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Natural vegetation cover on private lands: locations and risk of loss in the northwestern United States

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Abstract. Although natural habitats are being lost globally, the extent and fate of natural habitats on private lands in the United States have not been quantified at the resolution relevant for conservation planning. Here we provide information on the locations and risk of loss of areas of natural vegetation cover (NVC) on private lands across the northwestern United States to motivate discussion on needs and opportunities to slow their loss. Specific questions were as follows: (1) Where are the remaining areas of NVC on private lands? (2) Which regions and communities have had the highest loss rates of NVC? and (3) In which socioecological settings is NVC at greatest risk of loss? NVC location and change were mapped using two land cover classifications during 2001–2011, the most recent period with available data. Associations between NVC loss and market proximity, demographic, infrastructure, natural amenity, and climate factors were used to model probability of NVC loss in 2011. We found that NVC covered 64% of the study area in 2011. During 2001–2011, 2.5% of the area of NVC in 2001 was converted to development and croplands. Rates of loss were as high as 12% in some regions (e.g., western Washington). Housing development accounted for the majority of this NVC loss, increasing by 8% while croplands increased by 5%. Conversion of NVC for development and crops during 2001–2011 per capita varied 20–40 fold among "city spheres" (urban areas >10,000 people and 40-min commuting distance). NVC loss was statistically associated with urban fringe development, forest edge vegetation, proximity to highways, public land, and waterbodies and was associated with New West demographic city spheres. Of the NVC on private lands in 2011, 11% was projected to have >20% probability of future loss over the next decade. We conclude that portions of the northwestern United States, one of the last stronghold for extensive natural habitats in the contiguous United States, are rapidly losing NVC to development, particularly in the New West communities that typically have the highest motivation and capacity to conserve them.

Key words: conservation; habitat loss; land use; natural habitats; natural vegetation cover; northwestern United States; private lands.

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Introduction

Globally, biodiversity loss is one of the top threats facing humanity today (Ceballos et al. 2020) and has led to a reduction in ecosystem services (Cardinale et al. 2007). Habitat destruction and fragmentation is the leading cause of biodiversity loss across many of the Earth's biomes (Newbold et al. 2016). Rates of habitat loss are increasing globally due to growing human population pressures and climate change (Díaz et al. 2019). Deforestation in parts of the tropics, for example, now approaches tipping points resulting in forest conversion to degraded savanna (Lovejoy and Nobre et al. 2018). Within the United States, the robust public lands system and strong environmental laws are widely assumed to adequately protect natural habitats (Keiter et al. 2018). The natural habitats remaining on private lands in the United States, however, are at risk of loss (Hansen et al. 2014) despite being of high ecological value (Scott et al. 2001). Unfortunately, the distribution of natural habitats on private land in the United States has not been adequately mapped because low-density residential development, a leading type of land use intensification, and is difficult to quantify from remote sensing. The purpose of this paper is to provide information on the locations and risk of loss of areas of a component of natural habitat—natural vegetation cover (NVC)—on private lands to motivate discussion on needs and opportunities to slow their loss.

Locations where nature has been relatively uninfluenced by modern anthropogenic pressures and retains ecological elements that are characteristic of the region such as NVC have been referred to as natural habitats, natural vegetation, intact habitats, wildlands, and/or areas of high ecological integrity (Balmford et al. 2002, Parrish et al. 2009, Beyer et al. 2020). These remaining natural habitats provide a wide range of values and ecosystem services, including carbon sequestration and climate connectivity and adaptation, pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling and hydrological services, refuges for imperiled biodiversity, and Indigenous cultural practices (Power 2010, Watson et al. 2016, O'Bryan et al. 2018).

Human activities may reduce the ecological value of natural habitats through habitat destruction, which is the conversion of NVC to human land uses such as croplands or urban areas. Natural habitats may also be degraded by human pressures such as hunting, selective logging, introduction of invasive species, changes in fire and other natural disturbances, and climate change (Barlow et al. 2016). Thus, efforts to quantify human impacts on natural habitats at global scales have relied on satellite imagery that can detect some types of habitat destruction (e.g., Hansen et al. 2013) and on indices of human pressure derived from multiple sources that are used to infer habitat destruction or alteration (e.g., Venter et al. 2016, Kennedy et al. 2019, Theobald et al. 2020).

We focus in this analysis on areas of remaining NVC. We define NVC as locations where native vegetation is the dominant cover type and there is no detectable agricultural, residential, urban, commercial, or human infrastructure cover. We use the term habitat loss or destruction to refer to conversion of NVC to the human-dominated land use classes. Risk of loss is used to denote probability of conversion from NVC to a more intense human land use. NVC differs from natural habitat in that areas of NVC can occur in close proximity to the human-dominated land use classes and be influenced by human activities within them (e.g., selective logging) and edge effects from adjacent land use (e.g., invasive species) (Hansen et al. 2005). Thus, these areas may have some level of alteration or degradation due to human pressure (Barlow et al. 2016). Nonetheless, the presence of NVC often results in these areas supporting native species and ecological processes more typical of natural habitats than human-derived cover types and thus are of high relative ecological value even in urban areas (McKinney 2002). Consequently, areas of NVC are often prioritized for conservation easements and other protections.

NVC has been 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 almost totally modified by humans (e.g., the Mediterranean). The global area of tree cover is estimated to be only 54% of the area at the dawn of human civilization. Deforestation has slowed since its peak in the 1990s. However, forest declines continue in the tropics and in large intact forest landscapes globally (Potapov et al. 2017). Just 39% of land area is still classified as natural vegetation as defined by Hurtt et al. (2020). Within the United States during 1950–2000, a county-level analysis (Brown et al. 2005) revealed that urban area doubled to 2% of the land area, exurban area increased five-fold to 25% of the land area, and croplands decreased 11% to cover 31% of the land area, and thus a total of 58% of the land area was urban, exurban or croplands in 2000.

The distribution and loss rates of NVC 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 resolve low-density residential development well (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, Leu et al. 2008). Thus, mapping areas of remaining NVC requires knowledge of the low-density residential development. Fortunately, a new dataset was designed to complement the NLCD by better resolving low-density development. The National Land Use Dataset (NLUD) (Theobald 2014) does so through spatial analysis of publicly available, national-level spatial datasets, predominately based on census housing, employment, and infrastructure, as well as land cover from NLCD. The combination of NLCD and NLUD can be used to quantify the remaining NVC across the United States and rates of conversion to human land uses for the period 2001–2011.

The fate of NVC is especially important on private lands because they are at risk of loss and are especially important ecologically. Private lands may remain in NVC because they have been protected through conservation easements or open space policies. The bulk of NVC on private lands, however, may potentially be developed for housing, infrastructure, or agriculture. Moreover, because private lands are often in more mesic sites than public lands, with more fertile soils and favorable climates (Robinson et al. 2018), the remaining natural vegetation areas on private lands may be disproportionately important for the habitat values, contributions to landscape connectivity, and the ecological services they provide (Hansen et al. 2002, Leu et al. 2008, Theobald et al. 2012). Hence, the fate of private natural vegetation cover is of high importance for achieving conservation goals.

The risk of future loss of NVC to development is sometimes predictable based on correlates with past loss (e.g., Bierwagen et al. 2010). Land use change in the United States has been associated with urban and market proximity, infrastructure, social and economic factors such as education and employment, ecological factors relating to natural amenities, and climate (Carrión-Flores and Irwin 2004, Gude et al. 2006, York et al. 2011, Auch et al. 2012, Radeloff et al. 2012). The relative strengths of these factors and interactions among them, however, in contributing to land use change likely vary geographically (Kim et al. 2005, Chi and Marcouiller 2013). Moreover, their influence on land development may also vary with the spatial scale of analysis, with some having more influence at the scale of individual land parcels and others at the scale of neighborhoods, cities, or counties (Newbern and Herck 2006, Gray et al. 2008). In the absence of definitive studies on factors driving land use change, knowledge of correlates of land use change has been used to project risk of future loss of natural habitats and used in conservation planning (Gude et al. 2007, Visconti et al. 2010, Poudyal et al. 2016).

Improved knowledge of natural vegetation loss on private lands is especially important in the northwestern portion of the contiguous United States. The region includes the largest tracts of natural habitats in the contiguous 48 states (Wade and Theobald 2010). Centered on iconic national parks such Yellowstone and wilderness areas such as the Bob Marshall, the region supports biodiversity and ecosystem services invaluable to the nation. While this area is dominated by public lands that are largely protected from intense human land uses (Theobald 2013), the private lands in the region are preferentially located in areas with more equitable climate, fertile soils, and higher ecological productivity (Leu et al. 2008, Robinson et al. 2018). Many of the communities in the region are in transition from "Old West" natural resource-based demography to "New West" demography motivated by natural amenities, recreation, and services (McGranahan 1999, Winkler et al. 2007). Consequently, population growth and human pressures have increased substantially across the region (Hansen et al. 2014, U. S. Census Bureau 2018, Radeloff et al. 2018).

The goal of this study was to provide quantitative information about the current distribution of NVC on private lands, recent loss rates, socioecological correlates with loss, and probability of future loss in the NW United States to help motivate and inform discussion and action to slow its loss. We addressed the following questions for the period of 2001–2011, the most recent period of available data.

1. Where are the remaining areas of NVC on private lands?
2. Which regions and communities have had the highest loss rates of NVC?
3. In which socioecological settings is NVC at greatest risk of future loss?

