs (fig. 11, table 6).

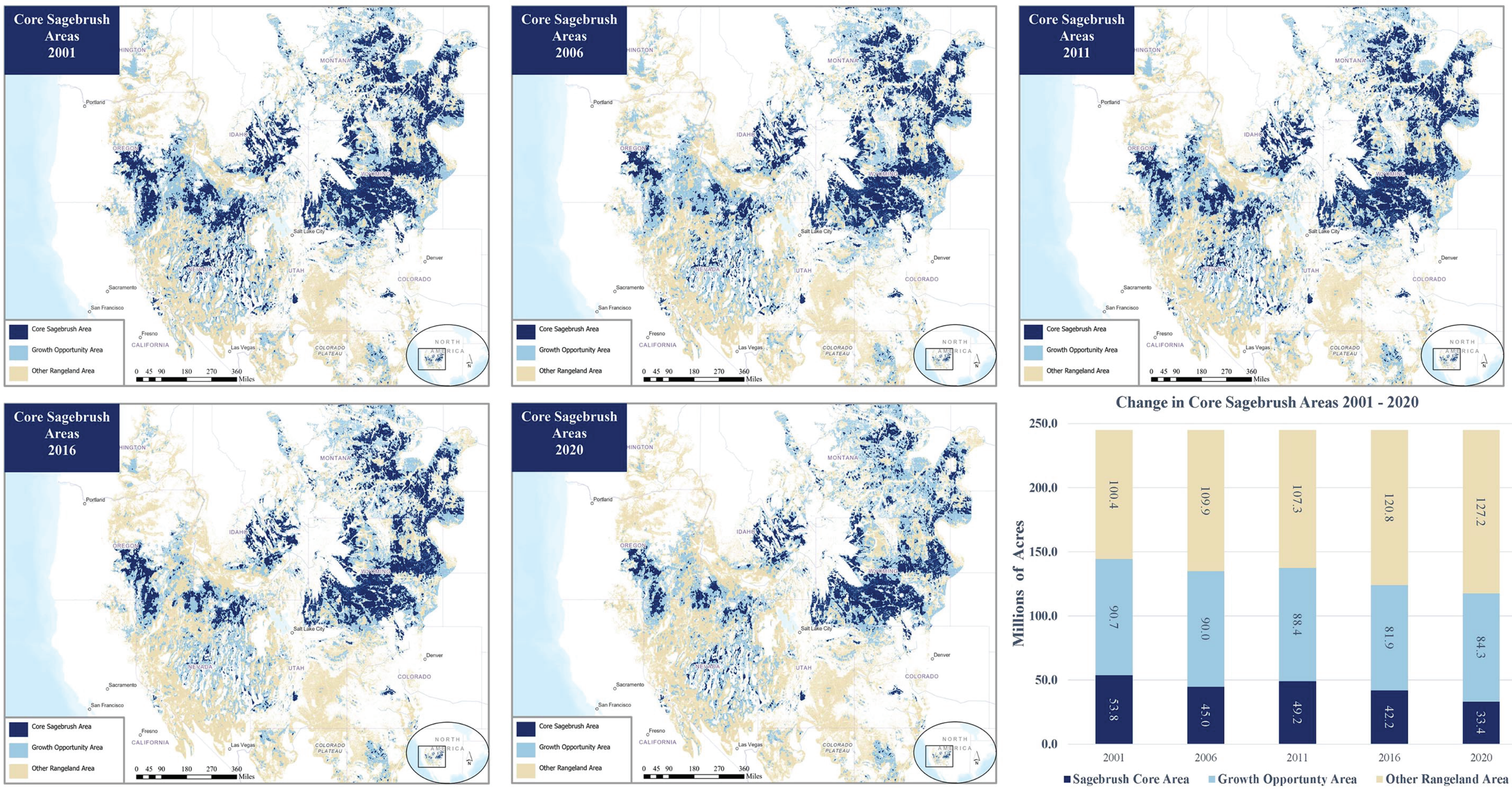

Figure 5. Change over time (from 2001 to 2020) in the size and extent of core sagebrush areas (CSAs) as well as growth opportunity areas (GOAs) and other rangeland areas (ORAs) within the sagebrush biome of the United States.

Table 4. Percent of five priority focal species populations encompassed within 2020 core sagebrush areas and within the 2020 core sagebrush areas plus the 2020 growth opportunity areas compared to the entire sagebrush ecological integrity model area.

[Species models used included *Centrocercus urophasianus* L. (greater sage-grouse), *Spizella breweri* (Cassin, 1856) (Brewer's sparrow), *Artemisiospiza nevadensis* (Ridgway, 1874) (sagebrush sparrow), *Oreoscoptes montanus* (J.K. Townsend, 1837) (sage thrasher), and *Brachylagus idahoensis* (Merriam, 1891) (pygmy rabbit). Numbers within the parentheses denote how much more of the priority species populations are predicted to be contained than would be expected based upon area alone. CSAs, core sagebrush areas; GOAs, growth opportunity areas; %, percent]

Species	Percent of population in CSAs	Percent of Population in CSAs + GOAs
Greater sage-grouse	40% (294%)	84% (175%)
Brewer's sparrow	21% (154%)	64% (133%)
Sagebrush sparrow	21% (154%)	61% (127%)
Sage thrasher	25% (184%)	67% (140%)
Pygmy rabbit	36% (265%)	78% (163%)

Table 5. The percent of existing management designations (as of 2020) within the sagebrush biome used by State and Federal agencies that are contained within core sagebrush areas and growth opportunity areas.

[The Natural Resources Conservation Service (NRCS) has prioritized efforts based upon *Centrocercus urophasianus* L. (greater sage-grouse) Priority Areas for Conservation (PACs) developed by the States. The Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS) have prioritized areas based upon greater sage-grouse designated Priority Habitat Management Areas (PHMAs). The U.S. Fish and Wildlife Service (USFWS) conservation efforts are based upon four sagebrush obligate songbirds—greater sage-grouse, *Spizella breweri* (Cassin, 1856) (Brewer's sparrow), *Artemisiospiza nevadensis* (Ridgway, 1874) (sagebrush sparrow), *Oreoscoptes montanus* (J.K. Townsend, 1837) (sage thrasher)—as well as *Brachylagus idahoensis* (Merriam, 1891) (pygmy rabbit). The USFWS areas represent the smallest total area within the sagebrush biome predicted to contain 50 percent of all obligate songbird populations; that is, Sagebrush Strategic Habitat Conservation (SHC) 50% Wildlife Population Cores. %, percent; CSA, core sagebrush area; GOA, growth opportunity area; NA, not applicable; ORA, other rangeland area; WLFW, Working Lands for Wildlife]

	States: Sage-grouse PACs and cores	NRCS: WLFW	BLM and USFS: PHMA	USFWS: Sagebrush SHC 50% Wildlife Population Cores
CSAs and GOAs	62%	62%	71%	75%
ORAs	19%	19%	15%	25%
Nonrangeland	19%	19%	14%	NA

