Received: 25 March 2021 | Revised: 17 August 2021 | Accepted: 15 September 2021

DOI: 10.1002/eap.2612

ARTICLE

ECOLOGICAL APPLICATIONS
ECOLOGICAL SOCIETY OF AMERICA

Informing conservation decisions to target private lands of highest ecological value and risk of loss

Andrew J. Hansen[1] | **Katrina Mullan**[2] | **David M. Theobald**[3] | **Nathaniel Robinson**[4] | **Alyson East**[1] | **Scott Powell**[5]

[1]Department of Ecology, Montana State University, Bozeman, Montana, USA

[2]Department of Economics, University of Montana, Missoula, Montana, USA

[3]Conservation Planning Technologies, Fort Collins, Colorado, USA

[4]The Nature Conservancy, Arlington, Virginia, USA

[5]Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, USA

Correspondence
Andrew J. Hansen
Email: hansen@montana.edu

Handling Editor: Dianne Brunton

Abstract

Natural habitats on private lands are potentially important components of national biodiversity conservation strategies, yet they are being rapidly lost to development. Conservation easements and other means of protecting these habitats have expanded in use and will be most effective if they target private lands of highest biodiversity value and risk of loss. We developed a Biodiversity Conservation Priority Index (BCPI) based on ecological value and risk of habitat loss for remaining areas of natural vegetation cover (NVC) in the northwestern United States and addressed two questions: (1) Which remaining NVC on private lands is the highest priority for biodiversity conservation based on ecological value and risk of development? And (2) are conservation easements in NVC placed preferentially in locations of high biodiversity conservation priority? Drawing on the concept of ecological integrity, we integrated five metrics of ecological structure, function, and composition to quantify ecological value of NVC. These included net primary productivity, species richness, ecosystem type representation, imperiled species range rarity, and connectivity among "Greater Wildland Ecosystems." Risk of habitat loss was derived from analysis of biophysical and sociodemographic predictors of NVC loss. Ecological value and risk of loss were combined into the BCPI. We then analyzed spatial patterns of BCPI to identify the NVC highest in biodiversity conservation priority and examined the relationship between BCPI and conservation easement status. We found that BCPI varied spatially across the study area and was highest in western and southern portions of the study area. High BCPI was associated with suburban and rural development, roads, urban proximity, valley bottom landforms, and low intensity of current development. Existing conservation easements were distributed more towards lower BCPI values than unprotected NVC at both the study area and region scales. The BCPI can be used to better inform land use decision making at local, regional, and potentially national scales in order to better achieve biodiversity goals.

KEYWORDS
conservation easements, conservation planning, conservation priority index, habitat loss, natural habitats, private lands

INTRODUCTION

Globally, biodiversity loss is one of the top threats facing humanity today (Ceballos et al., 2020) and is of high concern because it has led to a reduction in ecosystem services (Díaz et al., 2019). Habitat destruction and fragmentation is the leading cause of biodiversity loss across many of the Earth's biomes (Maxwell et al., 2016). The global community has recognized that maintenance of natural habitats is essential to sustaining nature and ecological services (Watson et al., 2018). Consequently, protection of natural habitats is the backbone of the global conservation strategy. The Convention on Biodiversity set a target of protecting 17% of the global land area by 2020 (CBD, 2010). Currently, many are advocating that the CBD set a target of protecting 30% of the terrestrial lands by 2030 (Dinerstein et al., 2020). Within the United States, the U.S. Congress has called for and the Presidential Administration has committed to conserving at least 30% of the U.S. lands and oceans by 2030 (Congressional Record, 2019, 2021; The White House, 2021).

Public and indigenous lands typically provide natural habitats, which have legal and/or cultural mandates for nature protection. The CBD protected-area targets cannot be met in many countries, however, without inclusion of natural habitats on private lands (Stolton et al., 2014). Because private lands are often in more mesic sites with fertile soils and favorable climates, relative to public lands (Joppa & Pfaff, 2009), natural habitats on private lands may be disproportionately important for the ecological services they provide (Leu et al., 2008). Thus, there is both an opportunity and a need to conserve remaining natural habitats on private lands to contribute to national and global biodiversity strategies (Bargelt et al., 2020; Watson et al., 2018).

Despite the global targets to protect natural habitats, habitat continues to be reduced globally and in the United States. A recent synthesis of global human impacts (Díaz et al., 2019) found that 40% of the world's land is now agricultural or urban. The most accessible and hospitable biomes have been largely modified by humans (e.g., temperate, tropical, and Mediterranean forests). Theobald et al. (2020) found that 49% of terrestrial lands in 2017 had been modified by human activities, not including fragmentation effects, a loss of approximately 19.1 million km^2 since 1990. Within the United States during 1950–2000, urban area doubled to 2%, exurban area increased five-fold to 25%, and a total of 58% of the land area was urban, exurban, or crop lands in 2000 (Brown et al., 2005; Theobald, 2001).

The distribution and loss rates of natural habitats across the United States have not been quantified at spatial scales relevant for management, however. While the National Land Cover Database (NLCD) has been developed and used to map moderate-resolution (30 m) land cover change (Jin et al., 2019), the method typically does not adequately resolve low-density residential development (Theobald, 2014). This type of development can degrade natural habitats both through habitat destruction (e.g., conversions to lawns and impervious surfaces) and through alteration of disturbance regimes, ecosystem processes, and biotic interactions (Hansen et al., 2005). Thus, mapping areas of remaining natural habitats requires refined knowledge of the low-density residential development.

The National Land Use Dataset (NLUD) of Theobald (2014) does map rural residential development and we recently integrated NLUD with NLCD to quantify the remaining natural vegetation cover (NVC) across the northwestern United States in 2001 and rates of conversion to human land uses for the period 2001–2011 (Hansen, Mullan, et al., 2021). NVC was defined as locations where native vegetation is the dominant cover type and there is no detectable agricultural, residential, urban, commercial, or human infrastructure cover. We found that NVC occupied 64% of the private lands across the northwestern U.S. study area in 2011. During 2001–2011, 2.5% of the area of NVC was lost to development and crop lands. Rates of loss were as high as 12% in some regions.

Given the high potential importance of remaining NVC on private lands to a nascent U.S. biodiversity strategy on the one hand (e.g., The White House, 2021), and the high rates of loss of these lands to development on the other hand (Hansen, Mullan, et al., 2021; Theobald et al., 2016), there is a need to identify which of the remaining areas of NVC best contribute to sustaining biodiversity and the level of threat of habitat conversion Such information would allow conservation decision makers to consider how well a parcel may contribute to biodiversity goals and the likelihood that this value will be lost to development if the parcel is not protected. In this paper, we present a method for developing a Biodiversity Conservation Priority Index (BCPI) that is based on ecological value and risk of development and apply the method to the remaining NVC on private lands in the northwestern United States.

While global conservation efforts have focused on the extent of natural habitats (Kennedy et al., 2019; Theobald et al., 2020; Watson et al., 2018), the quality of those habitats should also be considered (Grantham et al., 2020; Hansen et al., 2020; Theobald, 2013; Watson et al., 2018). In addition to conserving the most "wild" lands, Kennedy et al. (2019) argued for the need to consider private "working lands," often in lands adjacent to wild lands. This is because natural habitats may differ species richness, productivity, carbon storage, contribution to landscape connectivity, and in other ecological factors. Consequently, conservation scientists are now calling for the CBD to target not only the extent of natural habitats but also the ecological quality or integrity of those habitats (Hansen, Noble, et al., 2021; Theobald, 2010, 2013; Watson et al., 2018). Ecological integrity refers to the ecological structure, function, and composition characteristics of a region (Parrish et al., 2003; Theobald, 2013; Wurtzebach & Schultz, 2016). Areas of high ecological integrity best meet various biodiversity objectives and best sustain many ecological services (Carter et al., 2019; Scholes & Biggs, 2005; Tierney et al., 2009). Thus, we draw on fine-scale national data sets representing elements of ecological structure, function, and composition, and integrate them into an index of ecological value.

We then intersect ecological value with risk of habitat loss as a basis for ranking biodiversity conservation priority. Human land use and pressure are products of social, economic, abiotic conditions, and infrastructure; thus habitat loss is often predictable based on these factors (Reisig et al., 2021; Theobald, 2003). The logic of focusing conservation on high-risk places is that they will likely be destroyed if not protected (Margules & Pressey, 2000; Wilson et al., 2009; Withey et al., 2012). Our overarching intent is to provide conservation practitioners with an objective ranking of biodiversity conservation priority of remaining private NVC based on metrics of ecological integrity and risk of loss.

The type of decision we seek to inform is how to allocate limited resources to best maintain biodiversity and ecological function through the protection and stewardship of NVC on private lands. Such decisions often consider how well biological goals will be met as well as the potential for the natural habitat on a parcel of land to be degraded in biodiversity if not protected (Armsworth et al., 2020; Wilson et al., 2009; Withey et al., 2012). Additional factors are typically considered in conservation decision making. These often include land cost, policy influencing land use and conservation easements, land owner willingness to participate on conservation programs (Wallace et al., 2008), and level of interest in local conservation organizations in selecting parcels to best meet biodiversity goals (Armsworth et al., 2020; Naidoo et al., 2006; Polasky et al., 2008). Our products on ecological value and risk are meant to be used as inputs into conservation planning efforts that typically consider a broader set of socioeconomic, policy, and human behavioral factors (e.g., Armsworth et al., 2020; Polasky et al., 2008).

One important application for the BCPI is to inform selecting lands for conservation easements. Conservation easements are agreements between landowners and conservation easement holders in which landowners agree to restrictions on land use to achieve conservation purposes in exchange for payment, tax benefits, or development permits (Owley & Rissman, 2016). The purposes for easements typically involve maintenance of open space, agricultural lands, scenic value, water resources, recreation, wildlife habitat, and natural ecosystems (Farr et al., 2018). Conservation easements are an important means to conserve private lands in the United States and their application has expanded rapidly (Rissman et al., 2017). Currently 40 million acres (1 acre = 0.4 ha) are estimated to be under conservation easement in the United States (https://www.conservationeasement.us/storymap/index.html).

The effectiveness of conservation easements to sustain native species, wildlife habitat, and natural ecosystems is not well quantified, however. While it is widely assumed that easements created for open space, agriculture, scenery, recreation, natural habitats, and water resources also contribute to wildlife and natural habitat protection, evidence of this is mixed (Bargelt et al., 2020; Farr et al., 2018; Graves et al., 2019; Quintas-Soriano et al., 2016). These studies largely conclude that existing conservation easements under-performed with regards to various biodiversity conservation objectives. One reason underlying this is the lack of information on biodiversity conservation value that can be used in selecting lands for easements.

Thus, with the goal of providing knowledge to guide selection of remaining NVC on private lands for biodiversity conservation, including placement of conservation easements, we addressed two questions across the northwestern United States.