Answering to these questions is intended to help to inform efforts to conserve these areas of high ecological value.

Methods

Study area

The study area includes the Rocky Mountain portions of Montana, Wyoming, Colorado, and Utah and the entire states of Idaho, Washington, and Oregon (Fig. 1). This area was selected to be large enough to include large expanses of NVC and a variety of community types, yet be small enough to track local and community-scale development. The study area boundaries were placed to coincide with US Environmental Protection Agency (EPA) Level III ecoregions (Omernik 1987) and state boundaries.

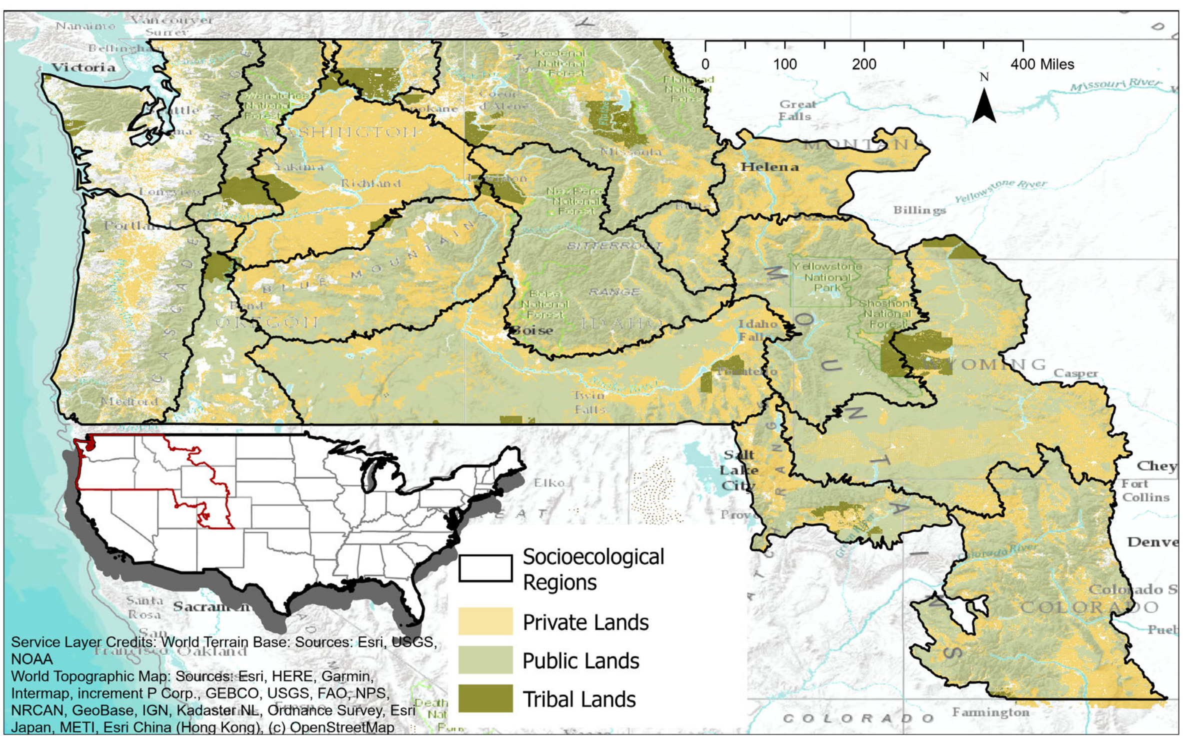

Fig. 1. Map of the study area showing mountain ranges, rivers, cities, states, land allocation, and the boundaries of socioecological regions defined for this study (1 mile = 1.609 km).

Topography of the region is mostly mountainous with intervening plains and basins. Major topographic features include portions of the Rocky Mountains, the Blue Mountains, the Snake River Plains, the Columbia and Great Basins, the Cascade Mountains, and the Coast Range. Public lands cover 61% of the study area. Native American tribal lands are dispersed throughout the study area and represent 4% of the area. The remaining 35% of the study area are private lands. These are centered on valley bottoms, rivers, sea coasts, and areas of fertile soil.

Land use grades from the urban centers of large cities such as Seattle, WA, to smaller cities such as Missoula, MT, through croplands, rural residential areas, to natural habitats. Population growth has been variable across the study area. Counties in the region had a 37% average growth rate during 1990–2010, compared to the national average of 18%, and the total population of the region grew by about 40%, (US Census 2010*a*). Some counties in eastern Oregon, central Washington, and Wyoming, however, had little population change.

To assess geographical variation in the distribution of NVC, we defined socioecological 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 define regions that were likely to be relatively homogeneous in patterns of NVC, correlates of land development, ecological consequences, and thus conservation priorities. We refer to these as socioecological (SE) regions.

Quantification of NVC, developed lands, and croplands

Land cover and land use were derived from the NLCD 2016 (Jin et al. 2019) and NLUD (Theobald 2014) as described above. NLUD is available for 2001 and 2011 and we used the 2001 and 2011 time periods of the NLCD 2016 product and focused analysis on the 2001–2011 period.

We applied a water mask (from Hansen et al. 2013) to restrict the NLCD and NLUD data to terrestrial settings. We also excluded, where data allowed, private industrial timberlands from the developable private lands layer. This was done because these lands are prevented by various laws from home and crop development. The data used to identify these lands were provided by the National Council on Air and Stream Improvement for the states of Washington, Oregon and Montana (J. Verschuyl, *personal communication* 2/1/2020).

We combined classes from NLCD and NLUD to map NVC, developed lands, and croplands (Table 1). NLCD and NLUD are 30-m raster datasets. In both datasets, we labeled as developed classes defined based on human dwellings, infrastructure, pasture, or mining. If either NLCD or NLUD showed a developed class in a cell, that cell was labeled as developed for these analyses. Cultivated crops (from NLCD or NLUD) were labeled as croplands. NVC included natural vegetation types and recreation and conservation lands that did not show the human alterations captured by the developed and crop classes. The lowest density residential development class in both datasets is residential exurban low in NLUD which is defined as 1 dwelling per 40 acres (0.01 dwellings per ha) to 1 dwelling per 2.5 acres (0.16 dwellings per ha). Thus, NVC included locations with home densities below this level. We included timber harvest and livestock grazing lands in the NVC class. This was done because data do not exist to resolve them accurately over the full study area and because the impacts of timber harvest and livestock grazing generally do not lead to loss of NVC.

After reclassifying NLCD and NLUD into NVC, developed, and croplands, we summarized the distribution of these land use types in 2001 and in 2011 and calculated rates of change over the decadal time period. The results were summarized within SE regions for private land as derived from the Protected Areas Database (PAD-US) 2.0 (USGS 2018). We estimated by SE region the areal extent and rates of loss of NVC under conversion to developed and croplands for the period 2001–2011.

We also summarized the loss of NVC in and around communities. We defined "city spheres" as urban areas and the surrounding zone within 40 min of driving time distance. An urban area is defined by the US Census Bureau as the continuously built-up area of dense settlement surrounding one or more census places. We selected urban areas that overlapped census places with a

Table 1. Classes of the NLUD (Theobald 2014) and NLCD (Jin et al. 2019) databases used to derive NVC, developed and cropland classes.

Land use classification	NLUD classes	NLCD classes
NVC	2: Wetlands	12 Perennial Ice/Snow
	3: Recreation and conservation	31 Barren land
	4: Timber	41 Deciduous forest
	5: Grazing	42 Evergreen forest
		43 Mixed forest
		52 Shrub/Scrub
		90 Woody Wetlands
		95 Emergent Herbaceous
		71 Grassland/Herbaceous
Developed	1: Reservoirs/canals	21 Developed, Open space
	6: Pastureland	22 Developed, Low intensity
	8: Mining	23 Developed, Medium intensity
	9: Urban parks/golf courses	24 Developed, High intensity
	10: Residential exurban low	81 Pasture/Hay
	11: Residential exurban	
	12: Residential suburban	
	13: Residential medium	
	14: Residential high	
	15: Commercial	
	16: Industrial and utility	
	17: Institutional	
	18: Transportation	
Crop	7: Cropland	82 Cultivated crops

population >10,000. Because the commuting zones of city spheres overlapped, we assigned locations within commuting distance of more than one urban area to the nearest urban area. These methods resulted in 88 city spheres across the study area. We quantified change in NVC within city spheres during 2001–2011 in terms of areal extent, percent change, and areal extent per capita. The latter was provided as a simple measure of the extent of NVC lost during the period for each resident present in 2011. Finally, we identified the characteristics of city spheres with high loss rates using the regression methods described in the next section.

Probability of future loss

To evaluate the risk of loss of NVC in 2011, we developed regression models for loss to development and loss to cropland during 2001–2011. We included as potential correlates in the model access to urban markets, transportation infrastructure, demographic and socio-economic characteristics of communities, natural resources, natural amenities, and climate, consistent with previous studies (Carrion-Flores and Irwin 2004, Gude et al. 2006, York et al. 2011, Auch et al. 2012).

Land use decisions are known to be influenced by drivers at multiple spatial scales, including fine-scale characteristics of a given parcel such as vegetation type or proximity to a highway, and community-scale characteristics such as average levels of income and education or community size (Carrión-Flores and Irwin 2004). Thus, we developed potential correlates at resolutions approximating 30-m land use cells (termed pixels) and at the resolution of city spheres.