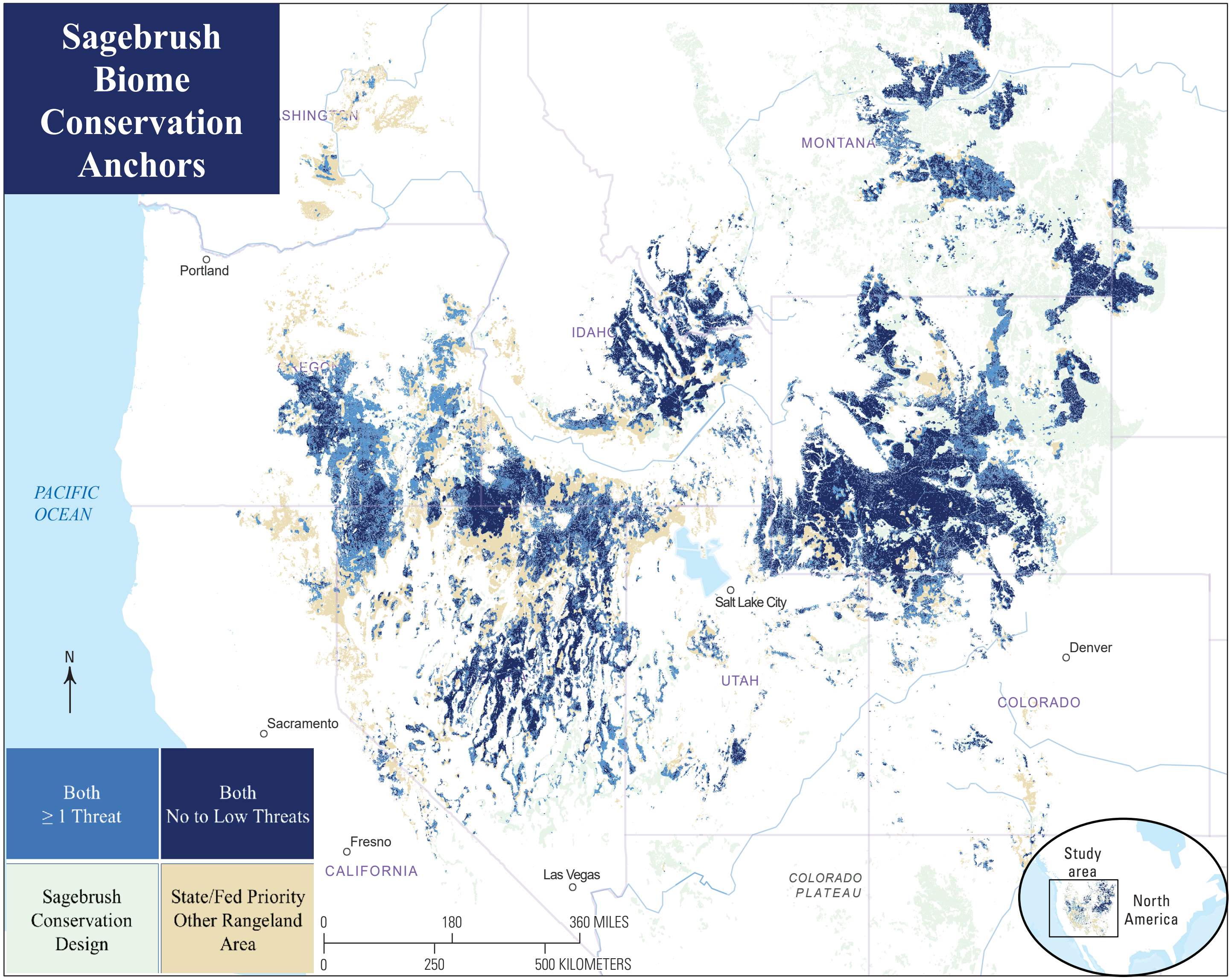

Figure 6. Identifying anchor points (that is, areas of spatial congruence) between core sagebrush areas (CSAs) and growth opportunity areas (GOAs) and existing (as of 2020) agency prioritizations within the sagebrush biome. Locations where core sagebrush areas and growth opportunity areas co-occur with at least one other agency designation were labeled Both. These designations included: (a) *Centrocercus urophasianus* L. (greater sage-grouse) Priority Areas for Conservation (PACs), as used by State agencies and the National Resources Conservation Service; (b) Priority Habitat Management Areas (PHMAs), as used by the Bureau of Land Management and the U.S. Forest Service; and (c) Sagebrush Strategic Habitat Conservation (SHC) 50% Wildlife Population Cores for sagebrush obligate birds—greater sage-grouse, *Spizella breweri* (Cassin, 1856) (Brewer's sparrow), *Artemisiospiza nevadensis* (Ridgway, 1874) (sagebrush sparrow), and *Oreoscoptes montanus* (J.K. Townsend, 1837) (sage thrasher)—as used by the U.S. Fish and Wildlife Service. Additionally, the location of the areas with spatial congruence between plans which also had no to low threats for invasive annual grasses, human modification, and conifer woodlands expansion were identified (dark blue). These areas represent anchor points for conservation delivery actions. Fed, Federal

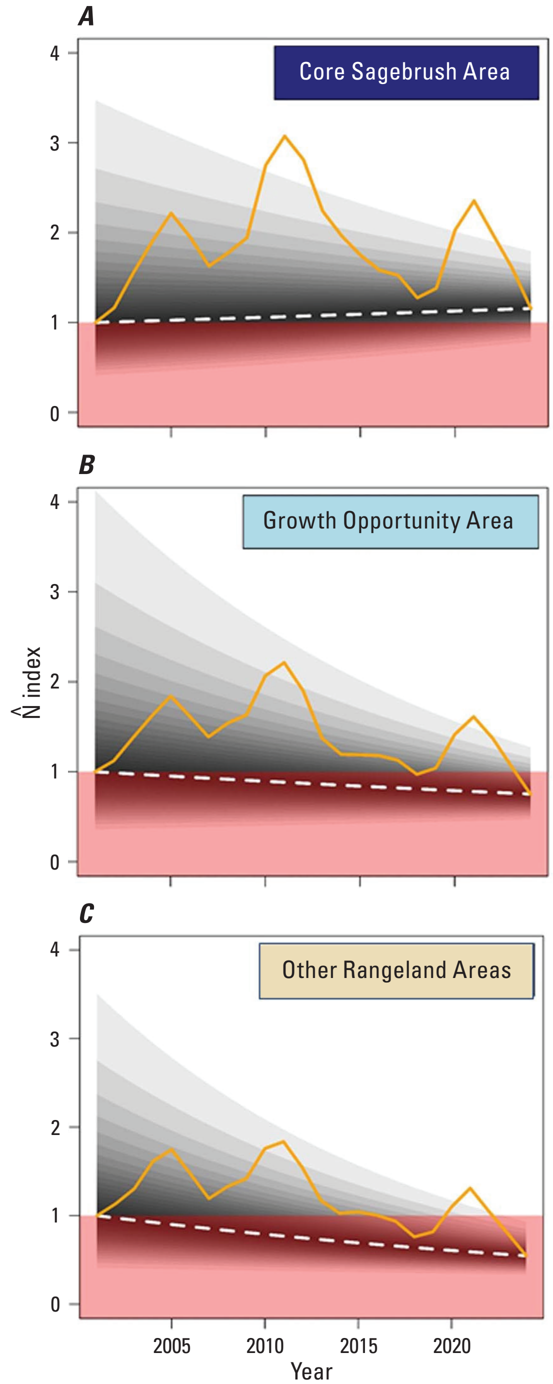

Figure 7. Median estimates (orange solid line) of *Centrocercus urophasianus* L. (greater sage-grouse) abundance index (1996 to 2019) based on results from Coates and others (2021) and summarized within *A*, core sagebrush areas (CSAs), *B*, growth opportunity areas (GOAs), and *C*, other rangeland areas (ORAs). Trend (dashed white line) and 95 percent credible interval (gray polygons) are plotted against a region depicting values below the 1996 median estimate (light-red polygon).

