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Trends in vital signs for Greater Yellowstone: application of a Wildland Health Index

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Abstract. The Earth's remaining tracts of wildlands are being altered by increased human pressure and climate change. Yet, there is no systematic approach for quantifying change in the ecological condition of wildland ecosystems. This paper applies a Wildland Health Index (WHI) to evaluate trends in ecological vital signs in the Greater Yellowstone Ecosystem (GYE). Components of the WHI include criteria for judging ecosystem health, vital signs consistent with these criteria, monitoring at spatial scales relevant to the ecosystem, evaluating trends in condition, and communicating with decision makers. The GYE, while large, intact, and with substantial management capacity, is undergoing increasing human pressure and climate change. Thus, assessment of trends in ecological health is needed to prioritize management. We synthesized current knowledge to evaluate trends in stressors and vital signs of ecosystem function, composition, and structure for 1970 to present and forecasted to 2100. Results were summarized in a WHI Scorecard to illustrate trends in the higher level vital signs of interest to policy makers. We found that human population has doubled, and housing density has tripled in the GYE since 1970 and both are projected to double again by 2050. Human development is now estimated to cover 31% of the GYE. Temperature has warmed 0.8°C since 1950 and is projected to increase 2.5–5.3°C by 2100. These changes in land use and climate have reduced snowpack and stream flows, increased stream temperatures, favored pest outbreaks and forest die-off, fragmented habitat types, expanded invasive species, and reduced native fish populations. Large mammal populations, in contrast, have been increasing in numbers and expanding in range. These trends differ among land allocation types. The WHI Scorecard rated 6 of 9 vital signs as relatively stable or improving in national parks and designated wilderness. On private lands, in contrast, five vital signs were rated as deteriorating. Confidence in our evaluation is not high because of lack of monitoring across the full GYE. While the National Park Service has a rigorous monitoring program, fewer vital signs are tracked on other federal lands and still fewer on private lands. Thus, trends in ecological condition are not evaluated across the entire GYE nor widely reported in the media. We recommend that the WHI approach be systematically applied across the GYE and other large wildland ecosystems in the United States to better inform management to sustain these wildlands.

Key words: climate change; ecological vital signs; Greater Yellowstone Ecosystem; human development; private lands; Wildland Health Index.