In order to reduce data dimension and facilitate interpretation, we created indices of remoteness, community type, and climate using factor analysis (Table 2). Natural amenities did not demonstrate sufficient spatial covariation to generate a single meaningful index capturing high vs. low amenity places, so we included these variables individually in the models. Our index of community type captures the distinction between "Old

Table 2. Indices used predictors in analyses of natural cover loss.

Hypothesized drivers	Conceptual basis	Input variables†	Resolution
Market remoteness index	Von Thünen (1826)	IHS (Distance to Highway) IHS (Distance to Interstate) IHS (Distance to Rail) IHS (Distance to Pop. > 50k) IHS (Distance to Pop. > 2.5k) IHS (Distance to Pop. > 250k) IHS (Distance to Airport)	30 m
New west index	Winkler et al. (2007)	Bachelor's degree or higher Moved from a different state Housing over $200K Employment in extractive industry Employment in FIRE (e.g., finance) industry Employment in tourism industry Housing units in seasonal use	County
Climate index	Egan and Mullin (2016)	Average July high temperature Average January low temperature Average annual precipitation	90 m
Prior development	Imhoff et al. (1997)	1992 intensity of nighttime lights (DMSP-OLS) in four classes Urban - >3000 Suburban - DMSP-OLS = 300–3000 Suburban fringe - DMSP-OLS <300 and <20 km from suburban Rural - DMSP-OLS <300 and >20 km from suburban	30 m

† Variables denoted IHS(x) use the Inverse Hyperbolic Sine transformation of the original variable to account for non-linearity in the effect of distance. The effect is similar to a log transformation.

West" communities, with stable populations and economies based on resource extraction, and "New West" communities, with amenity-seeking migrants and economies based on tourism and financial services or technology (Power and Barrett 2001, Winkler et al. 2007). The pixel-level and city-sphere explanatory variables and indices used to model conversion to developed and croplands are described in Table 3.

We used a stratified random sample of 30-m pixels to estimate the correlates with NVC loss, in order to avoid computational limitations and reduce spatial autocorrelation. The stratification process was implemented with the goals of (1) achieving sufficient variation in explanatory variables and (2) ensuring a sufficient number of observations transitioned from NVC to develop between 2001 and 2011 through oversampling where conversion was likely to occur. We used pixels from the Global Grid, measuring approximately 1 km^2, for the first stage of the sampling method (Theobald 2016). Global Grid pixels were stratified based on county-scale climate, urban/rural designation and demographic characteristics, and pixel-scale prior development density based on 1990 nightlight intensity as measured by the Defense Meteorological Satellite Program-Operational Line Scanner (DMSP-OLS), and an index of natural amenities (Table 4). We selected 100 of the Global Grid pixels from each of the 96 strata unless fewer than 100 were available in which case all were selected. We then randomly sampled 5 30-m cells from each of the selected Global Grid pixels, drawing only from points that were classified as NVC in 2001, for a total sample size of 10,412 cells. We excluded land where data suggested that development was prohibited by law or policy from the sampling frame. This included conservation easements as mapped in the Protected Areas Database, industrial timberlands, and in Oregon the zoning classes of Public/Open Space/Conservation Exclusive Farm Use. Other states do not have statewide zoning and planning and all private land use types other than mentioned above were included in the modeling. We estimated all regression models using survey weights to account for the sampling procedure.

Each sample pixel was associated with the nearest city-sphere, and predictor information was extracted for each sample at the pixel and city-sphere scales. To provide realistic measures of accessibility to urban areas, infrastructure, and natural amenities in the rural, mountainous landscapes that characterize our study area, we used cost distance calculated as travel time measured in minutes, rather than Euclidean distances. This travel time is calculated as a function of the location of roads, highways, and interstates, speed limits on those roads, and the terrain of the path between two points of interest. All cost distance variables were transformed using the Inverse Hyperbolic Sine transformation in order to reduce skewness. This transformation creates a non-linear relationship between the dependent and independent variables, which can be interpreted in a similar manner to a log transformation.

Table 3. Descriptions and data sources of the pixel and city-scale explanatory variables included in the analysis.

Variable	Description	Data source
Pixel scale		
Distance to public land and by type	Travel time along roads to nearest US Fish and Wildlife Service, National Park Service, Bureau of Land Management, US Forest Service, or State Land (minutes)	1
Distance to ski area	Travel time to nearest ski area (minutes)	2
Forest pattern	Moving average of the standard deviation of forest/non-forest variation; high values are associated with a mixed forest/non-forest landscape and low values with a uniformly forested or non-forested landscape	3
Topographic complexity	Moving average of the standard deviation of elevation; high values are associated with a topographically complex landscape and low values with a uniformly flat or steep landscape	4
Distance to large river	Travel time to nearest River >8 m wide (minutes)	5
Distance to Waterbody >1 km^2	Travel time to nearest waterbody >1 km^2 in area (minutes)	5
Distance to census place	Travel time to nearest census place with population >10,000 (minutes)	6
Distance to highway	Travel time to nearest highway (minutes)	6
Distance to interstate	Travel time to nearest interstate (minutes)	6
Distance to airport	Travel time to nearest national airport (minutes)	6
Distance to rail	Travel time to nearest railway terminal (minutes)	6
Suburban development	Prior development density, based on 1992 intensity of nighttime lights (DMSP-OLS): Binary variable = 1 if DMSP-OLS = 300–3000	7
Suburban fringe development	Prior development density, based on 1992 intensity of nighttime lights (DMSP-OLS): Binary variable = 1 if DMSP-OLS <300 and <20 km from Suburban development	7
Climate index	Climate index calculated using factor analysis of temperature and precipitation variables; Negative values are associated with drier, more extreme climates, and positive values with wetter, milder climates	8
Soil productivity index†	Index of soil productivity based on family-level soil taxonomy information; high values are associated with more productive soils and low values with less productive soils	9
Slope†	Landform slope (degrees)	4
Elevation†	Elevation above sea level (m)	
City-sphere scale		
Market remoteness index	Remoteness index calculated using factor analysis of travel time to urban centers and transportation infrastructure; positive values are associated with remote places and negative values with accessible places	10, 11
New west index	Socio-demographic index calculated using factor analysis of demographic and socio-economic variables selected following Winkler et al. (2007); positive values are associated with New West characteristics and negative values with Old West characteristics	12
Climate index	Climate index calculated using factor analysis of temperature and precipitation variables; Negative values are associated with drier, more extreme climates and positive values with wetter, milder climates	13
% developed in 2000	Proportion of private land in a developed land use in 2000	7
Distance to public land and by type	Travel time to nearest US Fish and Wildlife Service, National Park Service, Bureau of Land Management, US Forest Service, or State Land (minutes)	14
Percent public land	Percent of the area of the city sphere in public land.	14
Percent in waterbody	Percent of the area of the city sphere covered by waterbodies.	5
Distance to large river	Travel time to nearest River >8 meters wide (minutes)	5

(Table 3. Continued.)

Variable	Description	Data source
Topographic complexity	Moving average of the standard deviation of elevation; high values are associated with a topographically complex landscape and low values with a uniformly flat or steep landscape	4
Distance to ski area	Travel time to nearest ski area (minutes)	15

Notes on Data Sources
1. USGS Protected Areas Database v1.4.
2. NOAA National Operational Hydrologic Remote Sensing Center (2007).
3. USGS National Land cover Data.
4. USGS NED.
5. National Hydrography Dataset (US Geological Survey 2017).
6. TIGER Shapefiles: Roads (US Census Bureau 2010*b*).
7. This study.
8. Representative Concentration Pathways (RCP) Database 8.5 (Riahi et al. 2007)
9. Schaetzl et al. (2012).
10. TIGER Shapefiles: Places (US Census Bureau 2010*b*).
11. National Transportation Atlas Database (Bureau of Transportation Statistics 2016).
12. US Census Bureau (1990, 2010*a*).
13. Representative Concentration Pathways (RCP) Database 8.5 (Riahi et al. 2007).
14. USGS Protected Areas Database v1.4.
15. National Weather Service: NOAA (2007).
† Used in modeling conversion to agriculture.

Table 4. Stratification scheme for selecting pixels for modeling NVC loss.

Spatial scale	Criterion	Category	Sample size
County	Climate: thresholds based on terciles of climate index	Mild	23,117
		Moderate	41,983
		Harsh	58,602
County	Rural/Urban: US Census Bureau designation	Rural	64,429
		Urban	59,273
County	New West / Old West: threshold based on median of New West index	New West	56,506
		Old West	67,196
Pixel	Natural Amenity Index: threshold based on median value of NA index	High NAs	53,843
		Low NAs	69,859
Pixel	Nightlight Density: thresholds based on Imhoff et al. (1997)	Rural	29,539
		Rural transitional	42,326
		Transitional	51,837

We used probit models to estimate the probability of a given pixel being converted from NVC to developed land or from NVC to cropland during the period 2001–2011. This probability was estimated as a function of location and predictor variables at the pixel and city-sphere scales. The predictor variables were not scaled to have the same range. The non-linear transformation used for the probit model means that the magnitude of the effect of each predictor variable depends on the values taken by all other predictors. To simplify the presentation of the results, the coefficients presented in the Results are the average effects of a one-unit change in a predictor variable. We include those coefficients to highlight which variables are significantly associated with wildland loss. The probit model constrains the estimated probabilities to values between 0 and 1 by using the normal distribution (Φ) as a link function in the non-linear regression model, as shown in equation X:

$$P(y=1|x)=\Phi\big(\beta_0 + \sum\beta_s \text{Plot attributes}_{sp} + \sum\beta_t \text{City attributes}_{tc}\big)$$

where y is the observed binary response variable and takes values of 1 if a NVC pixel in 2001 was converted by 2011 and 0 if it remained in NVC; x

is the set of predictor variables at the pixel (p) or city (c) scale; and β_s and β_t are coefficients on the relationship between likelihood of conversion and pixel and city attributes, respectively.