1. Which remaining NVC on private lands is the highest priority for biodiversity conservation based on ecological integrity and risk of loss?
2. Are conservation easements in NVC placed preferentially in locations of high biodiversity conservation priority?

METHODS

Study area

Systematic prioritization of lands for conservation is especially important in the Northwest United States. The study area includes the Rocky Mountain portions of Montana, Wyoming, Colorado, and Utah and the entire states of Idaho, Washington, and Oregon (Figure 1). Centered on iconic national parks such as Yellowstone and wilderness areas such as the Bob Marshall, the region includes the largest tracts of natural habitat in the contiguous 48 states (Wade & Theobald, 2010). While this area is dominated by public lands that are largely protected from intense human land uses (Theobald, 2013), private lands tend to be located in areas of less harsh climate, fertile soils and more productive vegetation that are most important to biodiversity (Scott et al., 2001). The region was slow to undergo human development since Euro-American settlement due to its remoteness (Huston, 2005). But since 1970, population densities and land use intensification have been increasing rapidly, partially driven by the level of natural amenities the region affords (Reisig et al., 2021; Theobald, 2001). Consequently, NVC is being lost to development at high rates in communities with high in-migration of relatively wealthy and educated individuals that value high natural amenities (Reisig et al., 2021).

Land use grades from the urban centers of large cities such as Seattle, WA, Portland, OR, and Boise, ID, and smaller cities such as Laramie, WY, Missoula, MT, and Bend, OR, through croplands and exurban and rural residential areas to wildlands. We generated socio-ecological regions (hereafter termed regions) that were defined across the study area based on ecoregions, watershed boundaries, protected area centered ecosystem boundaries, urban proximity, socioeconomics, and study area boundaries (Hansen, Mullan, et al., 2021). Specifically, we defined these regions based on EPA Level III ecoregions, hydrologic unit code 4 watershed boundaries, protected area centered ecosystem boundaries (Hansen et al., 2011), urban proximity, community characteristics, and study area boundaries. Our goal was to identify regions that were likely to be relatively homogeneous in patterns of NVC, correlates of land development, ecological consequences, and thus conservation priorities.

Thirty four percent of private lands were developed (housing, commercial, industrial, or infrastructure uses) or crop lands in 2011 (Hansen, Mullan, et al., 2021). Developed lands increased during 2001–2011 by 8% and crop lands by 5% resulting in a decline of wildlands by 2.5%. Wildland loss was statistically significantly associated with urban fringe development, forest edge vegetation, proximity to highways, public land, and lakes and rivers. Rates of loss were also higher within the commuting zones of cities with demographic structures characterized as "New West" (Winkler et al., 2007), namely those with relatively high-income, educated populations working in service industries and often having migrated from elsewhere.

Overview of methods

We describe here the general flow of methods, and details are provided in the following sections. A BCPI for NVC

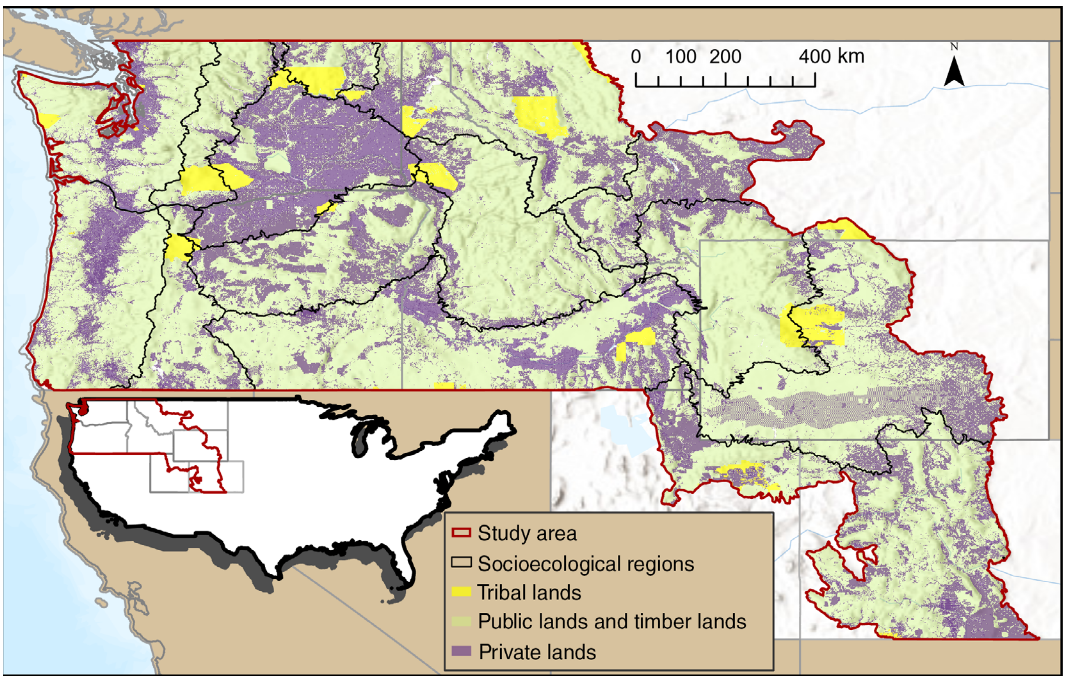

FIGURE 1 The study area of northwestern United States showing states, land allocation, and the boundaries of socioecological regions as defined under Study Area. From Hansen, Mullan, et al., 2021. (ESRI, 2015, 2017)

in 2011 was developed based on ecological value and risk of loss. Ecological value was calculated based on five metrics relating to ecological structure, function, and composition. Risk of loss for 2011 conditions was estimated using a statistical function of wildland loss during 2001–2011 based on socioecological predictors. Ecological value and risk of loss were integrated to obtain the BCPI. This was done at the scale of the study area ($BCPI^{SA}$) and regions ($BCPI^{Regions}$). The distribution of areas of high $BCPI^{SA}$ was then summarized across the study area by region. BCPI was quantified relative to sociodemographic and biophysical predictors at the study area and region scales. The BCPI scores for lands that were in conservation easements were then compared to those lands not protected by easements. The analysis was restricted to terrestrial NVC types on private lands. Wetlands and aquatic habitats were excluded because some of the data sets we drew on have lower accuracy for those habitat types.

Quantifying the BCPI

Consistent with the concept of ecological integrity (e.g., Parrish et al., 2003), we selected ecological metrics for valuation that represented elements of ecological structure, function, and composition. We endeavored to use existing published data sets for these ecological metrics. Criteria for selection were the following: representation of ecological structure, function, or composition; published in a credible source; and adequate spatial resolution (≤1 km) and extent (study area). Adequate data for landscape connectivity among large protected areas were not available, and we generated a connectivity layer to meet the needs of the study. The ecological metrics are summarized below and in Table 1. The resolution of all the layers was 30 m except for Protection-weighted Range-size Rarity of Imperiled Species, which was 990 m. Various other metrics and/or data sources could have been used (see e.g., Carter et al., 2019; Hansen, Noble, et al., 2021; Tierney et al., 2009; Walston & Hartmann, 2018), and we selected these metrics because in our judgment they best meet the criteria above.

Net primary productivity (NPP) is the amount of new biomass fixed by green plants through photosynthesis. It is important relative to ecosystem energy flow, carbon dynamics, disturbance recovery, and nutrient cycling (Running et al., 2004). NPP also represents foods and habitats for species and is thus a correlate and sometimes a predictor of biodiversity (Gaston, 2000). We used an NPP layer that applies the MODIS algorithm to Landsat data to produce annual NPP at a 30-m resolution (Robinson et al., 2018).

Vertebrate species richness represents the number of mammals, birds, reptiles, and amphibian species projected to occur within a cell. It was created by the U.S. Gap Analysis project by overlaying presence from species distribution models based on cover type, elevation, and water for 1590 species that occur in the conterminous United States (Gergely et al., 2019). Vertebrate species richness is an important metric relative to ecological value because it identifies locations that represent suitable habitat for large numbers of species.

Ecosystem type representation has been widely used for conservation planning (Belote et al., 2017). It is defined as the proportion of an ecosystem type that is within a protected area. It is especially relevant to private land conservation prioritization because protected areas are largely on public lands and ecosystem types with low representation thus are primarily on private lands. Following the methods of Belote et al. (2017), we used natural ecosystem types from the National Vegetation Classification System in GAP land cover data (Comer et al., 2003; USGS, 2011). We then estimated the percentage of total area of each ecosystem type occurring in strict protected areas (GAP status 1 or 2) (USGS, 2018) within the study area. In order to score locations poorly represented in protected areas as high in ecological value, we derived Ecosystem Type Representation on Private Lands as one minus Ecosystem Type Representation.

Protection-weighted range-size rarity of imperiled species (NatureServe; https://habitatsuitabilitymodeling-natureserve.hub.arcgis.com/pages/the-map-of-biodiversity-importance) is derived from habitat suitability models for 2216 of the nation's most imperiled species, and information on range size and degree of protection. Taxonomic groups include vertebrates, freshwater invertebrates, pollinators, and vascular plants. The layer is a key measure of ecological value because it identifies locations for species that are most at risk of extinction based on high imperilment, small range size, and poor protected area representation.

Connectivity among Greater Wildland Ecosystems (GWEs) was quantified as the contribution of private land NVC to connectivity among GWEs in and around the study area. GWEs were defined as the large protected areas and surrounding public and private natural habitats that have strong ecological and social connections with the core protected areas. Connectivity among GWEs is of concern for ecosystem types (Rehfeldt et al., 2012), tree species (Hansen & Phillips, 2018), and vertebrate species (Lawler et al., 2013). We chose to model habitat structural connectivity among GWEs using resistance surfaces generally relevant to forest-dependent large mammal species. Resistance to movement was calculated using degree of human modification (Theobald, 2013), slope, and

TABLE 1 Description and evaluation of metrics used to represent ecological value

Ecosystem component/metric	Description	Units/spatial/temporal resolution	Citation	Evaluation: Pros	Cons	Uncertainty
Ecosystem structure						
Connectivity	Contribution to connectivity among Greater Wildland Ecosystems for forest-dependent mammals	Probability of movement/30 m/2010	See Appendix S1	Depicts contribution of private land NVC to connectivity among large protected area ecosystems	Connectivity varies by species and this layer is only relevant for species that are sensitive to land use pressure, forest cover, and topographic complexity	The analysis is for generic species that are sensitive to land use, forest cover, and topographic complexity. No validation was done and uncertainty is unknown.
Ecosystem function						
Net primary productivity (NPP) (average annual)	New biomass fixed by green plants through photosynthesis. Unit Average annual NPP	Annual average/30 m/16 day	Robinson et al. (2018)	Represents foods and habitats for species may be a driver of species abundance and richness	Varies annually with climate; not familiar to some conservation decision makers	Correlation against flux tower NPP: 0.55–0.80; better captures the spatiotemporal variability in terrestrial production than MODIS 250-m product
Ecosystem composition						
Vertebrate species richness	No. mammals, birds, reptiles, and amphibian species projected to have suitable habitat	No. species with modeled suitable habitat/30 m/input layers from 2001 to 2007	Gergely et al. (2019)	Indicator of the no. species that may occur	Many areas of suitable habitat are unoccupied by a species	Habitat associations are based on expert opinion and the layer has unknown uncertainty
Protection-weighted range-size rarity of imperiled species	Summed protection-weighted range-size rarity for imperiled vertebrate, freshwater invertebrate, pollinator, and vascular plant species	High values identify areas where more unprotected, restricted-range species are likely to occur/990 m/time invariant	NatureServe[a]	Identifies locations of high conservation interest due to the restricted species range sizes and need for protection from threats such as habitat loss.	Relatively coarse in grain size	Uncertainty has not been assessed
Ecosystem representation	Proportion of the area of the ecosystem type that is within a protected area	Proportion of area protected/30 m/time invariant	Belote et al. (2017)	Ecosystem types poorly represented in protected areas are more valuable for conservation	Does not inform on the level of threat to the unprotected proportion of the ecosystem type	The level of uncertainty in the input data layers is known to be low

[a]https://habitatsuitabilitymodeling-natureserve.hub.arcgis.com/datasets/Natureserve::protection-weighted-range-size-rarity-of-imperiled-species-in-the-united-states/about.

canopy cover (Dickson et al., 2017) across the landscape. Connectivity across the resistance surfaces was estimated as current density using Circuitscape (McRae et al., 2013). The current densities from each calculation were then summed to produce maps of cumulative current density across the study area. Methods are described in more detail in Appendix S1.