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INTRODUCTION

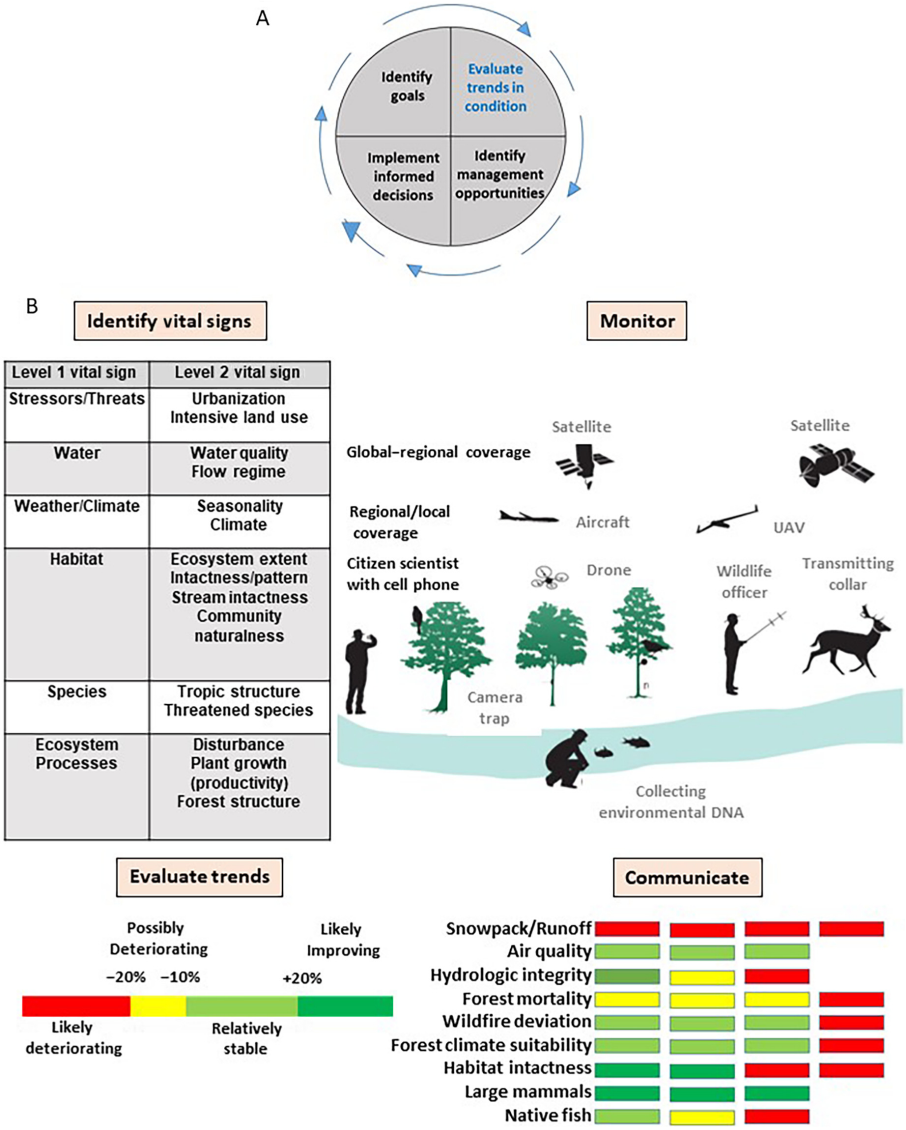
Large tracts of nature that are relatively free from the influences of people are being increasingly valued for their biodiversity and ecosystem services. Accordingly, parties to the Convention on Biodiversity (CBD 2010) mandated expansion of the global protected area coverage to better sustain species and ecosystems. Despite this policy favoring protected areas, net loss of wildlands continues (Watson et al. 2016). In this period of increasing human pressure and climate change, the need to track changes in ecosystem condition is widely recognized (Rockstrom et al. 2009, Radeloff et al. 2015, Scheffer et al. 2015, Jackson et al. 2016). In the case of wildlands, however, there is no systematic approach for quantifying whether and how essential ecological conditions are being maintained, degraded, or destroyed by human pressure and climate change. Herein, we use a Wildland Health Index (WHI) to evaluate trends in ecological vital signs in the Greater Yellowstone Ecosystem (GYE), one of the best-known large wildland landscapes.

Wildlands were defined as the habitats in which biodiversity, abiotic components, and ecosystem functioning are sufficiently intact that the majority of ecosystem services typically derived from such a habitat are still being sustainably and reliably supplied (Balmford et al. 2002). Wildlands are not necessarily devoid of people, but are rather locations where levels of human influence are low relative to other types of land use. These wildlands not only provide essential habitat for species sensitive to human activities, but also supply natural resources and ecosystem services to people, places of solitude and spiritual renewal for visitors, and benchmarks for comparison with more highly managed landscapes (Watson et al. 2018). Efforts to estimate trends in wildland extent have quantified change in human pressure. The human footprint increased by 9% globally during 1993–2009 (Venter et al. 2016). While 2.5 million km^2 of land was newly protected during this period, 3.3 million km^2 of relatively intact land (i.e., land with low human footprint) was lost (Watson et al. 2016). This loss represented 9.6% of the global wildlands. Even within designated protected areas, wildlands are being reduced due to downgrading, downsizing, and degazettement (Mascia and Pailler 2011). Currently, 33% of the global protected area coverage is under intense human pressure (Jones et al. 2018).

While quantification of human pressure is a tractable approach for estimating wildland extent at the global scale, it is too coarse to inform trends in the health of regional ecosystems, and it is at the regional scale that management actions are implemented. Methods are increasingly available to quantify the impacts of human activities on ecosystem structure, function, and composition (Ellis 2011) and to monitor the ecological condition of large wildland landscapes (Willis 2015). However, there are two current challenges to quantifying these impacts: first, identifying the attributes of wildland ecosystems that are highly valued and therefore high priorities for monitoring (Fancy et al. 2009) and second, evaluating the types and magnitudes of change in these attributes that denote improving or declining health. Without this evaluation, the maintenance or loss of wildland ecosystems and the services they provide is unknown (Hobbs et al. 2010).