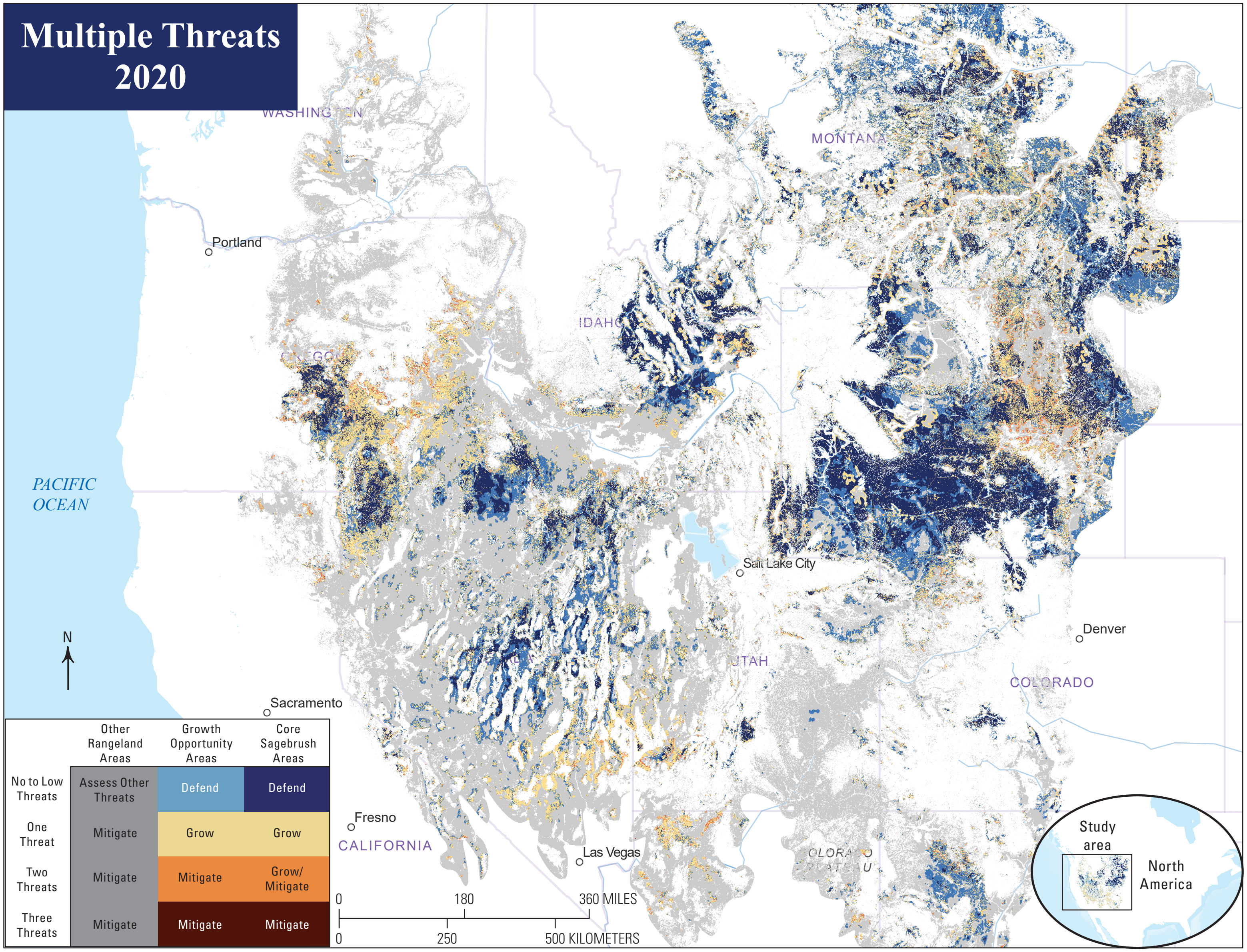

Figure 8. Location and extent of three mapped threats spatially intersected with core sagebrush areas and growth opportunity areas across the sagebrush biome of the United States for 2020. Blue areas (dark and light, representing core sagebrush areas [CSAs] and growth opportunity areas [GOAs], respectively) are locations of high sagebrush ecological integrity and could serve as anchor points in an overall biome-wide strategy.

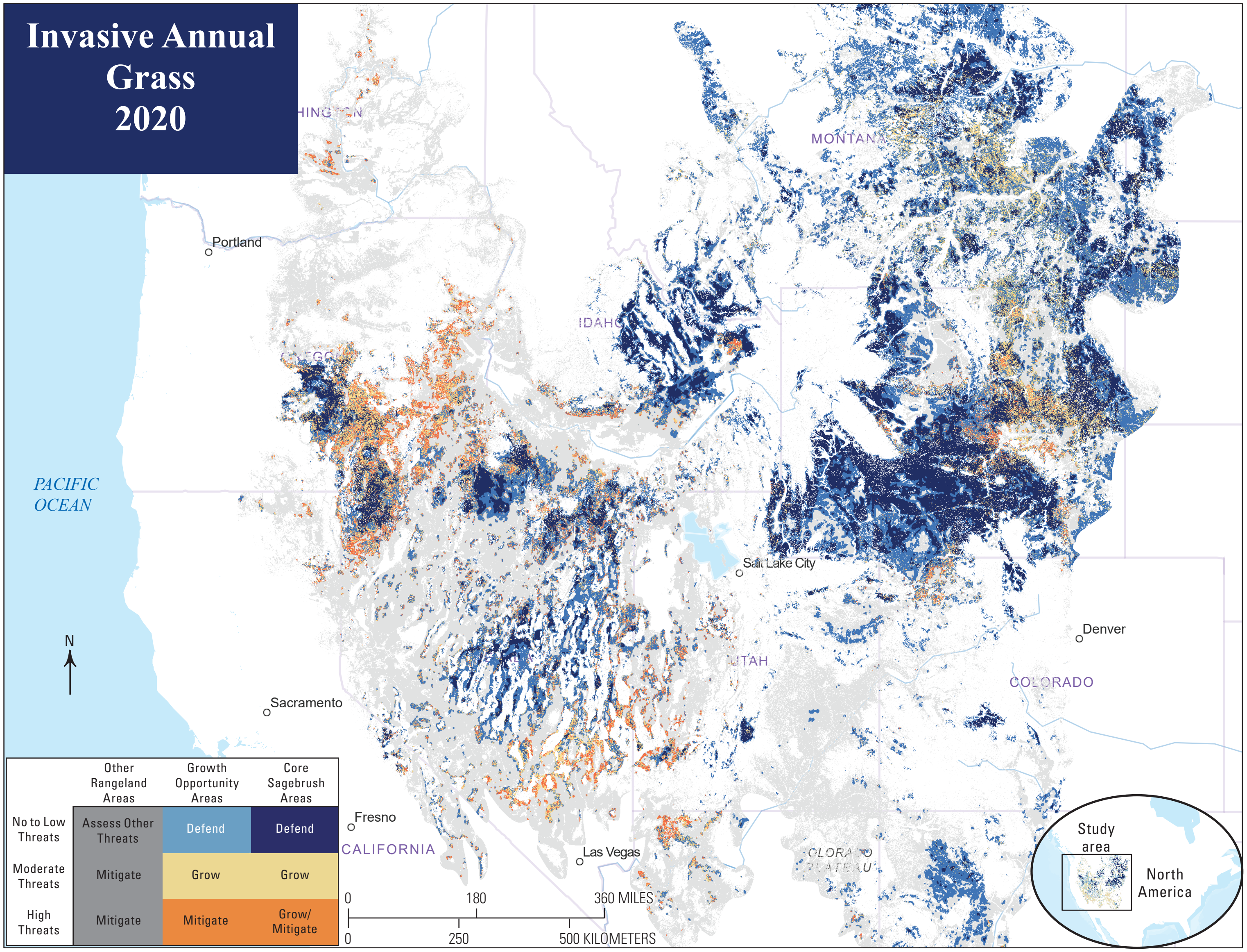

Figure 9. Location and extent of the invasive annual grass threat across the sagebrush biome in the United States for 2020. Blue areas (dark and light, representing core sagebrush areas [CSAs] and growth opportunity areas [GOAs], respectively) are locations of high sagebrush ecological integrity and could serve as anchor points in an overall biome-wide strategy. A separate, high-resolution portable document format (PDF) version of this map is available at https://doi.org/10.3133/ofr20221081 so stakeholders can zoom in and see the results at much smaller scales.