We estimated models with survey weights to account for the stratification of the sample, and with clustered standard errors to account for spatial correlation in the unobserved determinants of NVC conversion among points that fall within the same Global Grid cell. Each of these models was estimated with state fixed effects in order to control for differences between states in land use regulations and other policies. The selection of variables for inclusion in the final models and the amount of variation explained were both evaluated using the McKelvey and Zavoina (1975) pseudo R^2.

We used the best models of NVC loss to development and to cropland to predict probability of risk of loss of NVC under 2011 conditions. This was done under the assumption that correlations between predictors and the response variable would continue in the post-2011 period. This assumption was necessary because the actual drivers and mechanisms of land use change are likely complex, context-dependent, and vary among land owners and locations (Brown et al. 2000). Our approach is consistent with the common practice of modeling land use change using state and transition models parameterized in one period and applied to a future period (Lambin 1997, Brown et al. 2000). The results were used to map the distributions of probability of loss of NVC, based on the highest probability of loss to developed or croplands.

Results

Location of remaining NVC

NVC covered 372,546 km^2 or 66% of the private lands across the study area in 2011 (Table 5, Fig. 2). The area of NVC relative to the area of the ecoregion was relatively high in the Wyoming Basin, Blue Mountains, Upper Colombia, Colorado Mountains, High Divide, Greater Yellowstone. Area of NVC was proportionally underrepresented in the Western Washington, Western Oregon, Palouse Prairie, Snake River Plain, and Oregon Cascades. In some parts of the study area, NVC on private lands had similar areal extent to that on public lands and/or was adjacent to that on public lands, suggesting potential contribution to structural connectivity.

Developed lands and croplands covered 16.6% and 16.5% of the private lands across the study area, respectively. High proportions of developed lands were in Western Washington (71%) and Western Oregon (56%). The Palouse Prairie and

Table 5. Areal distribution of NVC among private lands among SE regions in 2011 and proportion of private lands in NVC, developed lands, and croplands in 2011.

SE region	Area (km^2)	2011 area in NVC (km^2)	Region % NVC/ Study area % NVC	NVC (%)	Developed (%)	Crop (%)
Study area	372546	246560	1.00	66.18	16.63	16.54
Blue Mountains	29709	26145	1.33	88.00	6.01	5.75
Colorado Mountains	44163	36572	1.25	82.81	14.40	2.41
Greater Yellowstone	14362	11434	1.20	79.61	11.49	8.39
High Divide	27586	23471	1.29	85.09	8.12	6.56
Kootenai Spokane	26788	18397	1.04	68.67	23.81	6.85
Oregon Cascades	8613	5343	0.94	62.03	24.79	9.41
Palouse Prairie	59405	23815	0.61	40.09	7.44	52.24
Selway–Bitterroot	12178	9285	1.15	76.24	11.87	11.51
Snake River Plain	44334	22021	0.75	49.67	11.75	37.74
Uinta Wasatch	14890	11184	1.13	75.12	19.02	5.20
Upper Colombia	4182	3534	1.28	84.50	12.08	3.07
Washington Cascades	5034	3308	0.99	65.71	25.80	7.78
Western Oregon	22439	8003	0.54	35.67	56.27	6.88
Western Washington	15433	3908	0.38	25.32	71.24	1.35
Wyoming Basin	43430	40140	1.40	92.42	4.75	2.28

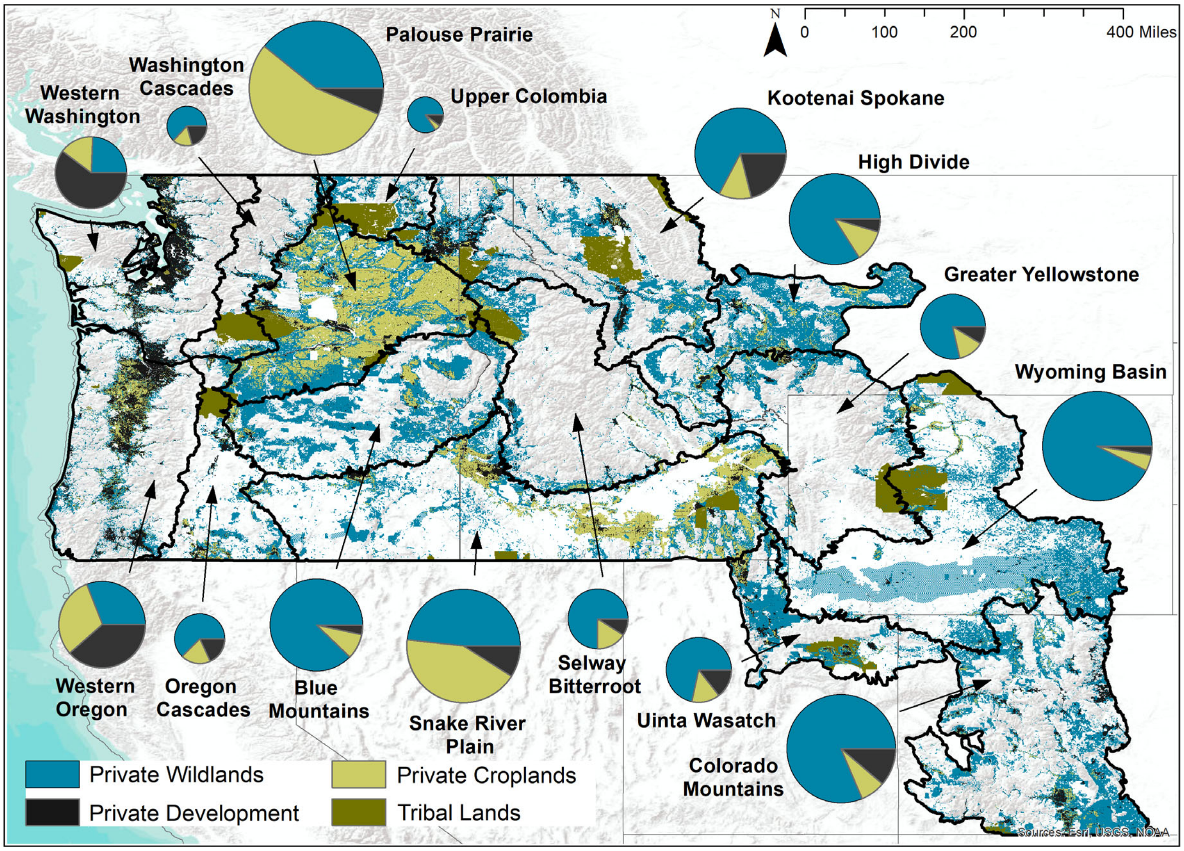

Fig. 2. Spatial patterns of NVC (denoted "Wildlands" in the legend), developed lands, and croplands on private lands in 2011 and proportional coverage of each of these land types within SE regions.

Snake River Plain SE regions had relatively high proportions in crops (52% and 38%, respectively) (Fig. 2).

Loss of NVC 2001–2011

Across the study area, 6350 km^2 or 2.5% of NVC on private lands were converted to development and croplands during 2001–2011 (Table 6). The largest area of NVC lost between 2001–2011 was in the Kootenai Spokane (1188 km^2) and Colorado Mountains (924 km^2) SE regions (Table 6) Fig. 3). Rates of NVC loss to development and crops during 2001–2011 were particularly high in the Western Washington (−12%), Western Oregon (−6%), Washington Cascades (−6%), and Kootenai Spokane (−6%) SE regions. Proportional increase in developed lands was relatively high in the Upper Columbia (25%), Kootenai Spokane (19%), Greater Yellowstone (17%), Washington Cascades (16%), and Colorado Mountains (13%) SE Regions. Area in crops increased especially in the High Divide (16%), Selway–Bitterroot (10%), and Upper Columbia (7%) SE Regions.

Examples of local areas with high loss of NVC are depicted in Fig. 4. In the Bend, OR, region, natural vegetation remains between the cities of Bend, Redmond, and Prineville but has also undergone high rates of loss during 2001–2011. In the Spokane, WA region, natural cover fringes urban areas and conversion of natural vegetation to development during 2001–2011 was largely on the edges of existing development. Near Bozeman, MT, NVC dominates the high plains and forests outside of cities but has undergone substantial loss near the expanding ski resort town of Big Sky and in the rural Paradise Valley along the banks of the Yellowstone River. Low-density residential development is extensive in this area as illustrated in the area east of Bozeman, MT, in

Table 6. Area and proportion of NVC lost to development and crops 2001–2011.