The WHI is an approach for evaluating trends in the ecological condition of large wildland ecosystems. The concept for WHI was derived at the workshop entitled, "Sustaining Wildland Ecosystems through Monitoring and Communication to Stakeholders" sponsored by the NASA Ecological Forecasting Program in February 2016 (Hansen et al. 2016*a*). It was developed as a scientific monitoring and assessment step within a general conservation planning cycle (see Glick et al. 2011, Groves and Game 2016, Fig. 1A). The key components of the WHI include establishing criteria for judging ecosystem health, identifying vital signs consistent with these criteria, monitoring vital signs at spatial scales relevant to the ecosystem, analyzing current trends and future projections to evaluate trends, and communicating the conclusions to decision makers (Fig. 1B).

The theoretical basis of the WHI is derived from the concept of ecological integrity (Parks Canada Agency 2008), which is defined as "a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change, and supporting processes." Thus, the focus of monitoring and



Level 1 vital sign	Level 2 vital sign
Stressors/Threats	Urbanization Intensive land use
Water	Water quality Flow regime
Weather/Climate	Seasonality Climate
Habitat	Ecosystem extent Intactness/pattern Stream intactness Community naturalness
Species	Tropic structure Threatened species
Ecosystem Processes	Disturbance Plant growth (productivity) Forest structure

Fig. 1. Components of the Wildland Health Index (WHI) approach. The WHI is designed as the scientific assessment component of the Climate Planning Cycle (A). The purpose of the WHI (B) is to communicate to decision makers trends in vital signs of ecological integrity. The monitoring depiction is from Turner (2014).

evaluation is on stressors and on vital signs of ecosystem structure, function, and composition (Table 1). Specific vital signs are tailored to the management goals and ecological attributes of the wildland system to which it is being applied. Vital signs are hierarchically organized, include metrics sufficiently detailed for scientific understanding and design of management strategies (Level II and Level III), and are integrated into higher level metrics that are useful to policy makers (Level I). Trends in the condition of vital signs are evaluated through analysis of monitoring data to determine the direction and magnitude of change over time. Projections under alternative future scenarios can be made with statistical or process models. These trends, in the context of the projections, are classified on a scale from deteriorating to improving based on statistical analysis and expert opinion. The results are summarized in a WHI Scorecard with a simple

Table 1. Vital signs of ecological integrity that comprise the Wildland Health Index for assessing condition of large wildland landscapes.

Category	Level 1 Vital sign	Level 2 Vital sign	Level 3 Vital sign
Stressors	Human pressure	Human footprint Developed lands Hydrologic modification Recreational pressure Resource extraction	Population density Built environments Nighttime lights Land use Transportation Recreation Hunting/poaching Mining/logging
	Weather and climate	Growing degree days Days above or below hot or cold thresholds Moisture/drought indices Climate change velocity	Temperature Precipitation Vapor pressure deficit Wind speed Solar radiation
	Pollution	Air quality Water quality Artificial light Noise	Atmospheric emissions greenhouse gases Nitrogenous compounds ozone Particulates/smoke Dissolved oxygen Sediments/nutrients/toxins; hormones/pathogens Light/noise source/intensity
	Invasive species	Invasive abundance/biomass Keystone invasives Pests/disease	Invasive plants/animals: Introduced pests/pathogens Zoonotic diseases
Ecosystem structure	Habitat structural condition	Vegetation structural complexity Extent/intactness Integrity Fragmentation/connectivity	Canopy cover Canopy height Time since disturbance Biomass Leaf area index Stream/river morphology
Ecosystem function	Water	Water quantity Flow regime	Snow cover phenology Frozen/non-frozen season Stream/river hydrology Stream/river chemistry Soil moisture
	Productivity	Net primary productivity Phenology Secondary productivity	Photosynthetic rate Light use efficiency Water use efficiency Start/peak/end of growing season Population growth rates
	Nutrient cycling	Nutrient retention	Biogeochemistry of vegetation/soil/water
	Disturbance	Fire regime Flooding regime Avalanche/landslide regime Pest outbreak regime	Type, seasonal timing, intensity, and frequency of event-based external disruptions to ecosystem processes and structure
Ecosystem composition	Genetic	Genetic composition	Co-ancestry Allelic diversity Population genetic differentiation Breed and variety diversity
	Species populations	Functional role endangerment status	Distribution Population abundance Age/size structure
	Community composition	Taxonomic diversity Functional diversity Species interactions Trophic structure	Richness Evenness Functional types

Note: Derived from Feld et al. (2010), Pereira et al. (2013), Hall et al. (2014), and Hansen et al. (2016*a*).

color-coded scheme for effective communication to policy makers and other stakeholders.