Risk of loss of NVC was derived from our companion study (Hansen, Mullan, et al., 2021). In that work, we mapped the locations of private wildlands in 2001 and 2011 based on the National Land Use Data product (NLUD) (Theobald, 2014) and the National Land Cover Data set (Jin et al., 2019). We then estimated rates of conversion from wildland to developed or crop classes during 2001–2011. Probability of conversion was modeled using methods and predictor data sets of Reisig et al. (2021). Predictor data included market proximity, socio-demographic, infrastructure, natural amenity, and climate factors modeled for 30-m pixels and for cities and their surrounding commuting zones. The best model explained 61% of the variation in probability of conversion and was used to project risk of loss of remaining wildlands to development based on conditions in 2011.

In order to derive scores for relative ecological value, risk of loss, and BCPI, we converted the absolute values for the ecological metrics and risk of loss to relative values. This was done because our intention was to compare the ecological value and risk of development among private NVC across the study area to prioritize conservation importance. To this end, we did not normalize the ecological metrics by ecosystem type, given that the goal was to rank the metrics across all ecosystem types. Also, we did not want the upper values of the BCPI to be overly strongly influenced by extreme high values of the ecological metrics or risk of loss, so we classifying cells into one of 20 classes (ventiles) based on the frequency distribution of values across the study area. Locations in the 0–5th percentile range were placed in class 1, for example, and those in the 95–100 percentile range into class 20. The scores of the five ecological metrics were then averaged to get an overall relative ecological value score.

BCPI was then derived by averaging the overall ecological value and the risk of habitat loss. Thus, locations with high ecological value and high risk of development received the highest score ($BCPI^{SA}$). Because some users may wish to organize their conservation planning based on rankings of locations with regions, we also derived relative BCPI within each region ($BCPI^{Region}$). In addition to the outputs that integrate the individual metrics (e.g., BCPI, ecological value), we also provide links to the individual ecological value metrics and risk of loss so that users can analyze them individually if desired.

Question 1. Which remaining natural habitats on private lands are highest priority for biodiversity conservation based on ecological integrity and risk of loss?

We evaluated the distribution of CPI^{SA} values among the regions of the study area with violin plots of cells within each ventile in each ecoregion. Violin plots are similar to box plots, except that they also show the probability density of the data at different values, smoothed by a kernel density estimator. These plots show a marker for the median of the data, a box indicating the interquartile range (25th to 75th percentiles), 1.5 × the interquartile range, and outlier samples. We use violin plots rather than box plots to show the statistics and the entire distribution of the data with regions. In order to reduce the number of samples to a manageable data set, we aggregated the 30-m data to a 250-m resolution using a maximum BCPI rule to reduce the number of samples from ~500,056,597 to 7,200,815. This allowed the violin plots to include all the 250-m cells of NVC within each region.

In order to describe the spatial patterns of $BCPI^{SA}$ and $BCPI^{Region}$, we used multivariate regression analysis to identify patterns of association between sociodemographic/biophysical predictors and $BCPI^{SA}$ and $BCPI^{Region}$ scores. Predictor variables included landform (Theobald et al., 2015), natural land cover (Jin et al., 2019), and market remoteness index and proximity to previous development from Reisig et al. (2021). These variables were selected to characterize the landscape study region along the dimensions most relevant to ecological value and risk of conversion. We estimated the regression models using ordinary least squares with a simple random sample of 900,041,250 m pixels drawn from all NVC on private land in the study region. We controlled for possible differences among regions by including region in addition to the other covariates for the $BCPI^{Region}$ model.

Question 2. Are conservation easements in NVC placed preferentially in locations of high biodiversity conservation priority?

The locations of existing conservation easements up through 2020 were derived from the National Conservation Easement Database (NCED, 2020). NCED is a spatial database of conservation easements in the United States, including conservation easements held by private nonprofits, government agencies, and tribes. NCED was established in 2009 and is managed by nonprofit organizations, mainly Ducks Unlimited and The Trust for Public Land.

The NCED identifies conservation easements by purpose. We were interested primarily in the distribution of easements purposed for environmental value (ENV) by NCED and defined as for "the protection of a relatively natural habitat of fish, wildlife, or plants, or similar ecosystem" (IRS, 1986). Thus, we assigned private lands to one of three classes: ENV conservation easements, OTHER conservation easements (all other purposes), and non-conservation easements. We then overlaid the three classes of private lands on the maps of developed lands, and crop lands derived from Hansen, Mullan, et al. (2021) and obtained the proportion of area of conservation easements among these three land use types.

We then assessed the distribution of BCPI scores across private NVC categorized by ENV conservation easement, OTHER conservation easement, and non-conservation easement. These distributions were represented by cumulative rank sum distribution functions using data at the 250 m resolution as described under Question 1. Differences in medians among groups were examined using Wilcoxon rank sum tests for nonparametric data (Wilcoxon, 1945).

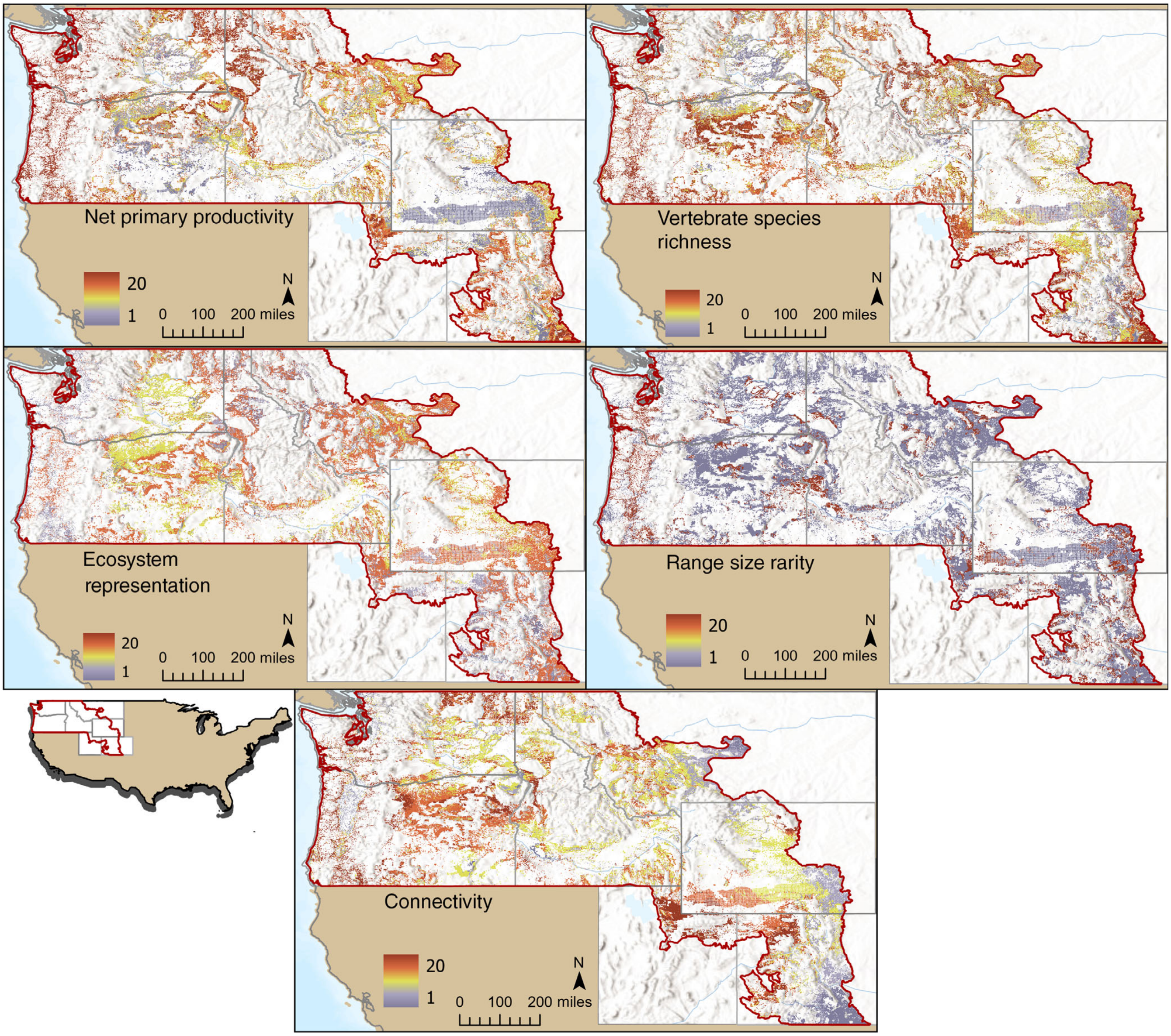

FIGURE 2 Maps of relative values of ecological themes and cumulative ecological value rank across the study area for net primary productivity, vertebrate species richness, ecosystem type representation, range size rarity, and connectivity among Greater Wildland Ecosystems. (ESRI, 2015, 2017). 1 mile = 1.6 km