SE region	Area of NVC lost 2001–2011 (km^2)	NVC % change 2001–2011	% of NVC lost to development 2001–2011	% of NVC lost to crop 2001–2011
Study area	6350	−2.51	2.06	0.59
Blue Mountains	190	−0.72	0.51	0.25
Colorado Mountains	924	−2.47	2.27	0.24
Greater Yellowstone	343	−2.92	2.40	0.59
High Divide	430	−1.80	0.69	1.20
Kootenai Spokane	1188	−6.06	5.97	0.14
Oregon Cascades	192	−3.46	3.08	0.59
Palouse Prairie	442	−1.82	0.89	1.41
Selway–Bitterroot	291	−3.04	1.58	1.52
Snake River Plain	425	−1.89	0.71	1.44
Uinta Wasatch	323	−2.80	2.61	0.25
Upper Columbia	136	−3.69	3.48	0.29
Washington Cascades	211	−6.00	5.59	0.61
Western Oregon	553	−6.46	6.92	0.01
Western Washington	546	−12.26	12.64	0.01
Wyoming Basin	157	−0.39	0.30	0.13

the forested area that lays between the Greater Yellowstone and Crown of the Continent ecosystems (Fig. 5).

City spheres differed considerably in area and in proportion developed, thus area remaining in NVC and proportion of area in NVC also differed substantially (Table 7, Fig. 6). The largest area of loss of NVC was in larger cities such as Spokane and Seattle, WA, along with mid-sized cities such as Bozeman, MT. The average loss of NVC during 2001–2011 per resident in 2011 was 0.02 ha/person. The per capita loss was relatively high (>0.20 ha/person) in mid-sized and small cities such as Prineville, OR, Mountain Home, ID, Anaconda-Deer Lodge, MT, Kalispell, MT, and Ellensburg, WA. In contrast, mainly larger cities had very low NVC conversion rates per capita (<0.01) such as Seattle, WA, Colorado Springs CO, and Denver-Aurora, CO.

Locations and settings most at risk of NVC loss

Settings associated with NVC loss to development were near highways, suburban areas (based on their night light brightness), state land, water bodies >1 km^2, and mixed forest/non-forest vegetation (Table 8). Loss was also higher on average around city spheres with New West demographics. The best model explained 56% of the variation. Probability of wildland conversion to cropland was associated with higher soil productivity, flatter slopes, proximity to highways, interstates, and suburban development. It was also associated with city spheres that were remote from markets, tended toward New West demographics, had drier climates, and had higher proportions of land developed in 2001. The best-fit model accounted for 61% of the variation in the probability of conversion. City spheres with high per capita consumption rates of NVC during 2001–2011 were more remote from markets, had New West demographics, were more developed in 2001, were closer to national parks, and had complex topography.

Using these models to project risk of NVC loss under 2011 conditions revealed that the majority of the area with moderate to high risk of loss were in the Spokane, WA, and Coeur d' Arlene, ID, area, in the Colorado Mountains, and in Western Oregon and Washington (Fig. 7). The SE regions with the highest proportions of remaining NVC in the moderate to high risk of loss categories in 2011 were Western Washington, Western Oregon, Upper Columbia, and Colorado Mountains (Table 9, Fig. 8).

Discussion

The importance of private lands to conservation is widely recognized (Knight and Cowling 2007, Kamal et al. 2015). While protected areas

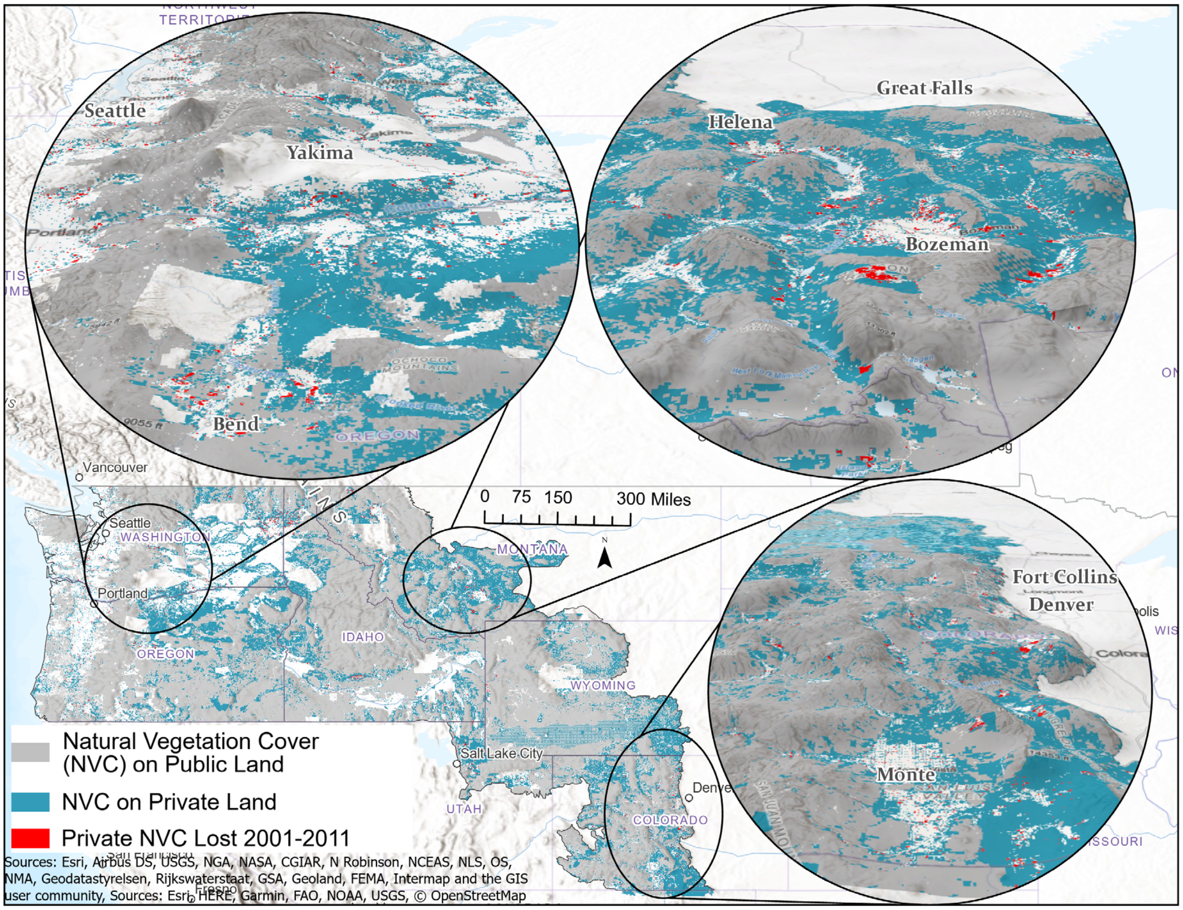

Fig. 3. Examples of locations where NVC on private lands is extensive relative to that on public lands: Palouse Prairie and Blue Mountains SE regions in eastern Washington and Oregon Upper (upper left insert); High Divide SE region lying between the Greater Yellowstone and Crown of the Continent ecosystems (Upper right insert); and Colorado Mountains SE region (lower right insert).

represent the cornerstone of the global conservation effort, many studies have shown that protected areas are insufficient for meeting biodiversity objectives because of their limited spatial coverage (currently about 15% of the land area, Dinerstein et al. 2020) and lack of representativeness of species and ecosystems (Aycrigg et al. 2013, Jenkins et al. 2015), and isolation (Saura et al. 2018). Thus, the Post-2020 Global Biodiversity Framework (CBD 2020) is calling for goals and targets to expand protected area coverage to 30% of land and sea area by 2030, increase representativeness, and improve connectivity, with recognition that private lands are essential for contributing to these endpoints. Similarly, the Half Earth (Wilson 2016) and Global Safety Net for Nature (Dinerstein et al. 2020) initiatives call for global conservation of natural habitats. Conservation on private lands can be advanced through ecological management strategies within urban, suburban, agricultural, and forestry land uses; however, maintaining natural vegetation cover is one of the most effective strategies (Balmford et al. 2002, McKinney 2002, Watson et al. 2018). Thus, there is a need to map the locations of NVC on private lands, assess rates of loss, project risk of future loss, and use this information in the context of large landscape conservation planning (e.g., Belote et al. 2017).