The WHI is designed to be applicable to large wildland ecosystems. The vital signs were selected to be most relevant to the ecological integrity (as defined above) of ecosystems centered on protected areas and managed to perpetuate biodiversity and wilderness character. To the extent that other ecological health evaluation approaches have objectives that differ from the WHI, the vital signs and thresholds for evaluation may or may not overlap with those of the WHI. While the steps within the WHI are widely advocated (Fancy et al. 2009, Hobbs et al. 2010, Pereira et al. 2013, Scheffer et al. 2015), we are aware of relatively few programs that systematically evaluate the health of large, multi-jurisdictional wildland ecosystems using a diverse collection of physical and biological indicators (Brandt et al. 2014).

We chose the GYE for this first detailed application of the WHI because it is one of the best known and most intensively studied park-centered ecosystems, while also being subject to a host of pressures ranging from climate change to human modification of land cover (Hansen and Phillips 2016). The GYE is also well suited to demonstrate the WHI approach because of its high profile in the development of conservation goals, ecological value, and substantial management infrastructure. The designation of Yellowstone as the world's first national park was instrumental in the subsequent development of the global protected area network (Schullery 1997). Thus, conservation success or failure in the GYE will likely have ripple effects through the global conservation community. The Yellowstone wildland is unique in its location within the temperate zone of the world, its large spatial area, its full community of native species, and its regulation by natural ecological processes (Noss et al. 2002). Thus, its ecological value is of national and international significance. While the federal lands in the region are immense, they are not large enough to encompass the flows of water, wildlife, and wildfire essential to ecological functioning; therefore, the concept of greater ecosystem was conceived here more than 50 yr ago and the identity of the GYE is widely recognized (Keiter and Boyce 1991). Accordingly, an interagency committee was created in 1964 to coordinate management across the federal lands of the GYE (www.fedgycc.org). However, increasing human pressure and climate change have the potential to degrade ecological integrity of the GYE (Hansen et al. 2016*b*). While conservation infrastructure and capacity are relatively well developed, no systematic evaluation of change in the ecological health is regularly conducted across the full GYE.

The goal of this paper is to assess trends in condition of vital signs of ecological structure, function, and composition in the GYE using the WHI approach. We synthesize existing data and knowledge from peer-reviewed publications and unpublished reports to summarize trends in human pressure and in ecological vital signs for the recent past (c. 1970–2015) and forecasts for the coming century. We also do new analyses where data are adequate to supplement the previous efforts. We synthesize these results to identify the Level I vital signs that are improving or deteriorating to inform decision makers for prioritizing management actions. The application of the WHI to the GYE is intended to both inform future management in the GYE and demonstrate the value of the WHI for wildland ecosystems more broadly.

METHODS

The study area is the GYE as defined by Hansen and Phillips (2016; Fig. 2). This delineation is based on objective analysis of the spatial domain of the ecosystem encompassing the national parks and designated wilderness areas, termed the Protected Area Centered Ecosystem (PACE; Hansen et al. 2011). It is also based on socioeconomic factors and includes the surrounding small cities and towns that interact strongly with the federal lands. Approximately 64% of this 97,985 km^2 area is in federal ownership and includes three national park units (Yellowstone and Grand Teton national parks (GTNP) and the John D. Rockefeller Jr. Memorial Parkway), five national forests, two national wildlife refuges, and several large wilderness areas. Management across these federal lands is facilitated by the Greater Yellowstone Coordinating Committee (GYCC). Tribal lands occupy 6.2% of the GYE. Private lands cover 31% of the ecosystem and include portions of 3 states and 20 counties. The federal lands provide a powerful economic engine that has created a diverse regional economy supporting quality of life, agriculture, and outdoor recreation (Quammen 2017). The region's human population resides in towns, small cities, and surrounding rural residential developments, usually on or near large river floodplains and serviced by roads and airports.