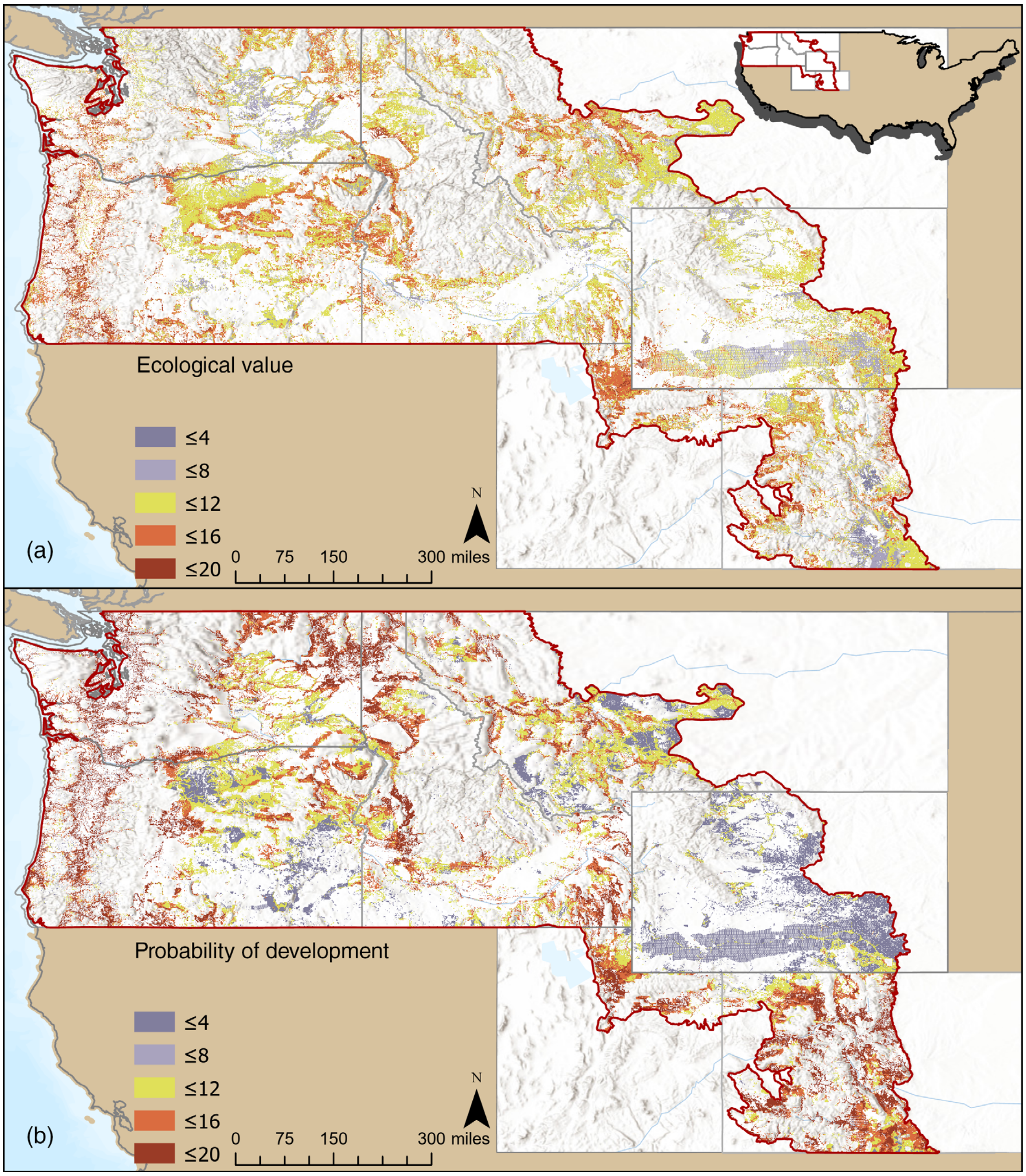

FIGURE 3 Relative ecological value expressed as (a) mean scores among the five ecological metrics and (b) probability of wildland loss (ESRI, 2015, 2017). 1 mile = 1.6 km

RESULTS

Q1. Which remaining natural habitats on private lands are the highest priorities for conservation?

The ecological metrics differed in spatial patterns across the study area (Figure 2). NPP was relatively high in forested mountains, especially west of the Cascades Mountain Crest. Species Richness tended to be higher in southern portions of the study area. Ecosystem representation on private lands and range size rarity were high in the portions of the study area away from mountains and dominated by private lands. Connectivity among GWEs was higher in areas that were more centrally located among the protected areas. Combining the five ecological metrics into relative ecological value resulted in high scores west of the Cascades Crest and in the southern half of the study area in mountain–valley-bottom interfaces (Figure 3a).

Probability of NVC conversion to development was relatively high from the east side of the Cascade Mountains to the Pacific Ocean, in the Spokane/Coeur d'Alene region in northeast Washington and northern Idaho, in

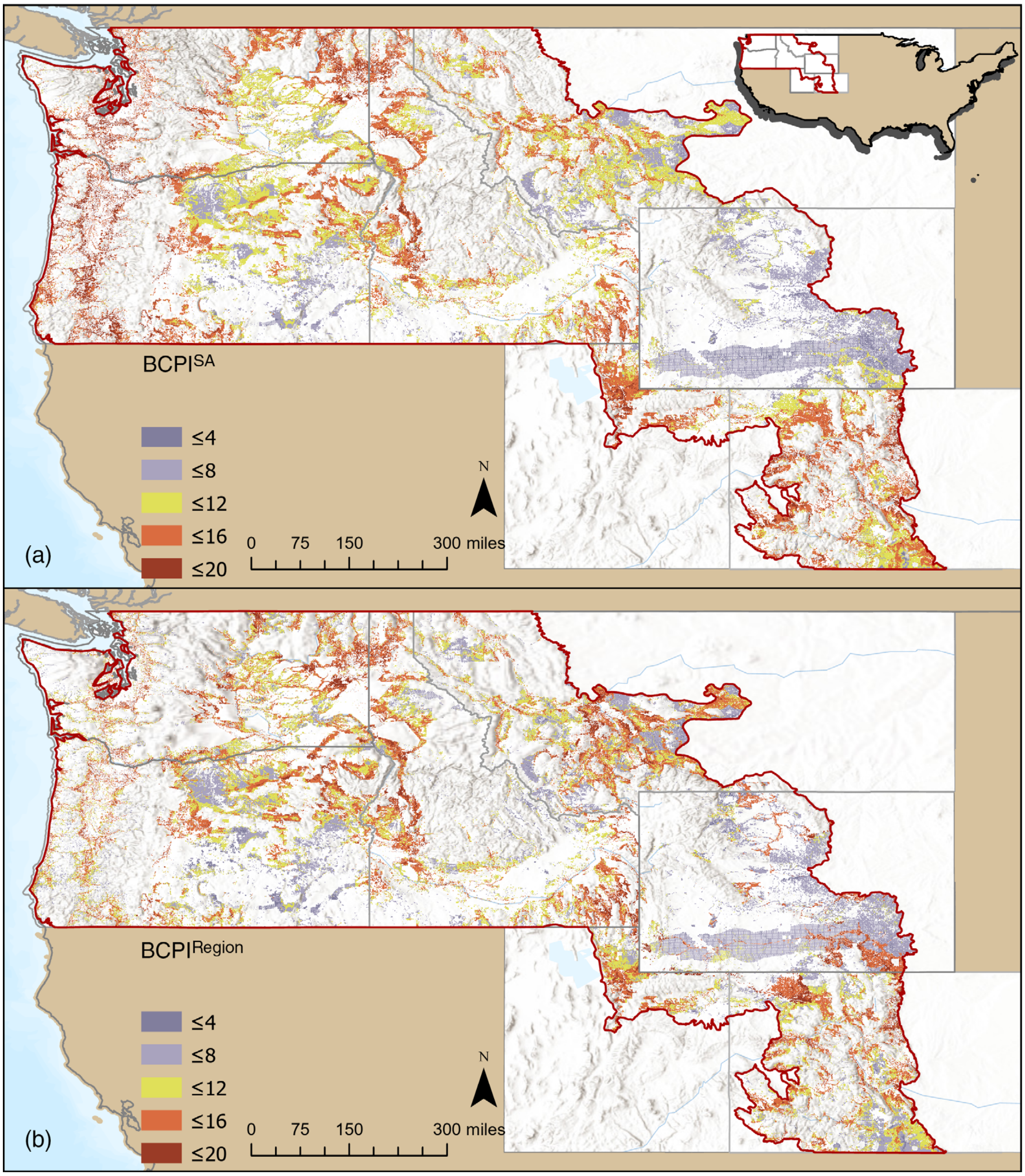

FIGURE 4 Biodiversity Conservation Priority Index (BCPI) values and locations of conservation easements (purple). (a) Biodiversity Conservation Priority Index of the study area (BCPI^{SA}) show rankings relative to those across the entire study area. (b) Biodiversity Conservation Priority Index of the regions (BCPI^{Region}) shows rankings within regions (ESRI, 2015, 2017). 1 mile = 1.6 km

the vicinity of Salt Lake City, Utah and in the Colorado Mountains (Figure 3b).

The spatial patterns of BCPI^{SA} (Figure 4a) tended to be high in the western and southern portion of the study area, but also in the Spokane/Coeur d'Alene and Salt Lake City areas. Regions differed substantially in BCPI^{SA} values (Figure 5). Median values for the four western-most regions, the Upper Colombia, and the two southern Rockies regions (Uinta Wasatch and Colorado Mountains) were 14–16, with BCPI values relatively normally distributed. In contrast, the large basin and plateau regions (Wyoming Basin, Palouse Prairie, and Snake River Plain) and northern Rockies (Greater Yellowstone, High Divide) had median values much lower (6–11) and the distributions were often skewed towards lower BCPI values.

Results for BCPI^{Region}, which ranks samples within regions, show increases in BCPI values relative to BCPI^{SA} for the highest priority locations in lower BCPI^{SA} regions such as the Wyoming Basin, Snake River Plain, and Greater Yellowstone, and decreases for the moderate priority locations in higher BCPI^{SA} regions such as Western Oregon and Washington (Figure 4b).