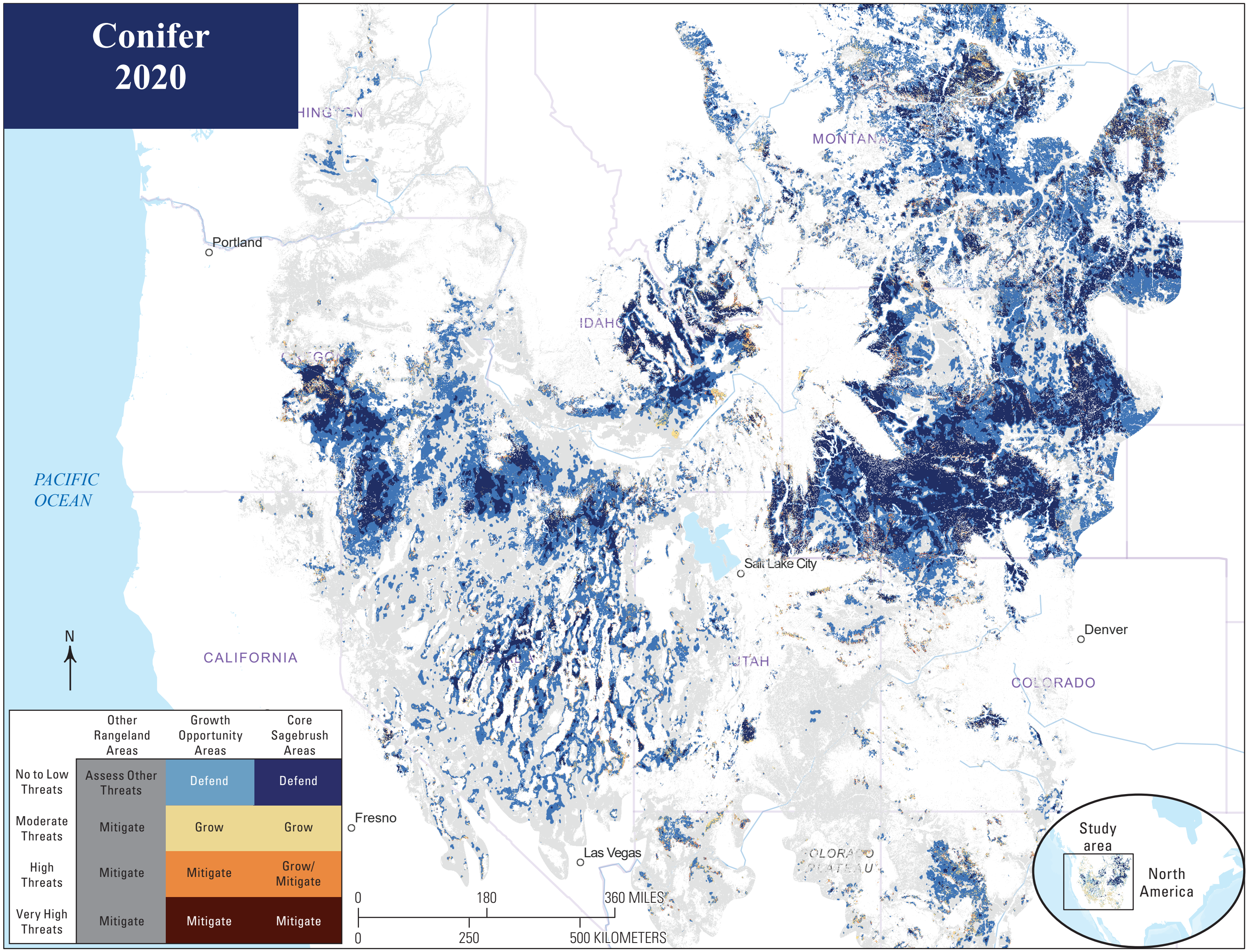

Figure 10. Location and extent of the conifer threat across the sagebrush biome in the United States for 2020. Blue areas (dark and light, representing core sagebrush areas [CSAs] and growth opportunity areas [GOAs], respectively) are locations of high sagebrush ecological integrity and could serve as anchor points in an overall biome-wide strategy. A separate, high-resolution portable document format (PDF) version of this map is available at https://doi.org/10.3133/ofr20221081 so stakeholders can zoom in and see the results at much smaller scales. By zooming in, one can see better that conifer threats are occurring at the edges of CSAs and GOAs and are not well represented at a range-wide extent.

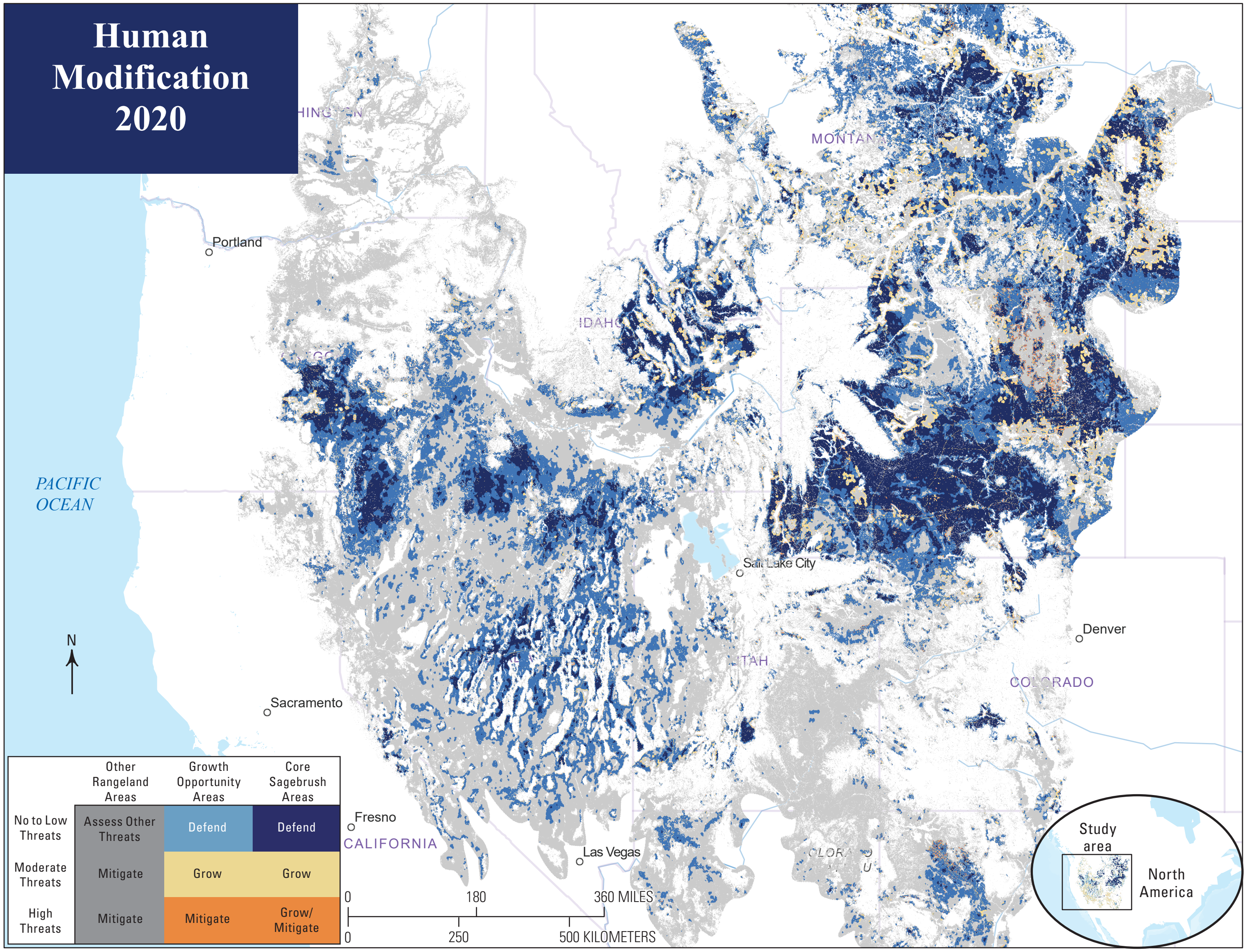

Figure 11. Location and extent of the human modification threat across the sagebrush biome in the United States for 2020. Blue areas (dark and light, representing core sagebrush areas [CSAs] and growth opportunity areas [GOAs], respectively) are locations of high sagebrush ecological integrity and could serve as anchor points in an overall biome-wide strategy. A separate, high-resolution portable document format (PDF) version of this map is available at https://doi.org/10.3133/ofr20221081 so that stakeholders can zoom in and see the results at much smaller scales. By zooming in, one can see better that human modification threats are occurring at the edges of CSAs and GOAs and are not well represented at a range-wide extent.

Table 6. Results of spatially explicit risk matrixes between core sagebrush areas, growth opportunity areas, and other rangeland areas by three of the largest known threats to the sagebrush biome of the United States (invasive annual grasses, conifer woodlands expansion, and human modification) as of 2020.

[Matrix values are areas in million acres; the colors correspond to the conceptual strategies outlined in figure 4. NA, not applicable]

Threat level	Area and threat		
	Other rangeland area	Growth opportunity area	Core sagebrush area
Invasive annual grass			
No to low	72.4	**61.0**	**29.8**
Moderate	19.4	**15.6**	**3.2**
High	35.5	**7.7**	**0.4**
Very high	NA	NA	NA
Conifer woodlands			
No to low	97.5	**73.8**	**32.1**
Moderate	17.0	**7.6**	**1.1**
High	7.6	**1.9**	**0.1**
Very high	5.1	1.0	0.1
Human modification			
No to low	93.7	**73.6**	**32.4**
Moderate	20.9	**9.4**	**0.8**
High	12.7	**1.4**	**0.1**
Very high	NA	NA	NA

Objective 4: Evaluate Spatial and Temporal Patterns of Change in Sagebrush Ecological Integrity

The team documented 53.8, 90.7, and 100.4 million acres of CSA, GOA, and ORA, respectively, in 2001 (fig. 5). By 2020, however, 20.4 million acres of CSA and 6.4 million acres of GOA had transitioned to ORA, leaving 33.4 and 84.3 million acres of CSA and GOA, respectively. This equates to an average of 0.9 million acres of CSA (CSA trend F-statistic = 10.64, $d.f.$ = 3, and p = 0.047, where the F-statistic is a value on the theoretical F distribution, d.f. is the degrees of freedom, and p is the probability value) or 1.3 million acres of CSA+GOA (CSA+GOA trend F-statistic = 24.13, $d.f.$ = 3, and p = 0.016) transitioning to ORA each year during the past two decades. Unabated, these rates would equate to one-half of the remaining CSA transitioning to ORA by 2042 and one-half of the remaining CSA+GOA transitioning to ORA by 2065.