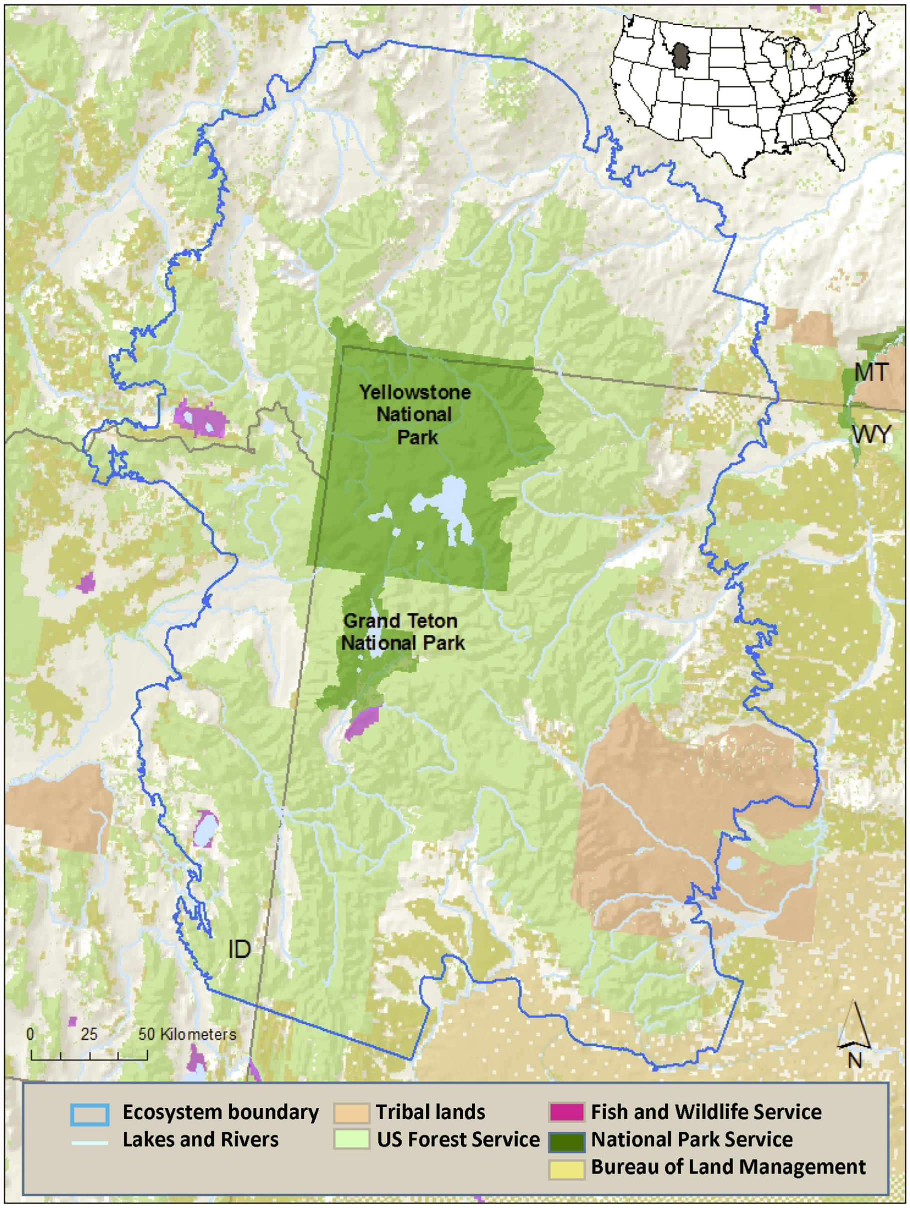


Fig. 2. Map of the Greater Yellowstone Ecosystem depicting land allocation types overlaying shaded relief. Modified from Hansen and Phillips (2016).

Seven Level I and 35 Level II or III vital signs were selected (Table 2) that were previously identified as relevant to wildlands by NPS Inventory and Monitoring Program (Jean et al. 2005) and by the WHI, and for which data or previous studies were adequate to draw inference on trends in condition. While these vital signs are a subset of the full suite likely needed to characterize ecological integrity, they are adequate to demonstrate the WHI approach and the need for it in the GYE. Data sources, spatial and temporal extent, and uncertainty vary among the vital signs. We used the best available information from previous publications and government reports. The methods used in those studies can be found within the primary sources. Some of the vital signs were tracked using rigorous, statistically valid designs; others were based on

Table 2. Trends or patterns in ecological condition of vital signs across the GYE based on best available information.