Regression models of the landscape characteristics that correlate with BCPI^{SA} (Table 2, full study area level)

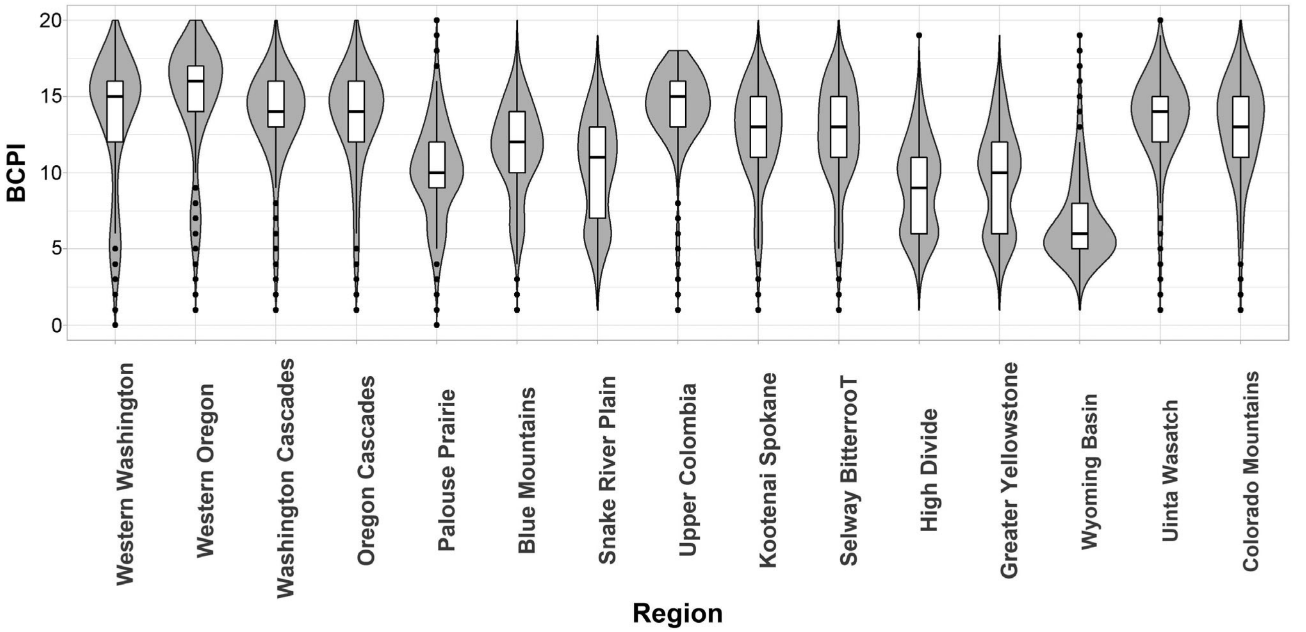

FIGURE 5 Violin plots of the distribution of study-area-scale Biodiversity Conservation Priority Index (BCPI) among ecoregions. The plots show median Biodiversity Conservation Priority Index of the study area ($BCPI^{SA}$) values (horizontal lines), 25th and 75th percentiles (white box upper and lower limits), 1.5× the interquartile range (whisker lines), and outliers (dots). The width of the gray polygon is the density of samples with that BCPI value

show that rural-distant locations (that are more than 20 km from developed areas) have lower CPI^{SA} values than urban, suburban, or rural-proximate locations. In particular, suburban and rural-proximate locations have the highest $BCPI^{SA}$ values across development classes. The results also show that land that is more remote from road networks and urban centers has lower $BCPI^{SA}$ values on average. Conditional on proximity and access to urban development, sloping or mountainous lands have lower $BCPI^{SA}$ values than valleys. Open lands such as wetlands and recreation areas have higher $BCPI^{SA}$ values than land with some residential buildings, while land used for extractive purposes such as timber or grazing has the lowest $BCPI^{SA}$ values of the alternative land uses.

The correlates of within-region variation in $BCPI^{Region}$ (Table 2, within region level) are qualitatively similar to the correlates with BCPI values over the study region as a whole. However, there are some quantitative differences. For example, the negative relationship between remoteness and BCPI values is stronger within regions than across the study region, and urban land has lower BCPI values on average relative to rural-proximate or suburban land. The within-region results also show a stronger positive relationship between open land and BCPI values and a weaker negative relationship between Extractive land uses and BCPI values, relative to built-up land.

Q2. How well have high-priority natural habitats been represented in conservation easements?

Some 4.5% of the private lands examined in the study are protected through easements as indicated in the NCED database. ENV easements comprise 32.6% of the protected lands. The area in ENV easements is distributed among land cover types as follows: 90% are in NVC, 8% are in developed, and 2% are in crop (Table 3). OTHER and non-easement types are better represented in developed and crop land cover types. Within NVC, 94.2% the area is not within easements, 3.9% is protected by OTHER easements, 2.0% is protected by ENV easements (Table 4).

The distributions of NVC lands across CPI^{SA} values overlapped substantially among conservation easement types, however, ENV easements were skewed to lower values compared with OTHER and non-easement types (Figure 6) and the median value of ENV was estimated to be 0.9999 units lower that non-easements (Wilcoxon's rank sum test statistic $[W] = 3.68 \times 10^{11}$, $p < 0.001$) and 1.0 units lower than OTHER ($W = 1.45 \times 10^{10}$, $p < 0.001$) (Table 5). The results for CPI^{Region} were similar.

DISCUSSION

As land use intensifies in the northwestern United States, remaining natural habitats on private lands are

TABLE 2 Relationships between Biodiversity Conservation Priority Index (BCPI) and various sociodemographic/biophysical metrics that are useful for characterizing the settings where BCPI is relatively low or high

Metric	Full study area level	Within region level[a]
Index of remoteness	−0.785*** (−123.32)	−1.274*** (−209.79)
Development: base = rural-distant (>20 km from urban)		
Rural-proximate (<20 km from urban)	2.701*** (289.23)	3.187*** (354.56)
Suburban	4.204*** (302.03)	4.577*** (340.64)
Urban	1.810*** (33.25)	0.857*** (16.87)
Landform: base = valley		
Low slope	−0.514*** (−44.79)	−0.403*** (−37.92)
Mountain	−0.634*** (−54.67)	−0.577*** (−53.71)
Land cover: base = built land (e.g., low-density residential)		
Extractive use (e.g., timber, grazing)	−1.662*** (−45.12)	−0.998*** (−28.56)
Open land (e.g., wetlands, recreation)	0.815*** (38.90)	1.443*** (72.93)
Constant	8.218*** (349.99)	4.819*** (178.29)
Observations	900,084	900,041
Adjusted R^2	0.218	0.321

Note: *t* statistics in parentheses.
[a]Region dummy variables included in model.
***$p < 0.001$.

TABLE 3 The proportion of each type of conservation easement within each of the private land cover types

Private land cover type	Conservation easement status: ENV easement	OTHER easement	Non-easement
NVC	0.895	0.858	0.657
Developed	0.082	0.107	0.171
Crop	0.022	0.034	0.173

Abbreviations: ENV, environmental-type easements; NVC, natural vegetation cover; OTHER, all other types of easements.

TABLE 4 The proportion of private land cover types within each of three categories of conservation easements

Private land cover type	Conservation easement status: NVC	Developed	Crop
ENV easement	0.020	0.007	0.002
OTHER easement	0.039	0.019	0.006
Non easement	0.942	0.974	0.992

Abbreviations: ENV, environmental-type easements; NVC, natural vegetation cover; OTHER, all other types of easements.

increasingly being lost. If biodiversity and ecosystem services are to be sustained in the region, it is critical to protect the natural habitats that contribute most to sustaining the biodiversity of the region. The aim of this study was to provide objective information to guide land-use decisions on the ecological value and risk of loss of natural habitats, especially about the placement of conservation easements on private lands. Our BCPI was generated at two spatial scales because the organizations that facilitate conservation easements differ in geographic scales of interest (Graves et al., 2019). Some operate at county levels, others at state levels, and federal programs at the national level. Thus, we ranked BCPI across the entire study area for use by organizations that operate over regional to national extents. We also ranked BCPI within regions for use by those organizations that are more locally focused.

We found that the metrics used to define ecological value differed in spatial pattern across the study area. NPP was relatively high in forests, west of the Cascade Crest and in the northwest Rocky Mountains, as influenced by the distribution of precipitation, temperature, and soil fertility (Running et al., 2004). Vertebrate species richness is associated with primary productivity, temperature, and habitat heterogeneity (Gaston, 2000). It was highest in mountainous areas in the southern and western portion of the study area. Ecosystem types most poorly represented in protected areas were largely outside of the mountain ecosystems that are dominated by public lands. Range size rarity was high in areas dominated by private lands, likely due to the complex interaction of human, biophysical, and demographic factors that lead to small population sizes. Connectivity among GWEs was high in the more centrally located regions as a result of the juxtapositioning of the GWEs and presence of corridors of forest-dominated NVC.

Combining the scores for the ecological metrics into the metric of relative ecological value resulted in high values largely west of the Cascade Crest. These patterns resulted from the various climatic, soil, and land allocation factors that control the individual ecological metrics. The spatial patterns of relative ecological value were

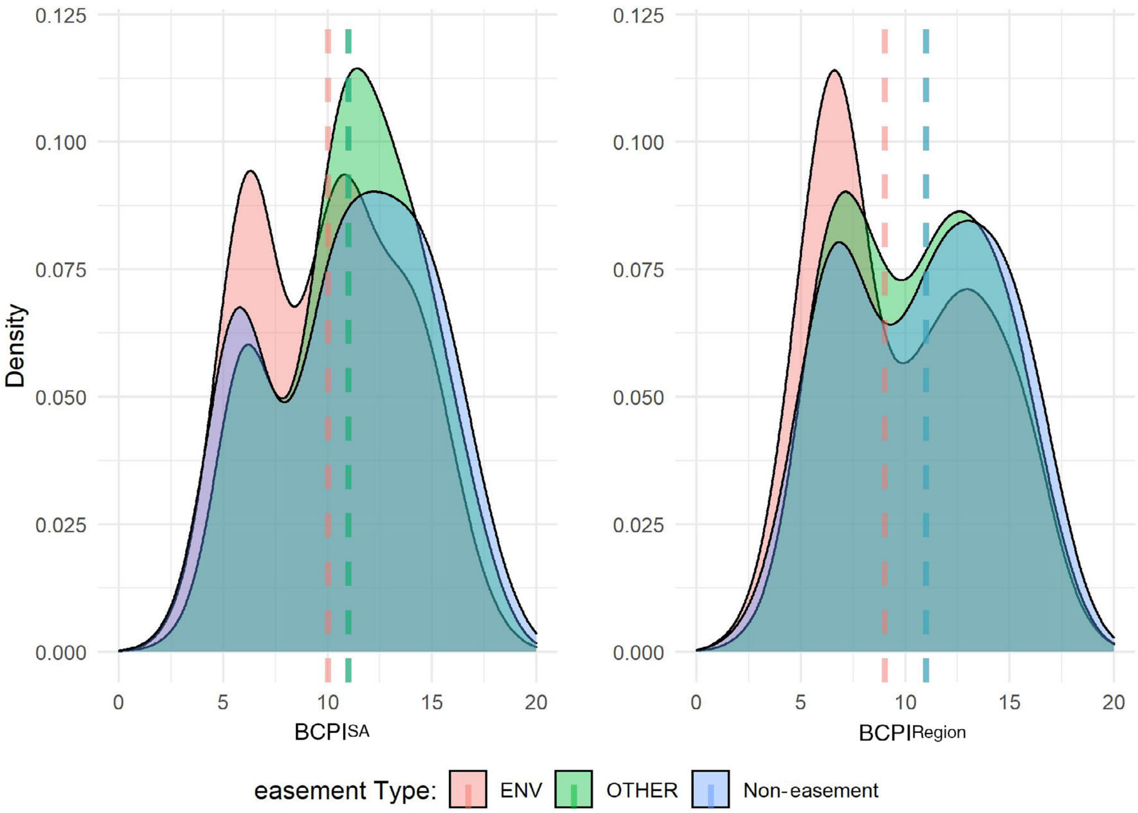

FIGURE 6 Cumulative distribution functions (a) Biodiversity Conservation Priority Index of the study area (BCPI^{SA}) and (b) Biodiversity Conservation Priority Index of the regions (BCPI^{Region}) for three categories regarding conservation easements. Vertical lines are median values. Easement types are ENV, environmental; OTHER, all other types; Non-easement, not within conservation easements

TABLE 5 Median Biodiversity Conservation Priority Index value among three types of conservation easement designations for the study area and for within regions

	Easement type		
CPI type	ENV easement	OTHER easement	Non easement
CPI^{SA}	10	11	11
CPI^{Region}	9	11	11

Note: The median value of ENV is lower than non-easements (Wilcoxon's rank sum test statistic [W] = 3.68×10^{11}, p value < 0.001) and OTHER ($W = 1.45 \times 10^{10}$, p value < 0.001). The results for CPI^{Region} were similar. Abbreviations are as defined in the Table 4 legend.

typically coincident with those of risk of development. Many of the factors that influence ecological value also are known drivers of human land use including climate, soils fertility, primary productivity, and proximity to treeline (Hansen, Mullan, et al., 2021). Thus, our map of BCPI is important in highlighting the locations high in both ecological value and with higher likelihood of being converted from NVC.