These ongoing and anticipated losses in areas of high ecological integrity have been driven primarily by the incursions of invasive annual grasses across the three ecoregions (fig. 12). By 2020 (the final year examined), more areas were moderately or highly threatened by invasive annual grasses than in any year prior, including more than one-half of the Southern Great Basin region. A sudden increase relative to 2016 (the penultimate year examined) was particularly pronounced in the Great Plains region, although none of this region had been deemed high risk. The threat of conifer expansion into the no to low category showed an increase compared with that of 2001; however, expansion into this category held steady from 2016 to 2020, especially in the Intermountain West and Southern Great Basin regions. The team also documented infill of conifer stands, showing an increase in the areas classified as high or very high risk, especially in the Intermountain West region. The footprint of human modification remained relatively constant over time within regions, but the footprints varied considerably across regions—for example, more than 90 percent of the Southern Great Basin region remained at no to low risk by 2020 compared with only 60 percent of the Great Plains region remaining at this level.

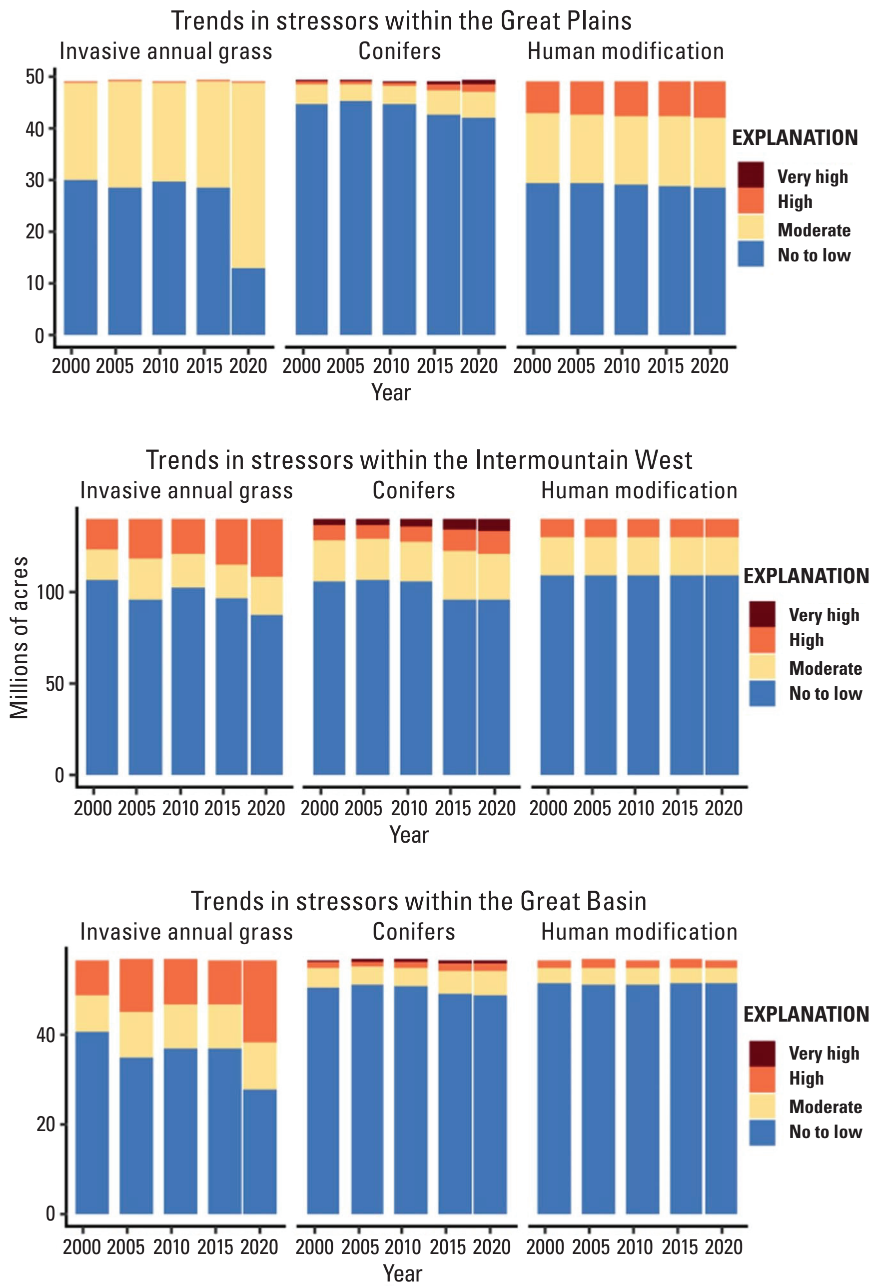

Figure 12. Trends in three primary threats (invasive annual grasses, conifer woodlands expansion, and human modification) to the three regions of the sagebrush biome (Great Plains, Intermountain West, and Southern Great Basin) in the United States from 1998 to 2020.

Objective 5: First Look at Climatic Effects on Core Sagebrush Areas, Growth Opportunity Areas, and Other Rangeland Areas

At the biome scale, climate change effects on the overall area of CSAs are relatively modest for the mid-century projections (table 7). Of the currently estimated 33.4 million acres of CSAs, 1.5 million acres (4.5 percent) are projected to change to GOAs and 1.7 million acres (5.0 percent) to change to ORAs by the year 2060. Of the 84.3 million GOA acres under current conditions, 2.4 million acres (2.8 percent) are predicted to shift to CSAs, and 12.8 million acres (15.2 percent) are predicted to shift to ORAs. Of the current ORAs, 1.9 million acres (1.5 percent) are expected to shift to GOAs, whereas no ORAs would shift to CSAs in the future projections. In combination, these trajectories suggest a net decline in CSAs of 0.8 million acres (2.4 percent) and a net decline in GOAs of 11.8 million acres (14 percent) during the next ~25 years.

Shifts from GOAs or CSAs to ORAs (14.5 million acres total) are expected primarily on the periphery of the sagebrush biome, particularly on the edges in the Northern Great Plains ecoregion, and in the southern and eastern portions of the Great Basin region (fig. 13). Areas shifting from GOAs to CSAs (2.4 million acres) typically represent expansion of existing CSAs and, as a result, are most abundant in the Great Basin region where current CSAs are composed of relatively small patches. Projected changes from CSAs or ORAs to GOAs (3.4 million acres) occur in small patches distributed around the biome, with the exception of the grassland interface on the most northern and eastern portions of the sagebrush biome (fig. 13).

Table 7. Climate change prediction confusion matrix showing the predicted amount of change of core sagebrush areas (CSAs), growth opportunity areas (GSAs), and other rangeland areas (ORAs) from 2030 to 2060, in million acres.