The aim of this study was to advance knowledge on the locations and loss rates of areas of

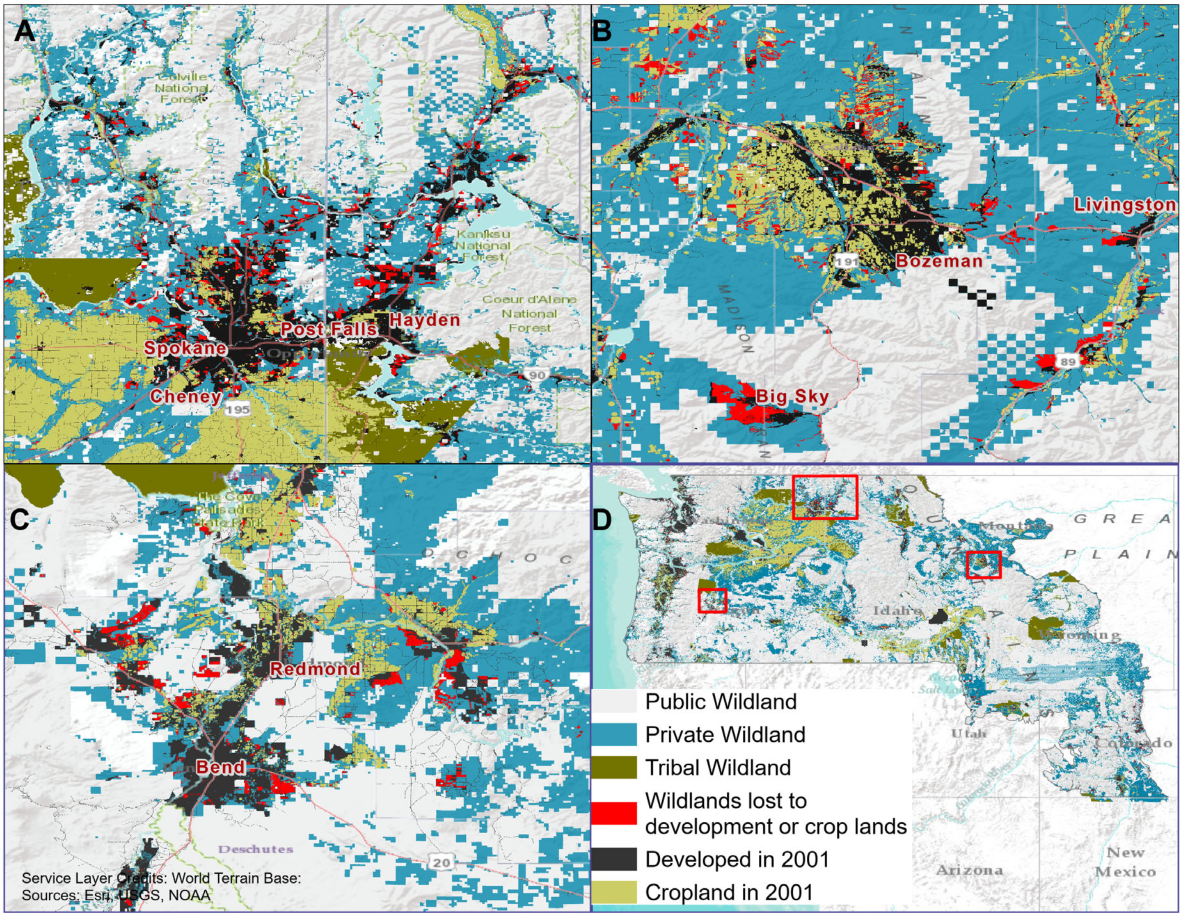

Fig. 4. Examples of local areas with high loss of NVC (denoted "Wildlands" in the legend). (A) Bend and Redmond, OR, area. (B) Spokane, WA, and Sandpoint, ID, area. (C) Bozeman, Big Sky, Paradise Valley, MT, area. (D) Location of the focal areas in the Study Area.

NVC on private lands in the northwestern continental United States and to project risk of future loss if past trends continue as a basis for conservation. The rugged landscapes of the study area were largely allocated to public lands in the late 1800s and human populations were slow to expand across the private lands. The high level of natural amenities in the region likely has contributed to the rapid population growth and land use intensification in recent decades (McGranahan 1999, Winkler et al. 2007). Decisions on where to place rural subdivisions and other intense land uses strongly impact the extent and ecological value of the remaining natural habitats (Poudyal et al. 2016). Given that many people and businesses have relocated to the region because they value natural scenery, wildlife, outdoor recreation, and wilderness, a critically important question is how these natural values can be maintained in the face of the rapidly increasing human pressures.

Locations and loss of NVC

We are aware of no previous studies mapping remaining NVC on private lands of the northwestern United States or summarizing rates of conversion to more intense land uses. However, several studies quantified land use change that is relevant to our findings.

Land cover change was assessed using NLCD for 2001–2016 for the conterminous United States (Jin et al. 2019). That study found that developed

Fig. 5. Example of an extensive area of forest that has been converted to low-density residential development just south of Bozeman Pass along Interstate 90 in Montana.

and crop classes increased in areal extent during this period and forest classes decreased, consistent with our results. However, the classes were not combined in a way to allow inference about change in NVC on private lands.

The conversion of natural forest cover to “wildland urban interface” (homes intermixed with natural forest cover) was quantified across the United States for 1990–2010 (Radeloff et al. 2018). Homes were mapped in a similar way to NLUD and this analysis is comparable to ours for loss of NVC for forested areas, but differs in not including non-forested natural vegetation cover and including public as well as private lands. The study found that the area of this type of wildland urban interface increased from 5.6% to 7.5% of the conterminous United States from 1990 to 2010, indicating a loss of area of NVC of 1.9% (0.095%/yr).

Within the Protected Area-Centered Ecosystems (national parks and surrounding public and private lands) in the NW United States, 22% of the private lands were developed by 2000 with a range from 6.2% around Craters of the Moon to 46.4% around Rocky Mountain National Park (Hansen et al. 2014). Within one of these ecosystems, the Greater Yellowstone Ecosystem, undeveloped lands (public and private) declined 33% between 1970 and 2010 and represented 31% of the ecosystem in 2016 (0.825%/yr) (Hansen and Phillips 2018).

Adhikari and Hansen (2018) used NLUD and NLCD to assess change in and around large tracts of public lands in the North Central United States during 2000–2010. They found that undeveloped lands (based on NLUD housing density) decreased 8% in area (0.8%/yr), and shifted to rural, exurban, and urban and suburban home densities. Similarly, NLCD developed land classes increased by 7.2%.

In this study, we found that the majority of private lands in the northwestern United States (66%) remained in NVC in 2011 and that 2.5% of the area of NVC in 2001 was lost to development (2%/yr) and croplands (0.6%/yr) by 2011. Rates of loss were as high as 12% in Western Washington (1.2%/yr) and also relatively high in the Upper Columbia and Spokane Kootenai, Greater Yellowstone, Uinta, Wasatch, and the Colorado Mountains SE regions. Housing development accounted for the majority of this NVC loss, increasing by 8% while croplands increased by 5%.

Table 7. Ranking of city spheres in NVC lost based on area and per capita area for the 20 highest- and 20 lowest-ranked city spheres.

Ranking based on based on area of NVC lost		Ranking based on per capita area of NVC lost	
City sphere	NVC Area lost (km^2)	City Sphere	Area lost per capita (ha/person)
Highest			
Spokane, WA—ID	431.26	Prineville, OR	0.4511
Kalispell, MT	197.27	Mountain Home, ID	0.3110
Coeur d'Alene, ID	195.65	Anaconda-Deer Lodge County, MT	0.2775
Bozeman, MT	183.04	Kalispell, MT	0.2565
Helena, MT	159.06	Helena, MT	0.2561
Portland, OR—WA	143.80	Ellensburg, WA	0.2555
Centralia, WA	124.42	Cody, WY	0.2128
Seattle, WA	116.03	Bozeman, MT	0.2107
Longview, WA—OR	113.90	City of The Dalles, OR—WA	0.1994
Missoula, MT	106.49	Centralia, WA	0.1766
Wenatchee, WA	93.68	Trinidad, CO	0.1694
Roseburg, OR	85.31	Baker City, OR	0.1680
City of The Dalles, OR—WA	82.21	Coeur d'Alene, ID	0.1605
Grants Pass, OR	78.57	Butte-Silver Bow, MT	0.1346
Moses Lake, WA	73.52	La Grande, OR	0.1324
Redmond, OR	72.98	Redmond, OR	0.1289
Ellensburg, WA	65.09	Cottage Grove, OR	0.1272
Eugene, OR	63.67	Moses Lake, WA	0.1133
Boise City, ID	61.48	Roseburg, OR	0.1126
Kennewick—Richland, WA	58.43	Longview, WA—OR	0.1100
Lowest			
Newberg, OR	13.97	Logan, UT	0.0160
Twin Falls, ID	13.59	Twin Falls, ID	0.0141
Woodburn, OR	13.50	Ferndale, WA	0.0113
Dallas, OR	13.05	Rexburg, ID	0.0100
Pendleton, OR	12.92	Nampa, ID	0.0098
Bremerton, WA	12.15	Salem, OR	0.0087
Astoria, OR	11.62	Portland, OR—WA	0.0073
Walla Walla, WA	10.92	Ogden—Layton, UT	0.0060
Colorado Springs, CO	10.49	Boulder, CO	0.0056
Blackfoot, ID	8.62	Bremerton, WA	0.0050
Evanston, WY	8.29	Provo—Orem, UT	0.0044
Rexburg, ID	5.36	Spanish Fork, UT	0.0041
Brigham City, UT	5.07	Seattle, WA	0.0037
Ferndale, WA	4.16	Pullman, WA	0.0035
Green River, WY	3.64	Lake Goodwin, WA	0.0023
Spanish Fork, UT	3.44	Colorado Springs, CO	0.0018
Pullman, WA	1.20	Salt Lake City, UT	0.0017
Albany, OR	0.69	Albany, OR	0.0010
Lake Goodwin, WA	0.66	Anacortes, WA	0.0008
Anacortes, WA	0.47	Denver—Aurora, CO	0.0007

Among the studies cited above and our results, the loss rates of undeveloped lands varied with the extent of area analyzed and proximity to cities and existing development. The range was about 0.01%/yr for public and private lands around protected areas to 1.2%/yr for Western Oregon found in this study, with an average across our entire study area of 0.25%/yr. In total, these results are strong evidence that areas of natural cover and natural habitats have been lost