We found that CPI^{SA} was higher west of the Cascades Crest, in the Upper Colombia Region and in the southern Rocky Mountains, and lower in the inland dry basin and plateau areas and in the northern Rocky Mountains. The CPI^{SA} and CPI^{Region} were highest in locations that were rural residential and suburban development, near roads, proximate to urban centers, on valley bottom landforms, and with undeveloped cover types. These relationships are the outcome of the inclusion of both ecological value and risk of development in the CPI.

Although conservation easements are widely seen as a vehicle for achieving biodiversity objectives, we found that only 2% of private lands with NVC were protected by an easement with the purpose of natural habitat and/or species protection. Moreover, easements designated with the purpose of protecting natural habitats (the ENV type) were largely not located in places of high ecological value or with high risk of development. Easements were commonly located in areas lower in BCPI than other types of easements and NVC not in easements. Thus, our mapped product can be useful to inform efforts to conserve these lands through easements.

Our approach for prioritizing lands for conservation is consistent with the conservation biology literature (e.g., Margules & Pressey, 2000; Withey et al., 2012), but includes nuances deemed appropriate for this application. We focused on natural habitats that are on private ownership, placed within the gradient of human modification (Theobald, 2004). Intact, private lands represent one of the six states of nature recognized in a general framework of conservation by Kuempel et al. (2020). Lands in this state are of high interest for conservation because they are likely to be degraded by human activity but also represent the best opportunity for expanding the areal extent of protected lands of high ecological quality (Watson et al., 2018). Strategically allocating funds, closing gaps in key spatial conservation objectives, and ultimately maintaining biodiversity in perpetuity for these lands requires knowledge about the benefits of conservation of these lands (Kuempel et al., 2020). Thus, we quantified the ecological characteristics of the remaining areas of NVC on private lands as a basis for ranking conservation priority.

We chose to select metrics of ecological value in the context of the concept of ecological integrity. Ecological integrity has long been used as a basis for monitoring and evaluating the health of ecological systems (Wurtzebach & Schultz, 2016). This is because the concept recognizes that the resilience of ecosystems is a function of ecological structure, function, and composition

TABLE 6 Summary of previous studies using the concept of ecological integrity to inform land management and conservation

Study	Study area	Objective	Metrics used to represent ecological integrity
Tierney et al., 2009	Acadia National Park, USA	Evaluate the ecological integrity of temperate zone, forested ecosystems, based on long-term monitoring data	Forest patch size; anthropogenic land use; stand structural class; structure snag abundance; CWD volume; tree regeneration; tree condition; biotic homogenization; indicator species, invasive exotic plants; indicator species, deer browse; tree growth and mortality rates; soil chemistry, acid stress; soil chemistry, nitrogen saturation
Carter et al., 2019	Public lands in Nevada, USA	Evaluate the ecological integrity of shrublands on multiple use lands to inform federal land management	Vegetation composition; presence of plants of management concern; percent cover of nonnative invasive plants; vegetation height; percent cover of bare ground; proportion of soil surface in large canopy gaps; vegetation area; vegetation alteration; patch size; structural connectivity; development
Walston & Hartmann, 2018	Public lands in a region of southern Colorado and northern New Mexico, USA	Quantify a Landscape Integrity Index as a landscape indicator of ecological integrity	Human influence and modification; species richness; vegetation departure from natural condition
Hansen, Noble, et al. 2021	Global forests	Monitor ecological integrity across global forests using earth observations to inform the post-2020 Global Biodiversity Framework.	Forest structural condition; lost forest configuration; NPP; burned area; species habitat index by group; local biodiversity intactness; biodiversity habitat index; bioclimatic ecosystem resilience

(Chapin III et al., 2011). Imperiled species cannot be recovered, for example, without maintaining the structure of the habitats they require and the production of foods and nutrients they consume. The concept is embraced for evaluating ecological condition, because it recognizes that ecosystems have a natural range of structure, function, and composition as determined by the climates, soils, and other factors characteristic of their region (Parrish et al., 2003). Consequently, the current draft of the CBD targets for 2030 includes increasing ecological integrity as a central goal (CBD, 2020).

The logic of using ecological integrity as an organizational framework for prioritization for biodiversity conservation is that if the resilience of ecological systems is dependent upon ecological structure, function, and composition being in within the range of natural variability, then all three ecological traits should be considered when selecting lands for meeting long-term biodiversity goals. In addition to "identifying the right lands for conservation," this approach has the advantage of providing a construct for monitoring and evaluating how well the lands selected for protection sustain biodiversity (e.g., Parks Canada Agency, 2011; Tierney et al., 2009). This approach has also been embraced for applications to public lands in portions of the United States and recommended for use in the post-2020 Global Biodiversity Framework (Table 6).

The selection of specific metrics of ecological value will strongly influence the outcomes of conservation priority efforts. Beyond selecting metrics that relate to ecological structure, function and composition, we chose metrics based on representation of key conservation objectives (e.g., maintaining imperiled species), minimizing redundancy among themes, availability of fine-scale spatial data, and tractability to diverse stakeholders. We feel that ours is a reasonable set of metrics for quantifying ecological value of wildlands in our study area and for demonstrating the approach. Others may choose to change or supplement this list for their particular applications. For example, the recent analysis of habitat suitability for species of concern by Dietz et al. (2020) may also be highly relevant for prioritizing lands for conservation.

Conservation expenditure should be prioritized so that scarce funds are used efficiently to prevent degradation of natural systems (Wilson et al., 2011; Withey et al., 2012). Risk of habitat loss has been widely used as a criteria for prioritizing policy choices (Tabor et al., 2018; Wilson et al., 2011). Risk of loss is important because it is an inefficient use of funds to invest in locations where the risk of exposure to threats is low or where there are no biodiversity assets impacted by a particular threat (Wilson et al., 2005). We note that the costs of acquiring conservation easements may be correlated with development risk so it is likely to be more expensive to protect the high-risk land. However, the benefits of using scarce funds to protect large areas of land that is at minimal risk of development will be low because it is unlikely to be converted regardless. So managers can use our results to determine which land is most worth protecting (i.e., benefits of protection = value × risk of loss in the absence of protection), and compare that with information from other sources on costs.

We are not aware of any studies that have intersected ecological value with risk of loss for private wildlands in the United States at management-relevant spatial scales (but see Theobald, 2003, Withey et al., 2012). Similar applications globally include overlaying human pressure on biodiversity intactness (Newbold et al., 2016), risk of deforestation on measures of species endangerment (Tracewski et al., 2016), projected roading on various biodiversity measures (Laurance et al., 2014), and deforestation risk on potential climate refugia (Tabor et al., 2018). These studies, like ours, were designed to provide objective information to allow conservation efforts to focus on locations of highest ecological value and greatest risk of loss by human modification.

Despite the considerable investment in conservation easements, their effectiveness in achieving biodiversity conservation objectives is often not high. Fouch et al. (2019) found that privately conserved lands did not differ significantly from non-conserved lands in the degree of human modification in North Carolina. In a region of Idaho, private land in conservation easements provided increased representation within the protected areas network for only 10% of the ecosystem types and protected potential landscape connectivity only slightly more effectively than randomly allocated areas (Graves et al., 2019). Across the United States, Bargelt et al. (2020) found that private protected areas contribute <1.1% to current protected area coverage. In South Africa, Shumba et al. (2020) found that private land conservation areas lost only slightly less natural land cover (3%) and biodiversity intactness (2%) than matched unprotected areas (6% and 4%, respectively). Our findings are consistent with these studies in finding that conservation easements often under-perform in targeting the lands most valuable for biodiversity conservation.

Improved information on ecological value and risk of development of lands available for easements would allow private land conservation efforts to be focused on the locations that can best meet biodiversity conservation objectives. Our BCPI allows for the selection of lands for conservation easements that would best meet NPP, species richness, ecosystem representation, imperiled species, and connectivity objectives under current conditions. Our approach was designed to be relevant under current climate conditions in order for conservation decisions to be made to be most relevant to achieving conservation goals today. As humaninduced climate change occurs in future decades, however, the elements of ecological integrity are likely to change also. Fortunately, projections of species habitat suitability and connectivity under future climate are available for the United States (Lawler et al., 2020) and our maps of BCPI could be overlaid with maps of climate resilience (Carroll & Noss, 2021; Lawler et al., 2020; TNC, 2018) to prioritize lands based both on current and potential future climates.

Users of the results of this study should do so with knowledge of its various assumptions and limitations. Our model to predict risk of wildland loss explained about half of the variation in the calibration data, thus indicating the level of uncertainty in our maps of risk of loss. Moreover, the model was calibrated with data from 2001 to 2011 and applied to conditions in 2011. Their relevance to likely development in 2020 should be evaluated when updated information on land use becomes available from the 2020 census. The application of our results from a 30-m analysis results should be carefully considered, as, land development decisions are influenced by ownership and legal and policy restrictions such as local zoning, which we did not take into account in modeling risk of development. Thus, we suggest that users should consider BCPI as a first filter and then overlay more detailed local information on parcel boundaries, ownership, land use restrictions, and other factors to identify those that are highest priorities for conservation. A final limitation of this study is that the current version of NCED includes only 50%–70% of existing conservation easements, depending on location (Foster et al., 2014). There is no indication that the easements reported in the NCED are biased relative to conservation outcomes, however, so it is unlikely that our results would change if the NCED was complete.