[Stable areas (unchanged between current and future) for each category are indicated in the primary diagonal (in bold). Areas of change between current condition (in rows) to future conditions (in columns) are shown in the other unshaded cells; for example, the area that changed from CSA to GOA is 1.5 million acres. The total area in each category under current conditions and future conditions are shown in shaded cells in the table's far right column and bottom row, respectively]

		Future condition (2030–2060)			
		CSA	**GOA**	**ORA**	**Current total**
Current condition (2020)	CSA	**30.2**	1.5	1.7	33.4
	GOA	2.4	**69.1**	12.8	84.3
	ORA	0.0	1.9	**125.3**	127.2
	Future total	32.6	72.5	139.7	

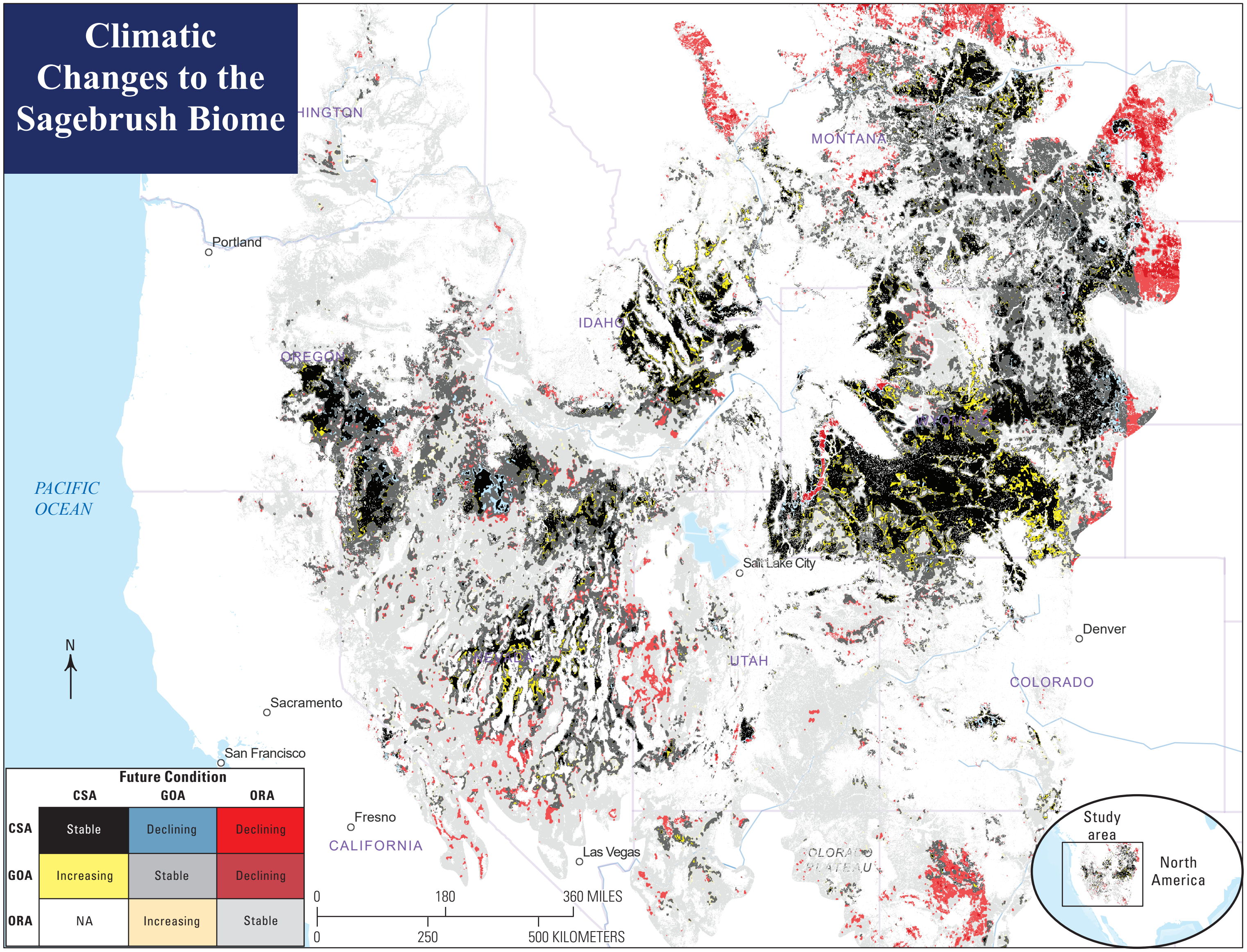

Figure 13. Stability and predicted changes (increasing, stable, decreasing) to the location of core sagebrush areas (CSAs), growth opportunity areas (GOAs), and other rangeland areas (ORAs) based upon projected changes to sagebrush ecological integrity from climate change across the sagebrush biome in the United States. Results presented here are based on estimated change in biomass for recent climate (1980 to 2010) and near-term future climate (2030 to 2060) under representative concentration pathway 8.5 (RCP 8.5) for the median value estimated from a representative set of 13 climate models (Palmquist and others, 2021).

Discussion

Our team developed a science-based strategy for the sagebrush biome to help unify conservation delivery, promote ecosystem-level setting of objectives, and provide a foundation for adaptive management. Our assessment of the condition of thesagebrush biome (that is, the location, amount, and conservation status) indicates that complex, ecosystem-level problems are driving more than ~73 percent of the threats identified as “grow the core” areas. Such problems may not be realistically addressed through command-and-control (Holling and Meffe, 1996) associated with regulatory-based solutions. Instead, active management and successful restoration may be able to more successfully mitigate complex ecosystem problems and (or) constrain their effects in space and time (Boyd and others, 2014). The spatial pattern of human modification indicates that threats are located on the periphery of CSAs and GOAs, have been largely stable for the past two decades (fig. 12), and are more prevalent in the Great Plains region where cropland is a larger ecosystem threat (fig. 11).

The ecological relevance of CSAs and GOAs have been demonstrated with independent datasets for sagebrush obligate species of conservation concern. Geographical patterns in SEI have been shown to be strongly associated with high priority species (table 4) and displayed clear links to population performance for greater sage-grouse (fig. 7). The link to sage-grouse population trends is important (fig. 7), as habitat management designations for this species have largely driven conservation actions across the sagebrush biome for the past several decades. Further, the positive trends in population abundance using Bayesian state-space models within CSAs (+15.7 percent) are one of the few positive trends compared to other trend analyses for this species (summarized in Coates and others, 2021). The evaluation of our model with independent empirically derived population models (Doherty and others, 2016; Coates and others, 2021), resource selection function models (Smith and others, 2019; USFWS, 2022b), and existing agency prioritization efforts (table 5), coupled with the stability of our results to simulated errors in our functional response curves (section 2 of appendix 1) suggest that our threat-based landscape conservation design, while simple, effectively identifies important habitats.

We parsed out the type, location, and acres of threats within the different categories (CSAs, GOAs, and ORAs) to help focus active management by identifying places where multiagency and organization efforts can protect CSAs that have higher levels of integrity with low cumulative threats (fig. 8). Across the sagebrush biome, the vast majority (83.2 percent) of CSAs were found to be located in the no to low risk category for all three threats (fig. 8, table 6) corresponding with our definition of SEI. Secondly, GOAs identify still-functioning ecosystems subject to moderate threats where conservation actions could address threats and grow them into CSAs. These GOAs are also especially important when adjacent to CSAs (NRCS, 2020, 2021b; WGA, 2020). Our risk analyses highlight areas where those threats are affecting CSAs and GOAs, as well as where they have already affected CSAs and GOAs. Mapped results of the risk analyses can be used to spatially prioritize and target conservation strategies (fig. 4). For example, the threats of conifer expansion and human modification are largely occurring on the periphery of CSAs and GOAs (fig. 10 and fig. 11). In contrast, invasive annual grasses have already affected a much greater proportion of CSAs and GOAs, with large areas of the Great Plains region under moderate threat and concentrations in the Southern Great Basin region under high threat (fig. 9).

The proposed threat-based design complements and enhances existing efforts to partition conservation within the sagebrush biome (fig. 6, table 5). The areas identified for conservation actions are largely within the boundaries of existing management and habitat designations (see fig. 6), and this design provides increased geographic specificity for prioritization, planning, and delivery within those boundaries. Specifically, the CSAs and GOAs help identify where (figs. 8 through 11) and how much (table 6) conservation is needed and provide insight into the magnitude of risk from ecosystem threats. Importantly, the ecosystem threats described herein are not static in space and time and may expand or contract in association with weather and climate factors, disturbances, and management practices (Reinhardt and others, 2020; Smith and others, 2022). Thus, as we and others have demonstrated, ecological conditions driven by such threats will display concomitant variability (Homer and others, 2015; Rigge, Shi, and others, 2021). The dynamic nature of these processes supports the idea of partitioning management resources within fluid geographies defined by current ecosystem attributes as opposed to management designations defined by static boundaries. We embrace that notion, and current designations within the proposed design are a product of the most recent analyses; we understand that those designations will change over time in accordance with spatially and temporally dynamic ecological conditions as driven by both desired and not desired change agents (fig. 5). As a result, this design serves not only as a decision support tool to inform conservation goals and management actions but also as a monitoring tool to track changes in ecological conditions over time. This approach also makes it possible to account for the interplay between spatial and temporal determinants of ecological conditions following disturbance. For example, the rate and extent of sagebrush recovery following fire is closely tied to elevation and other site factors, but it is also driven by antecedent, current, and following year precipitation amounts (Ziegenhagen and Miller, 2009) and restoration efforts (Boyd and others, 2014). Thus, the effects of wildfire or other disturbances in this design are determined by the observed post-disturbance conditions rather than generalized assumptions about disturbance impact.