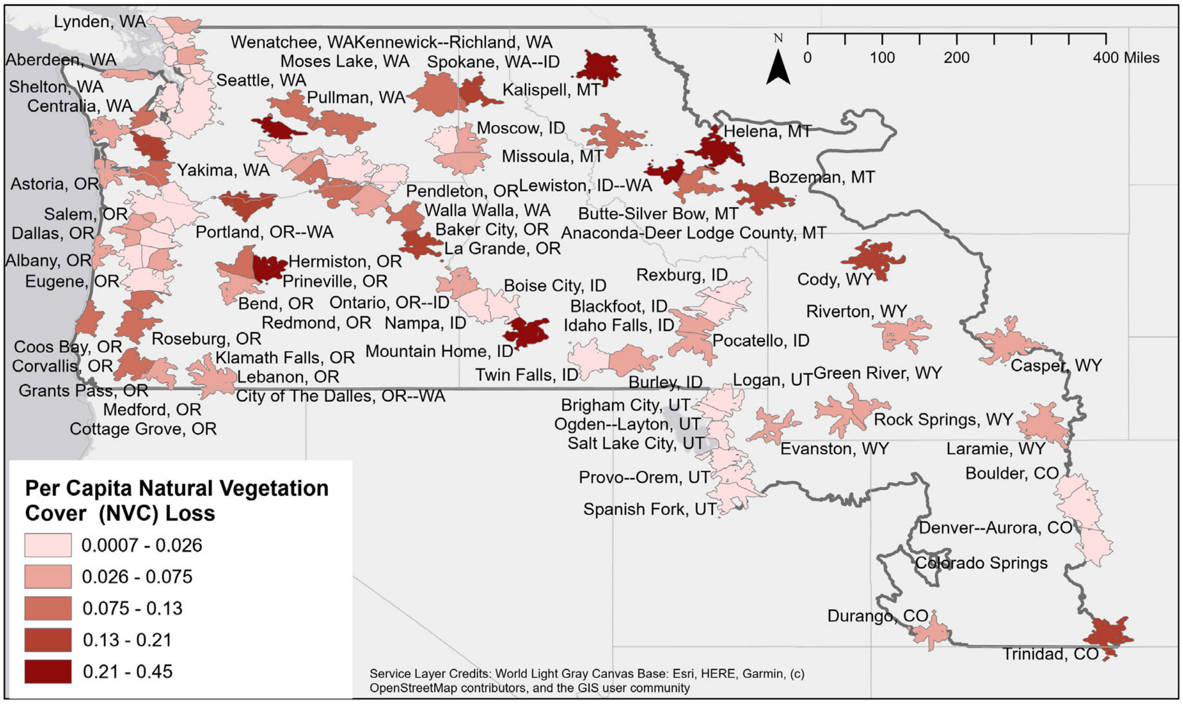

Fig. 6. Map of city spheres color-coded by per capita loss of NVC 2001–2011.

to development in recent decades at rates that are substantial over multi-decadal planning periods.

Correlates and risk of future loss

The loss of NVC was not random, but statistically associated with various demographic and biophysical factors. Positive associations were found with proximity to markets, existing development, roads, various natural amenities, and city spheres with New West demographics. While associations among these factors and land development are likely complex and context-dependent (Kim et al. 2005, Chi and Marcouiller 2013), our findings are generally consistent with those of Gude et al. (2006) in Greater Yellowstone and with Martinuzzi et al. (2015) around United States protected areas in terms of correlates with land change.

Land use changes are the product of decisions made by people, from individual land owners to local and state level government officials. Most of the loss of NVC in the study area was within or close to the commuting distance of cities. This begs the question of which city spheres are consuming NVC below or above the average rate. We found NVC consumption rates during 2001–2011 varied substantially among city spheres while the average was 0.02 $ha \cdot person^{-1} \cdot decade^{-1}$. The lowest rates of consumption were about 0.01 ha/person in Boulder, CO, Ogden-Layton, UT, Salem, OR, and Corvallis, OR. The highest rates were 20 to 40 times higher (0.20–0.44 ha/person) in Prineville, OR, Mountain Home, ID, Kalispell, MT, Bozeman, MT, and Cody, WY. This metric is influenced by the consumption of habitats during the decade of all people in the community, those that are long-term residents and those that were newcomers during the decade. We feel this is an appropriate metric because land use change is likely strongly influenced by the legacy of decades of decisions on policy and development. The city spheres with high consumption rates tended to be smaller cities more distant from large cities and markets, with New West demographics, close to national parks, and with the complex topography that increases scenic value. We do not know the extent to which rates of NVC conversion are influenced by zoning and planning regulations

Table 8. Average marginal effects from statistical analyses of conversion of NVC to development or crops 2001–2011.

	Analysis		
	Pixel level		City-sphere level
Variable	Probability of wildland converted to developed†	Probability of wildland converted to crop†	Per capita Wildland area converted
Pixel scale			
Distance to Highway	−0.195*** (0.045)	−0.207*** (0.040)	
Suburban Fringe development	−0.733*** (0.281)	0.483* (0.284)	
Suburban development	1.040*** (0.045)	0.796*** (0.284)	
Distance to State Land	−0.157*** (0.045)		
Distance to Waterbody >1 km^2	−0.157** (0.073)		
Forest pattern	0.235*** (0.035)		
Distance to census place		0.391***(0.138)	
Distance to interstate		−0.339***(0.077)	
Soil productivity index‡		0.037** (0.016)	
Slope‡		−0.077** (0.014)	
City-sphere scale			
Market remoteness index		1.189*** (0.272)	0.378** (0.157)
New west index	0.242** (0.100)	0.450** (0.185)	0.204** (0.102)
Climate index		−0.496*** (0.176)	
% developed in 2001		2.424*** (0.606)	3.865*** (0.819)
Distance to National Park			−0.375* (0.197)
Topographic complexity			−0.000** (0.000)
Constant	−0.854 (0.890)	−7.265*** (1.591)	
Observations	10412	10408	88
R^2	0.559	0.610	0.3935

Notes: Coefficients show the average effect of a one-unit change in the predictor variable on the probability of conversion. The most parsimonious models are indicated by the presence of effects for statistically significant variables. Coefficients, statistical significance level (*$P < 0.10$, **$P < 0.05$, ***$P < 0.01$), and standard errors (parentheses) are provided.

† State fixed effects were included but results not shown here.

‡ Only considered for probability of conversion to crop.

within cities, counties, or states. Analysis of the effectiveness of various regulatory and incentive-based policies may offer guidance to how communities can better sustain NVC. To the extent that communities with high rates of NVC loss are attracting relatively affluent, well-educated new residents that value natural amenities, these communities may have the resources and motivation to better sustain natural habitats.

Assuming that the correlates of loss during 2001–2011 are adequate predictors of future loss, we projected risk of NVC loss under 2011 conditions. We found that 5.3% of remaining NVC had moderate to high probability of development (>0.20%). Larger contiguous areas of moderate and high probability of development were projected for the lowlands west of the Cascades, the foothills east of the Cascades, northeastern Washington and Northern Idaho, the Upper Missouri Basin in Montana, the Wasatch Front in Utah, and the vicinity of Laramie, WY. Smaller areas with moderate to high probability of development were largely adjacent to previous development across the study area.

We suggest that the 2011 risk map should be used in conservation prioritization analyses as a relatively coarse indication of predicted pressures on NVC. These predicted pressures are based on attributes of the local area and of the closest city sphere. They do not, however, take into account legal or policy restrictions on development or attributes of land owners. Land trusts or others seeking to prioritize parcels for conservation could use our risk map as a first filter and then overlay more detailed local information on parcel boundaries, ownership, land use restrictions, and other factors to identify NVC parcels of high risk of development.

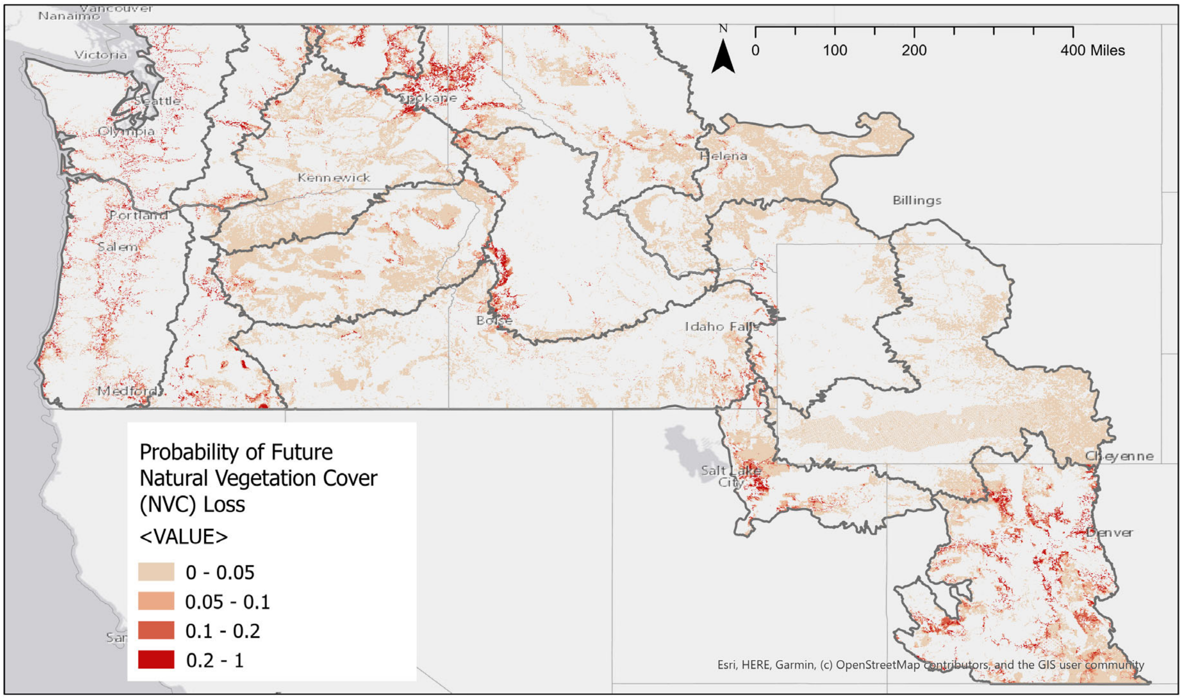

Fig. 7. Modeled probability of conversion of private NVC to development based on 2011 conditions.