We suggest that the BCPI is useful for various applications. Landowners may wish to report the ranking of their property to increase appeal to potential conservation buyers. City and county governments may wish to consider the index when making land use decisions. Land trusts can use the index to help select properties for conservation easements that will best forward their biodiversity goals. Last, the BCPI is relevant to the U.S. Congress resolution to create a national biodiversity strategy (Congressional Record, 2021) and the Biden Administration's commitment to protect 30% of the lands by 2030 (The White House, 2021). Applying our approach to the remaining United States would provide information to contribute to emerging U.S. biodiversity conservation initiatives.

CONCLUSION

The Northwestern United States is rapidly becoming more human dominated. The population growth and land use intensification is partially due to the high-quality natural amenities in the region (Reisig et al., 2021). Perhaps counterintuitively, some of the communities that most highly value natural amenities are losing NVC most rapidly (Hansen, Mullan, et al., 2021). Thus, there is an urgent need to better protect the highest priority remaining natural habitats on private lands. The results of this study offer information to contribute to this prioritization. We encourage environmental decision makers to draw on this information when evaluating the fates of NVC and to strive towards sustaining these valuable habitats.

ACKNOWLEDGMENTS

This work was supported by the NASA Land Cover Land Use Change Program under Grant No. NNX15AD41G.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Hansen & Robinson, 2022) are available in Figshare at https://doi.org/10.6084/m9.figshare.16692193.

ORCID

Andrew J. Hansen https://orcid.org/0000-0002-9545-3250

REFERENCES

Armsworth, P. R., A. E. Benefield, B. Dilkina, R. Fovargue, H. B. Jackson, D. Le Bouille, and C. Nolte. 2020. "Allocating Resources for Land Protection Using Continuous Optimization: Biodiversity Conservation in the United States." *Ecological Applications* 30: 1–13.

Bargelt, L., M. J. Fortin, and D. L. Murray. 2020. "Assessing Connectivity and the Contribution of Private Lands to Protected Area Networks in the United States." *PLoS One* 15: 1–13.

Belote, R. T., M. S. Dietz, C. N. Jenkins, P. S. McKinley, G. H. Irwin, T. J. Fullman, J. C. Leppi, and G. H. Aplet. 2017. "Wild, Connected, and Diverse: Building a more Resilient System of Protected Areas." *Ecological Applications* 27: 1050–6.

Brown, D. G., K. M. Johnson, T. R. Loveland, and D. M. Theobald. 2005. "Rural Land-Use Trends in the Conterminous United States, 1950-2000." *Ecological Applications* 15: 1851–63.

Carroll, C., and R. F. Noss. 2021. "Rewilding in the Face of Climate Change." *Conservation Biology* 35: 155–67.

Carter, S. K., E. Fleishman, I. I. F. Leinwand, C. H. Flather, N. B. Carr, F. A. Fogarty, M. Leu, B. R. Noon, M. E. Wohlfeil, and D. J. A. Wood. 2019. "Quantifying Ecological Integrity of Terrestrial Systems to Inform Management of Multiple-use Public Lands in the United States." *Environmental Management* 64: 1–19.

CBD. 2010. "Convention on Biological Diversity. Page COP 11 Decision X/2. Strategic Plan for Biodiversity 2011–2020." https://www.cbd.int.decision/cop/?id=12268.

CBD. 2020. "Convention on Biodiversity. Page Convention on Biodiversity." Report of the Open-Ended Working Group on the

Post-2020 Global Biodiversity Framework at its Second Meeting. https://www.cbd.int/meetings/WG2020-02.
Ceballos, G., P. R. Ehrlich, and P. H. Raven. 2020. "Vertebrates on the Brink as Indicators of Biological Annihilation and the Sixth Mass Extinction." *Proceedings of the National Academy of Sciences USA* 117: 13596–602.
Chapin, F. S., III, P. A. Matson, and P. M. Vitousek. 2011. *Principles of Terrestrial Ecosystem Ecology*. New York, NY: Springer.
Comer, P., D. Faber-Langendoen, R. Evans, S. Gawler, C. Josse, G. Kittel, S. Menard, et al. 2003. *Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems*. Arlington, VA: Page Nature Serve.
Congressional Record. 2019. "SENATE RESOLUTION 372." Congressional Record Vol. 165, No. 167 | PDF S597, S5976-S5976."
Congressional Record. 2021. "H.res.69—117th Congress - Expressing the Need for the Federal Government to Establish a National Biodiversity Strategy for Protecting Biodiversity for Current and Future Generations."
Díaz, S., J. Settele, E. Brondízio, H. Ngo, and M. Guèze. 2019. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn: IPBES Secretariat.
Dickson, B. G., C. M. Albano, B. H. McRae, J. J. Anderson, D. M. Theobald, L. J. Zachmann, T. D. Sisk, and M. P. Dombeck. 2017. "Informing Strategic Efforts to Expand and Connect Protected Areas Using a Model of Ecological Flow, with Application to the Western United States." *Conservation Letters* 10: 564–71.
Dietz, M. S., R. T. Belote, J. Gage, and B. A. Hahn. 2020. "An Assessment of Vulnerable Wildlife, their Habitats, and Protected Areas in the Contiguous United States." *Biological Conservation* 248: 1–10.
Dinerstein, E., A. R. Joshi, C. Vynne, A. T. L. Lee, F. Pharand-Deschênes, M. França, S. Fernando, et al. 2020. "A "Global Safety Net" to Reverse Biodiversity Loss and Stabilize Earth's Climate." *Science Advances* 6: 1–13.
ESRI. 2015. "World Hillshade [Basemap] Scale Not Given." July 9, 2015. https://www.arcgis.com/home/item.html?id=1b243539f4514b6ba35e7d995890db1d.
ESRI. 2017. "World Terrain Base [Basemap] Scale Not Given." October 26, 2017. https://www.arcgis.com/home/item.html?id=33064a20de0c48d2bb61efa8faca93a8.
Farr, C. M., S. E. Reed, and L. Pejchar. 2018. "How Often Are Conservation Developments Managed for Biodiversity Protection? A Case Study in Colorado, USA." *Landscape and Urban Planning* 169: 105–14.
Foster, K., T. Comendant, M. Lundin, and J. Strittholt. 2014. *Protecting Natural Vegetation: Comparative Analysis of Land Protection Mechanisms*. Corvallis, OR: Conservation Biology Institute.
Fouch, N., R. F. Baldwin, P. Gerard, C. Dyckman, and D. M. Theobald. 2019. "Landscape-Level Naturalness of Conservation Easements in a Mixed-Use Matrix." *Landscape Ecology* 34: 1967–87.
Gaston, K. J. 2000. "Global Patterns in Biodiversity." *Nature* 405: 220–7.
Gergely, K. J., K. G. Boykin, A. J. McKerrow, M. J. Rubino, N. M. Tarr, and S. G. Williams. 2019. "Gap Analysis Project (GAP) Terrestrial Vertebrate Species Richness Maps for the Conterminous U.S. U.S. Geological Survey Scientific Investigations Report 2019." https://doi.org/10.3133/sir20195034.
Grantham, H. S., A. Duncan, T. D. Evans, K. R. Jones, H. L. Beyer, R. Schuster, J. Walston, et al. 2020. "Anthropogenic Modification of Forests Means Only 40% of Remaining Forests Have High Ecosystem Integrity." *Nature Communications* 11: 1–10.
Graves, R. A., M. A. Williamson, R. T. Belote, and J. S. Brandt. 2019. "Quantifying the Contribution of Conservation Easements to Large-Landscape Conservation." *Biological Conservation* 232: 83–96.
Hansen, A., and N. Robinson. 2022. "Informing Conservation Decisions to Target Private Lands of Highest Ecological Value and Risk of Loss." Figshare, Dataset. https://doi.org/10.6084/m9.figshare.16692193.v1.
Hansen, A. J., P. Burns, J. Ervin, S. J. Goetz, M. Hansen, O. Venter, J. E. M. Watson, et al. 2020. "A Policy-Driven Framework for Conserving the Best of Earth's Remaining Moist Tropical Forests." *Nature Ecology and Evolution* 4: 1377–84.
Hansen, A. J., C. R. Davis, N. Piekielek, J. Gross, D. M. Theobald, S. Goetz, F. Melton, and R. Defries. 2011. "Delineating the Ecosystems Containing Protected Areas for Monitoring and Management." *Bioscience* 61: 363–73.
Hansen, A. J., R. L. Knight, J. M. Marzluff, S. Powell, K. Brown, P. H. Gude, and K. Jones. 2005. "Effects of Exurban Development on Biodiversity: Patterns, Mechanisms, and Research Needs." *Ecological Applications* 15: 1893–905.
Hansen, A. J., K. Mullan, D. Theobald, S. Powell, N. Robinson, and A. East. 2021. "Natural Vegetation Cover on Private Lands: Locations and Risk of Loss in the Northwestern United States." *Ecosphere* 12: e03756.
Hansen, A. J., B. P. Noble, J. Veneros, A. East, S. J. Goetz, C. Supples, J. E. M. Watson, et al. 2021. "Towards Monitoring Ecosystem Integrity within the Post-2020 Global Biodiversity Framework." *Conservation Letters* 14: e12822.
Hansen, A. J., and L. Phillips. 2018. "Trends in Vital Signs for Greater Yellowstone: Application of a Wildland Health Index." *Ecosphere* 9: 1–28.
Huston, M. A. 2005. "The Three Phases of Land-Use Change: Implications for Biodiversity." *Ecological Applications* 15: 1864–78.
IRS. 1986. "26 U.S.C., 170(h)(4)(A), Conservation Purpose, 153–54. United States."
Jin, S., C. Homer, L. Yang, P. Danielson, J. Dewitz, C. Li, Z. Zhu, G. Xian, and D. Howard. 2019. "Overall Methodology Design for the United States National Land Cover Database 2016 Products." *Remote Sensing* 11: 1–23.
Joppa, L. N., and A. Pfaff. 2009. "High and Far: Biases in the Location of Protected Areas." *PLoS ONE* 4: e8273.
Kennedy, C. M., J. R. Oakleaf, D. M. Theobald, S. Baruch-Mordo, and J. Kiesecker. 2019. "Managing the Middle: A Shift in Conservation Priorities Based on the Global Human Modification Gradient." *Global Change Biology* 25: 811–26.
Kuempel, C. D., A. L. M. Chauvenet, H. P. Possingham, and V. M. Adams. 2020. "Evidence-Based Guidelines for Prioritizing Investments to Meet International Conservation Objectives." *One Earth* 2: 55–63.
Laurance, W. F., G. R. Clements, S. Sloan, C. S. O'Connell, N. D. Mueller, M. Goosem, O. Venter, et al. 2014. "A Global Strategy for Road Building." *Nature* 513: 229–32.

Lawler, J. J., D. S. Rinnan, J. L. Michalak, J. C. Withey, C. R. Randels, and H. P. Possingham. 2020. "Planning for Climate Change through Additions to a National Protected Area Network: Implications for Cost and Configuration." *Philosophical Transactions of the Royal Society B* 375: 1–8.