Our analysis suggests that climate change (as represented here) alone is unlikely to be the dominant threat to SEI in the next few decades, although interactions of climate with wildfire and invasive annual grasses may be an important threat, especially in the longer term. Even during that short time frame, however, we project that climate change will exacerbate the observed trends of declining SEI. Furthermore, because climate effects will likely accelerate later in the 21st century (Intergovernmental Panel on Climate Change, 2021), preventing or lessening further degradation of the sagebrush biome could benefit from effective restoration strategies to enhance SEI before climate change further complicates efforts. In addition, it is important to recognize that the future scenarios evaluated in this analysis represent a conservative estimate of potential climate change effects for two reasons. First, these estimates of change in functional group abundance did not include interactions between climate change and the interaction between wildfire and invasives. Those interactions are expected to promote both stronger declines in big sagebrush and more substantial and widespread increases in invasive annual grasses (Bradley, 2009). Second, the mid-century changes considered here are likely to be less severe than changes in both climate and sagebrush plant communities that are likely to be observed by the end of the 21st century (Bradford and others, 2020; Palmquist and others, 2021). Future analyses may more completely describe the potential response of ecological integrity to a wide array of climate and disturbance scenarios, including quantification of uncertainty emerging from variability in climate trajectories.

As with any effort attempted at this scale, there are some important nuances and context that need to be applied when interpreting our results. First, the maps and matrixes developed in this threat-based design are most useful to inform large-scale planning (biome, State, region). The maps provide information about relative integrity and ecological context that highlight potential management interventions, but they lack site specific information and context. We modeled 244.9 million acres across the sagebrush biome, yet there were still greater sage-grouse lek locations (7.7 percent) outside of our study area. This is just one example of how local planning and site evaluation are critical to determine appropriate treatments. However, the threat matrixes and maps can facilitate conversations about shared values and goals, help set quantitative objectives and monitor success in achieving objectives, and inform discussions of strategies to meet shared goals. Second, resource prioritization is inherently hierarchical, and the relative importance of ORAs within biome subunits (for example, States or land management units within a State) may differ from that associated with a biome-wide ranking. Third, management in ORAs could focus on activities that promote containment of ecosystem problems, such as invasive annual grasses and wildfire, especially where ORAs pose a threat because of close proximity with CSAs and GOAs. Further, the current analyses did not account for the potential importance of ORAs for other uses (for example, restoring to allow connectivity of more intact landscapes, migration corridors, and distributions of small endemic populations) or for the potentially dynamic compositional changes associated with some highly affected landscapes (for example, recently burned areas with positive recovery trajectories).

This threat-based landscape conservation design is nascent and has some immediate steps that could be taken to enhance its strategic value for conserving the sagebrush biome. First and foremost, this work characterizes the types and location of threats and the rate of recent ecosystem loss on the landscape. To increase its utility, the design could be expanded to incorporate future threats, including invasive annual plants and grasses, wildfire, climate change and uncertainty, conifer expansion, anthropogenic disturbances, and their interactions. All these threats could be linked to spatially explicit threat modeling. Existing approaches for assessing ecological resistance and resilience (R&R; Chambers, Maestas, and others, 2017) across the sagebrush biome already represent geographic patterns and recognize the need to incorporate future shifts in R&R as a result of climate change (Bradford and others, 2019). Secondly, we did not explicitly integrate other societal or economic values when developing this design. Although in this version CSAs and GOAs are linked to focal species within this ecosystem, work could be done to quantify the relationship of CSAs and GOAs to ecosystem services beyond wildlife that are valued in the Western United States. Lastly, further work could explicitly link conservation efforts to where and how effectively efforts are reducing the rates of sagebrush ecosystem loss. Some threats in certain ecoregions, such as conifer expansion, have been reduced at local and regional levels, whereas other threats may require more frequent and (or) repeated intervention to have similar benefits. This "conservation report card" includes evaluating effectiveness at multiple scales and quantifying conservation benefit. Actions targeted to improve greater sage-grouse habitat are having benefits (Severson and others, 2017a, 2017c), but there is also opportunity to identify which areas within the CSAs and GOAs have the characteristics that will improve return on other conservation investments.

The extensive decrease in CSAs from 2001 to 2020 (fig. 5) highlights the potential benefit of timely, strategic landscape-scale restoration, coordinated effectively across agencies and partners, to reduce the degradation of the sagebrush biome. The notion that all CSAs could be degraded in less than 50 years based upon current rates of loss underscores the critical importance of a biome-wide conservation strategy. Concern about loss and degradation of the sagebrush biome is not new (Leopold, 1949; Baker and others, 1976; Knick and others, 2003; Wisdom and others, 2005; Miller and others, 2011), but we show that despite large increases in conservation actions within the sagebrush biome, especially during the past 6 years, an average of 1.3 million acres per year have transitioned to ORAs during the past two decades. This result translates into 26.8 million acres transitioning into ORAs at an annual rate of −0.89 percent in CSAs and −1.34 percent in CSAs and GOAs combined. The consequences of the loss in SEI through these transitions are significant and can be illustrated by the relative densities of greater sage-grouse populations. In 2019, CSAs contained 57.5 percent of greater sage-grouse on 13.6 percent of the landscape and GOAs contained 31.0 percent of greater sage-grouse on 34.4 percent of the landscape, whereas ORAs contained only 9 percent of greater sage-grouse on 51.9 percent of the landscape. It is important to note, however, that our findings also show that roughly one-quarter of ORAs are either the result of a lack of sagebrush or of depleted perennial herbaceous understory that could become or return to a GOA or CSA with successful rehabilitation or natural recovery (Pilliod and others, 2021). We recognize that our models do not incorporate all threats to the sagebrush ecosystem, but we believe our results support the prioritization of conservation efforts towards addressing the largest threats driving ecosystem loss and degradation.

Summary

Community-based conservation partners have demonstrated that it is possible to successfully scale up implementation to reduce threats across land ownerships in priority landscapes with local leadership and strategic investment (Reinhardt and others, 2020; NRCS, 2021a; Olsen and others, 2021). However, the models presented here indicate that more successful targeted restoration and management on 1.3 million acres per year would be needed to halt ecosystem degradation at a biome-wide scale should threats continue as they have in the past decades (fig. 5). Small incremental changes to the existing amount of conservation delivery and coordination will likely not abate the expected loss in sagebrush ecological integrity and consequently the loss of sagebrush obligates, such as greater sage-grouse (Coates and others, 2021). As climate-driven threats to sagebrush ecosystems continue to grow, stopping—much less, reversing—these declining trends could benefit from a paradigm shift in conducting conservation work, with increased resources directed toward an ecologically grounded planning design, that defends CSAs and grows GOAs sufficient to offset losses of about 1.3 million acres per year. Given the number of threats, the scale at which they operate, and the dispersed authority and responsibility to regulate and address threats, this effort may take an almost unprecedented degree of cooperation and collaboration, a bold vision, and ambitious goal setting. To date, substantial investments in collaborative efforts to remove conifers expanding into sagebrush plant communities by Oregon's SageCon partnership, the Sage-Grouse Initiative, and the Utah Watershed Restoration Initiative have matched the rate of loss to conifer expansion within the Great Basin (Reinhardt and others, 2020). The results in this study indicate that a similar focus could allocate limited conservation resources to where and when they have the highest probability of achieving desired uplift, which the design can inform.

In their 2003 paper, "Teetering on the Edge or Too Late?," Knick and others (2003) highlighted the need for aggressive management to stabilize the sagebrush ecosystem from fragmentation and degradation. Nearly two decades later, this study shows that their alarm is still relevant and even more urgent today. The design presented here can help leaders, land managers, and stakeholders of the sagebrush biome develop goals and quantifiable objectives associated with strategic management actions necessary to address primary landscape threats, and, importantly, monitor progress towards objectives through time. The 45.8 million acres of shared priorities among existing conservation frameworks highlighted in this study could help anchor and guide collaborative landscape-scale conservation in areas that still have no to low threats (fig. 6). This study broadly identifies how much (fig. 4 and table 6) and where conservation actions may be most beneficial (figs. 8 through 11), along with the rates of loss to be combatted annually to maintain current levels of CSAs and GOAs. Such information is critical to provide context for decisions about the amount and nature of conservation actions and funding requirements. The rates of losses and millions of acres identified in this report are daunting; however, there is clear precedence for successful conservation at this scale within North America (that is tens of millions of acres and billions of dollars). Just as State and Federal wildlife agencies from the United States and Canada responded to acute and chronic declines in waterfowl populations by coming together and developing the North American Waterfowl Management Plan (U.S. Fish and Wildlife Service and the Canadian Wildlife Service, 1986), it is possible for the conservation community to respond again for the sagebrush biome. Regardless of the final form of coordination leaders in the American West agree upon, a comparable collaborative effort and commitment to durable conservation could help prevent loss of the sagebrush biome.