Table 9. Proportion of NVC in ecoregions in each class of probability of development.

	Percentile classes and thresholds of probability of conversion to develop			
Socioecological region	<0.05	0.05 to <0.1	0.1 to <0.2	0.2 to 1.0
Study area	77.49	10.04	7.2	5.27
Blue Mountains	89.22	7.61	2.56	0.61
Colorado Mountains	52.61	21.1	16.79	9.51
Greater Yellowstone	90.98	5.2	2.68	1.14
High Divide	97.5	1.76	0.62	0.12
Kootenai Spokane	65.32	13.41	10.96	10.31
Oregon Cascades	53.96	17.98	13.76	14.3
Palouse Prairie	90.68	4.99	2.73	1.6
Selway–Bitterroot	64.4	15.11	12.14	8.35
Snake River Plain	87.64	8.27	3.1	1
Uinta Wasatch	65.75	17.01	10.56	6.68
Upper Columbia	39.01	25.4	20.78	14.82
Washington Cascades	46.32	26.46	16.95	10.28
Western Oregon	33.05	21.28	24.01	21.67
Western Washington	19.75	14.11	21.94	44.2
Wyoming Basin	98.23	1.23	0.45	0.09

In sum, our study advances current knowledge by mapping for the first time locations of NVC remaining on private land in the study area and finding that NVC is extensive in some SE regions and likely serves to supplement and to connect NVC on public and tribal lands. These lands represent an invaluable, at risk, but often underappreciated asset with regards to sustaining biodiversity and ecosystem services. Resulting largely by default of not having been developed and largely being unmapped, these natural vegetation areas are generally not included in regional or national conservation plans (but see Belote et al. 2017). The key implication of our finding is that the opportunity exists to develop a regional conservation strategy that local officials could use as one consideration for approving future development or for conserving habitats through open space initiatives or conservation easements. Some SE regions such as Western Oregon and Western Washington have relatively low levels of NVC and conservation of these habitats may be considered an especially high priority. By considering both the ecological value of these areas of NVC and risk of loss, systematic conservation planning (Margules and Pressey 2000, Visconti et al. 2010) could be used to develop strategies for public, tribal, and private lands for achieving conservation and biodiversity goals across large landscapes. It is at the spatial scale of the large

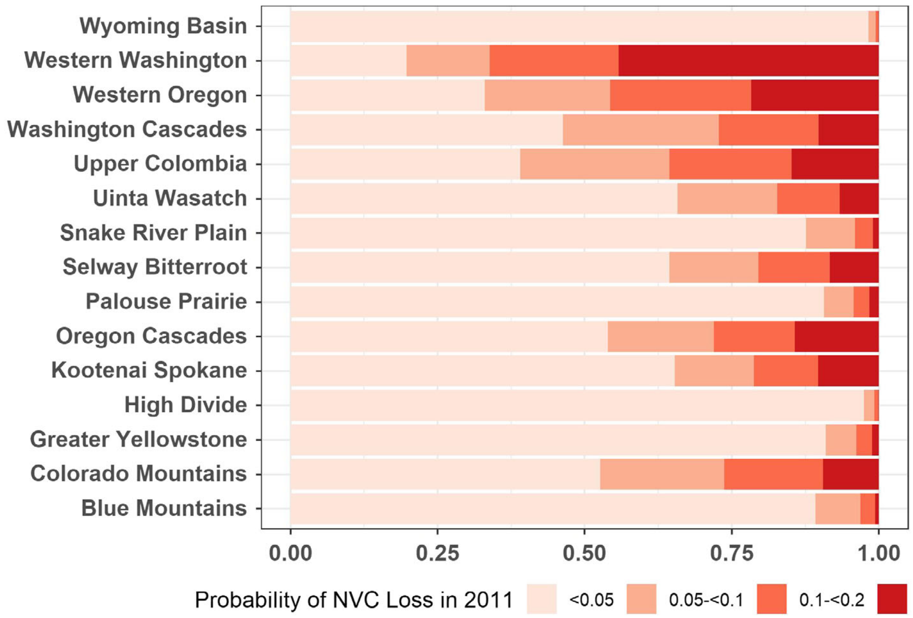

Fig. 8. Classes of probability of risk of loss to development and/or crops under 2011 conditions.

landscape surrounding protected areas to continental extents that conservation needs to be executed to sustain species and ecological systems under land use and climate change (Hansen et al. 2014, Belote et al. 2017, Dinerstein et al. 2020).

While we have focused in this paper on the ecological benefits of conserving the remaining NVC on private lands, there are additional important social and economic benefits. First, development in areas of remaining NVC often is at high risk of wildfire and consequential loss of property and lives (Radeloff et al. 2018). Human losses in the wildland urban interface in the study area have been increasing substantially in recent years and have motivated substantial discussion on policy to avoid future development in areas of remaining NVC (McWethy et al. 2019). At the same time, fires in the western United States have become more extreme under recent climate warming and this trend is projected to intensify (Williams et al. 2019). Thus, future development in the wildland urban interface is likely to be increasingly vulnerable to wildfire. Second, the costs to government of developing NVC are typically high. The tax revenues generated from rural homeowners are typically less than the cost to local governments of providing services (Coupal et al. 2002). Additionally, the cost of fire suppression to protect homes in these areas can be significant and is generally borne by local, state, and federal government (Gude et al. 2013). A third benefit to conserving NVC is the contribution to carbon storage. By sequestering carbon in vegetation biomass, NVC reduces atmospheric CO_2 that is causing climate warming (Buotte et al. 2020). Finally, policies to conserve NVC are best enacted now because the pressure to develop these areas is projected to accelerate as urban dwellers relocate to rural settings in response to the COVID-19 virus pandemic (https://www.redfin.com/blog/urban-vs-rural-homebuyer-interest-coronavirus/?mod=article_inline) and climate change (Fan et al. 2018). Thus, society has strong ecological, economic, and social motivations to conserve the remaining areas of NVC on private lands.

Scope and limitations

The results of this paper should be interpreted within the context of various assumptions and limitations.

1. Importantly, our analysis was only for the period 2001–2011. Thus, our maps do not reflect the current level of wildland loss. NLCD has been updated to 2016 (Jin et al.

2019) and NLUD is currently being updated based on the 2020 census. Completion of these updates would allow for an analysis like this one through 2016.
2. An assumption of the approach is that the fine-scale mapping of land use, especially low-density residential development, is reasonably accurate. This was found to be the case: The residential class of the NLUD had an accuracy of 74% against an independent reference dataset (Theobald 2014).
3. We did not consider resource extraction in assessment of NVC loss. Logging, mining, and outdoor recreation are known to alter the ecological characteristics of natural habitats. Unfortunately, spatially complete maps of these land uses are not available and could not be considered in the analyses.
4. Projected development in 2011 was based on the assumption that the correlates with NVC loss in the previous decade are adequate predictors of development risk in 2011. While it is reasonable that correlates such as proximity to markets, roads, and previous development are causal factors for land use change, this has not been demonstrated through scientific analysis. Even if the correlated predictors are causal, conditions could change at any time in ways that would lead to different land use outcomes. Nonetheless, using transition probabilities in one period to predict change in the next period is widely used in land use studies (Lambin 1997, Brown et al. 2000) and is likely the best available approach given current knowledge.
5. The metric of NVC consumption we focused on (area lost 2001–2011 per resident in 2011) is influenced both by population size in 2001, population growth rates 2001–2011 and land consumption during that decade. We feel this is an appropriate metric because all of these factors are likely influenced by the long-term policies and decisions of community members.

Implications and conclusions

The major implication of this work is that substantial portions of the private lands in the study area remain in natural vegetation cover, yet these areas are being lost to development. The pace of this loss may accelerate as the region continues to transition from a low-population Old West social system to a rapidly growing New West system, particularly in the COVID-19 era. The values derived from NVC will likely continue to be eroded to the detriment of ecological integrity and the human communities that are thriving partially due to the high quality of remaining natural habitats and the associated natural amenities. Thus, there is a need to prioritize the remaining areas of NVC in the region based on risk of future loss and ecological value and communicate the results to land use stakeholders in the region. The results of this study provide information on which areas of NVC are most at risk and the types of communities that have the greatest potential to either destroy or sustain remaining NVC. The highest rates of NVC loss are associated with communities that are relatively well-educated, affluent, and attracted to areas with high natural amenities. Such communities, perhaps, have the greatest capacity to conserve the remaining private NVC.

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