Lawler, J. J., A. S. Ruesch, J. D. Olden, and B. H. Mcrae. 2013. "Projected Climate-Driven Faunal Movement Routes." *Ecology Letters* 16: 1014–22.

Leu, M., S. E. Hanser, and S. T. Knick. 2008. "The Human Footprint in the West: A Large-Scale Analysis of Anthropogenic Impacts." *Ecological Applications* 18: 1119–39.

Margules, C. R., and R. L. Pressey. 2000. "A Framework for Systematic Conservation Planning." *Nature* 405: 243–53.

Maxwell, S. L., R. A. Fuller, T. M. Brooks, and J. E. M. Watson. 2016. "Biodiversity: The Ravages of Guns, Nets and Bulldozers." *Nature* 536: 288–91.

McRae, B. H., V. B. Shah, and T. K. Mohaptra. 2013. "Circuitscape 4 User Guide." https://docs.circuitscape.org/Circuitscape.jl/latest/usage/.

Naidoo, R., A. Balmford, P. J. Ferraro, S. Polasky, T. H. Ricketts, and M. Rouget. 2006. "Integrating Economic Costs into Conservation Planning." *Trends in Ecology and Evolution* 21: 681–7.

NCED. 2020. "National Conservation Easement Database Data Downloads." https://www.conservationeasement.us/downloads/.

Newbold, T., L. N. Hudson, A. P. Arnell, and S. Contu. 2016. "Dataset: Global map of the Biodiversity Intactness Index, from Newbold et al. (2016) Science." Natural History Museum Data Portal (data.nhm.ac.uk). https://doi.org/10.5519/0009936.

Owley, J., and A. R. Rissman. 2016. "Trends in Private Land Conservation: Increasing Complexity, Shifting Conservation Purposes and Allowable Private Land Uses." *Land Use Policy* 51: 76–84.

Parks Canada Agency. 2011. *Consolidated Guidelines for Ecological Integrity Monitoring in Canada's National Parks*. Quebec Canada: Protected Areas Establishment and Conservation Branch, Parks Canada.

Parrish, J. D., D. P. Braun, and R. S. Unnasch. 2003. "Are we Conserving What we Say we Are? Measuring Ecological Integrity within Protected Areas." *Bioscience* 53: 851–60.

Polasky, S., E. Nelson, J. Camm, B. Csuti, P. Fackler, E. Lonsdorf, C. Montgomery, et al. 2008. "Where to Put Things? Spatial Land Management to Sustain Biodiversity and Economic Returns." *Biological Conservation* 141: 1505–24.

Quintas-Soriano, C., B. Martín-López, F. Santos-Martín, M. Loureiro, C. Montes, J. Benayas, and M. García-Llorente. 2016. "Ecosystem Services Values in Spain: A Meta-Analysis." *Environmental Science and Policy* 55: 186–95.

Rehfeldt, G. E., N. L. Crookston, C. Sáenz-Romero, and E. M. Campbell. 2012. "North American Vegetation Model for Land-Use Planning in a Changing Climate: A Solution to Large Classification Problems." *Ecological Applications* 22: 119–41.

Reisig, D., K. Mullan, A. Hansen, S. Powell, D. Theobald, and R. Ulrich. 2021. "Natural Amenities and Low-Density Residential Development: Magnitude and Spatial Scale of Influences." *Land Use Policy* 105285: 1–12.

Rissman, A. R., J. Owley, A. W. L'roe, A. W. Morris, and C. B. Wardropper. 2017. "Public Access to Spatial Data on Private-Land Conservation." *Ecology and Society* 22: 1–24.

Robinson, N. P., B. W. Allred, W. K. Smith, M. O. Jones, A. Moreno, T. A. Erickson, D. E. Naugle, and S. W. Running. 2018. "Terrestrial Primary Production for the Conterminous United States Derived from Landsat 30 m and MODIS 250 m." *Remote Sensing in Ecology and Conservation* 4: 264–80.

Running, S. W., R. R. Nemani, F. A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto. 2004. "A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production." *Bioscience* 54: 547–60.

Scholes, R. J., and R. Biggs. 2005. "A Biodiversity Intactness Index." *Nature* 434: 45–9.

Scott, J. M., F. W. Davis, R. G. McGhie, R. G. Wright, C. Groves, and J. Estes. 2001. "Nature Reserves: Do they Capture the Full Range of America's Biological Diversity?" *Ecological Applications* 11: 999–1007.

Shumba, T., A. De Vos, R. Biggs, J. J. Esler, J. M. Ament, and H. S. Clements. 2020. "Effectiveness of Private Land Conservation Areas in Maintaining Natural Land Cover and Biodiversity Intactness." *Global Ecology and Conservation* 22: e00935.

Stolton, S., K. H. Redford, and N. Dudley. 2014. "The Futures of Privately Protected Areas: Developing Capacity for a Protected Planet." Protected Area Technical Report Series: 128. Gland, Switzerland: IUCN.

Tabor, K., J. Hewson, H. Tien, M. González-Roglich, D. Hole, and J. W. Williams. 2018. "Tropical Protected Areas under Increasing Threats from Climate Change and Deforestation." *Land* 7: 1–14.

The White House. 2021. "FACT SHEET: President Biden Takes Executive Actions to Tackle the Climate Crisis at Home and Abroad, Create Jobs, and Restore Scientific Integrity across Federal Government." January 27, 2021.

Theobald, D., C. Kennedy, B. Chen, J. Oakleaf, S. Baruch-Mordo, and J. Kiesecker. 2020. "Earth Transformed: Detailed Mapping of Global Human Modification from 1990 to 2017." *Earth System Science Data* 12: 1953–2020.

Theobald, D. M. 2001. "Land-Use Dynamics beyond the American Urban Fringe." *Geographical Review* 91: 544–64.

Theobald, D. M. 2003. "Targeting Conservation Action through Assessment of Protection and Exurban Threats." *Conservation Biology* 17: 1624–37.

Theobald, D. M. 2004. "Placing Exurban Land-Use Change in a Human Modification Framework." *Frontiers in Ecology and the Environment* 2: 139–44.

Theobald, D. M. 2010. "Estimating Natural Landscape Changes from 1992 to 2030 in the Conterminous US." *Landscape Ecology* 25: 999–1011.

Theobald, D. M. 2013. "A General Model to Quantify Ecological Integrity for Landscape Assessments and US Application." *Landscape Ecology* 28: 1859–74.

Theobald, D. M. 2014. "Development and Applications of a Comprehensive Land Use Classification and Map for the US." *PLoS ONE* 9: 1–14.

Theobald, D. M., D. Harrison-Atlas, W. B. Monahan, and C. M. Albano. 2015. "Ecologically-Relevant Maps of Landforms and Physiographic Diversity for Climate Adaptation Planning." *PLoS ONE* 10: 1–17.

Theobald, D. M., L. J. Zachmann, B. G. Dickson, M. E. Gray, C. M. Albano, V. Landau, and D. Harrison-Atlas. 2016. *Description of the Approach, Data, and Analytical Methods Used to Estimate Natural Land Loss in the Western US*. Truckee, CA: Conservation Science Partners.

Tierney, G. L., D. Faber-Langendoen, B. R. Mitchell, W. G. Shriver, and J. P. Gibbs. 2009. "Monitoring and Evaluating the Ecological Integrity of Forest Ecosystems." *Frontiers in Ecology and the Environment* 7: 308–16.

TNC. 2018. "Resilient Land Mapping Tool: Resilient and Connected Network Dataset." http://maps.tnc.org/resilientland/.

Tracewski, Ł., S. H. M. Butchart, M. Di Marco, G. F. Ficetola, C. Rondinini, A. Symes, H. Wheatley, A. E. Beresford, and G. M. Buchanan. 2016. "Toward Quantification of the Impact of 21st-Century Deforestation on the Extinction Risk of Terrestrial Vertebrates." *Conservation Biology: The Journal of the Society for Conservation Biology* 30: 1070–9.

USGS. 2011. *U.S. Geological Survey Gap Analysis Project, 20160513, GAP/LANDFIRE National Terrestrial Ecosystems 2011*. Reston, VA: U.S. Geological Survey.

USGS. 2018. *(USGS) Gap Analysis Project (GAP), (2018), Protected Areas Database of the United States (PAD-US)*. Reston, VA: U. S. Geological Survey.

Wade, A. A., and D. M. Theobald. 2010. "Residential Development Encroachment on U.S. Protected Areas." *Conservation Biology* 24: 151–61.

Wallace, G. N., D. M. Theobald, T. Ernst, and K. King. 2008. "Assessing the Ecological and Social Benefits of Private Land Conservation in Colorado." *Conservation Biology* 22: 284–96.

Walston, L. J., and H. M. Hartmann. 2018. "Development of a Landscape Integrity Model Framework to Support Regional Conservation Planning." *PLoS ONE* 13: 1–16.

Watson, J. E. M., O. Venter, J. Lee, K. R. Jones, J. G. Robinson, H. P. Possingham, and J. R. Allan. 2018. "Protect the Last of the Wild." *Nature* 563: 27–30.

Wilcoxon, F. 1945. "Individual Comparisons by Ranking Methods." *Biometrics Bulletin* 1: 80–3.

Wilson, K., R. L. Pressey, A. Newton, M. Burgman, H. Possingham, and C. Weston. 2005. "Measuring and Incorporating Vulnerability into Conservation Planning." *Environmental Management* 35: 527–43.

Wilson, K. A., J. Carwardine, and H. P. Possingham. 2009. "Setting Conservation Priorities. The Year in Ecology and Conservation Biology." *Annals of the New York Academy of Sciences* 1162: 237–64. https://doi.org/10.1111/j.1749-6632.2009.04149.xC.

Wilson, K. A., M. C. Evans, M. di Marco, D. C. Green, L. Boitani, H. P. Possingham, F. Chiozza, and C. Rondinini. 2011. "Prioritizing Conservation Investments for Mammal Species Globally." *Philosophical Transactions of the Royal Society B* 366: 2670–80.

Winkler, R., D. R. Field, A. E. Luloff, R. S. Krannich, and T. Williams. 2007. "Social Landscapes of the Inter-Mountain West: A Comparison of "Old West" and "New West" Communities." *Rural Sociology* 72: 478–501.

Withey, J. C., J. J. Lawler, S. Polasky, A. J. Plantinga, E. J. Nelson, P. Kareiva, C. B. Wilsey, et al. 2012. "Maximising Return on Conservation Investment in the Conterminous USA." *Ecology Letters* 15: 1249–56.

Wurtzebach, Z., and C. Schultz. 2016. "Measuring Ecological Integrity: History, Practical Applications, and Research Opportunities." *Bioscience* 66: 446–57.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Hansen, Andrew J., Katrina Mullan, David M. Theobald, Nathaniel Robinson, Alyson East, and Scott Powell. 2022. "Informing Conservation Decisions to Target Private Lands of Highest Ecological Value and Risk of Loss." *Ecological Applications* 32(5): e2612. https://doi.org/10.1002/eap.2612