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Appendix 1. Supporting Information

The supporting information in this appendix is provided to help readers further understand this research. In addition, a companion data release (Doherty and others, 2022) is being published in conjunction with this report.

Biome-Wide Levels of Threat

Figure 1.1 shows the percent cover of three classes of threats (invasive annual grass cover, human modification, and conifer woodlands encroachment) discussed in this report that decreased the sagebrush ecological integrity across the sagebrush biome of the United States for 2020.

Evaluation of Sensitivity to Cover-to-Quality Estimates (*Q*)

To understand the sensitivity of the sagebrush ecological integrity (SEI) model results to uncertainties associated with the expert-based estimates that convert percent cover of sagebrush, perennial grass, annual grass, and trees (conifers), and the degree of human modification to an estimate of "quality" (ranging from 0.0 to 1.0), the team ran a series of Monte Carlo simulations (n=30). For each realization n, the estimates that translated percent cover to quality (Q) were randomly adjusted, and the resulting variability of Q (fig. 2 and 3 in the main body of the report) across the realizations was examined. Specifically, for each factor individually, the estimates were randomized by raising the best estimate (used as the reported model results) to the power of a random value, where the random value is drawn from a normal distribution bounded by ± 1 standard deviation values ranging 0.5 to 1.5, resulting in Q values ranging from 0 to 1.0. This provides a variety of simulated new curves that represent a range of potential errors in describing the ecological relationships between percent cover and the resulting patch-scale sagebrush ecological integrity. The simulated Q values were then substituted for the best-estimate Q values in equation 1 (in the main body of the report) to create a new representation of sagebrush ecological integrity for each realization.

To understand how the randomized Q values might affect the stability of the conservation designations (core sagebrush area [CSA], growth opportunity area [GOA], and other rangeland area [ORA]) that are based on classification of the Q values (figs 2 and 3), we calculated the three discrete classes for each realization of the Monte Carlo simulations. Within each Monte Carlo realization, the original logic class designation by way of SEI_{2000} values derived through the advisory group was used. That is, the SEI values were first max-normalized using the 99th percentile value and a minimum value of 0.002. The normalized values were then binned using equal-interval class breaks of 0.1, so that bins ranged from 1 to 10 and values greater than or equal to 9 represented the top ~10 percent of possible raw values. Within each Monte Carlo simulation, the top 20 percent of scores were then grouped as CSAs; the next 50 percent highest scores, as GOAs; and the lowest 30 percent of scores, as ORAs. To calculate the variability of the CSAs, GOAs, and ORAs, a count was made for each pixel of the number of times the realized class equaled the class from our original analysis, divided by the number of realizations n.

Results

For the 30 randomized sensitivity runs, the results were consistent with the original estimate for 95.1 percent, 94.2 percent, and 97.7 percent of CSAs, GOAs, and ORAs, respectively.

Discussion

The results support our interpretation that our "best-estimate" or original results discussed in the main body of the report are, at a biome-wide extent, insensitive to the estimated relationships specified in the SEI model. This relative insensitivity is likely due largely to the inclusion of multiple factors and variables, and especially to the smoothing of the continuous Q_{2000} values and classifying them into three broad classes (CSAs, GOAs, and ORAs). Slightly higher sensitivity (reducing to two-thirds concurrence) does occur in localized settings, particularly at the edges between cores sagebrush areas and growth opportunity areas. Potential future efforts could focus on reducing the uncertainty of the estimates through additional quantitative-based elicitation from experts, and (or) fitting estimates on the basis of species-specific empirical results.

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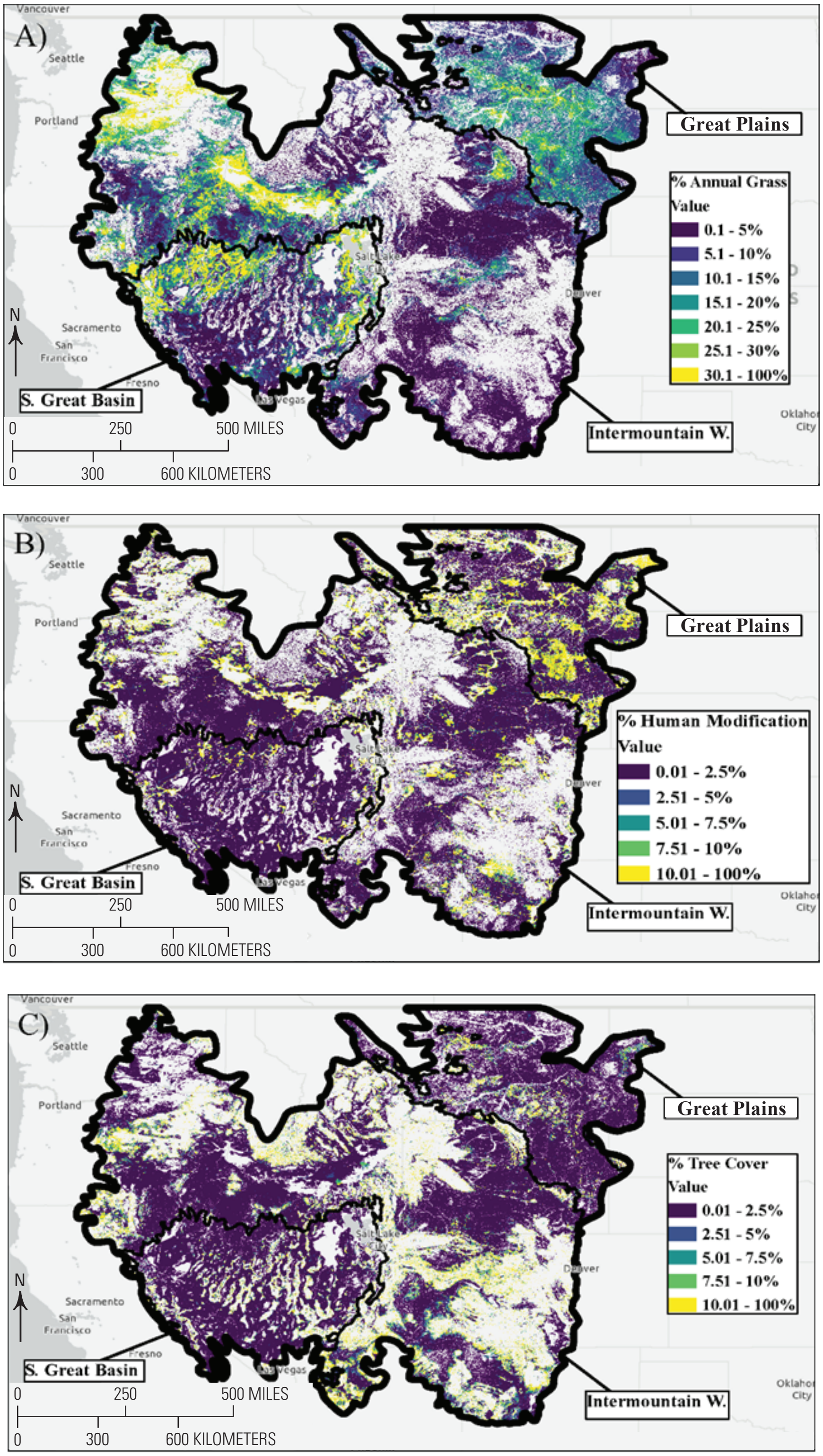

Figure 1.1. Percent cover of three selected threats that decreased the sagebrush ecological integrity across the sagebrush biome of the United States in 2020. The three threats examined are *A*, invasive annual grass cover; *B*, human modification; and *C*, tree cover (conifer encroachment).

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For more information, contact
Sagebrush Ecosystem Specialist
Land Management Research Program
Ecosystems Mission Area
U.S. Geological Survey
2150 Centre Ave., Bldg. C
Fort Collins, CO 80526

https://www.usgs.gov/mission-areas/ecosystems/land-management-research-program

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