Category and Level 1 vital sign	Level II and Level III vital signs	Trend and magnitude	Spatial/temporal extent	Trend and level of confidence	Source
Stressors					
Human pressure	Human density	+0.0168% per yr	GYE counties	Increasing	U.S. Census (https://www.census.gov/)
	Home density	+0.0238% per yr	1970–2015	H	
	Land use		GYE	Intensifying	Theobald (2013)
	Undeveloped	−0.700% per yr	1970–2010	I	
	Rural	+1.975% per yr			
	Exurban	+8.175% per yr			
	Suburban/urban	+10.075% per yr			
	Developed lands	31%	GYE	Expanding	Hansen and Phillips (2016)
			Pre-settlement to 2010	I	
	Public lands visitation		National Parks	Increasing	NPS IRMA (https://irma.nps.gov)
	Yellowstone NP	+0.0135% per yr	1970–2016	H	
	Grant Teton NP	+0.0068% per yr	1980–2016		
	Ski area use			Increasing	Individual ski area records, personal communication
	Bridger Bowl	69% increase 1985–2015		I	
		16% increase 2008–2015			
	Big Sky	12% increase 2008–2013			
	Moonlight Basin	5% increase 2009–2013			
Climate	Temperature	+0.78°C	YELL PACE	Increasing	Gross et al. (2016)
	Precipitation	−0.10.2 mm	1950s to 2000s	H	
	Temperature	2.4°–5.7°C/century	2010–2100	L	
		+8–16%			
	Precipitation				
Ecosystem function					
Snow	Snow water equivalent (April 1)	1990s >20% below long-term average	GYE	Decreasing	Pederson et al. (2011)
			1200–2000	H	
		Declines in 70% of sites			
		−36% to −66%	YNP	H	Tercek et al. (2015)
			1961–2012		Melton et al. (2016)
			GYE	L	
			1970–2015 to 2070–2099		
Water	Flow regime		GYE	Decreasing	Al-Chokhachy et al. (2017)
	Average peak discharge	7.5 d earlier	1970–2015	H	
	Summer min flows	−27.50%			
	Ann total volume	−15.60%			Melton et al. (2016)
	Runoff	+0.8% to +3.8%	1970–2015 to 2070–2099	L	
	Stream temperature	≥+1.0°C	GYE	H	Al-Chokhachy et al. (2013)
			1900–2010		
		+1°C to >3°C			
			2015–2069		
	River Integrity Index	27% of major rivers on private land rated as altered.	GYE	Decreasing H	Harrison-Atlas et al. (2017)

(Table 2. Continued.)

Category and Level 1 vital sign	Level II and Level III vital signs	Trend and magnitude	Spatial/temporal extent	Trend and level of confidence	Source
Disturbance	Forest mortality		GYE	Increasing	
	Whitebark pine	82% of range had moderate to severe mortality	2010	M	Macfarlane et al. (2013)
		2 × increase in area affected			
		68% increase in years suitable for beetle outbreaks	1951–2016		Chang (2017)
			2000–2010 to 2070–2099		Buotte et al. (2016)
	Fire	No trend	GYE	Increasing	MTBS
	Area burned		1989–2015	M	Eidenshink et al. (2007)
		>1988 in most years	2010–2075		Westerling et al. (2011)
		19.86			Clark et al. (2017)
			1910–2008 to 2100		
Ecosystem structure					
Habitat Intactness	Habitat lost to development	−50% to −89% on private lands	GYE	Declining	Hansen and Phillips (2016)
	(See Table 6)	−10% to 57% on all lands	Historic to 2000	M	
Ecosystem composition					
Forest Cover			GYE	Variable	Powell and Hansen (2007)
	Conifer cover	+0.51% per yr N aspects, low elevations	1971–1999	H	
		−10%			Brown et al. (2006)
	Aspen cover		1956–2001	H	Piekielek et al. (2015)
		+31% to +40%			
	Area of suitable habitat	+32% to +55%	1950–1970 to 2100	L	
	Sagebrush	−22% to −29%			
	Juniper	−10% to −60%			
	Limber pine	−53% to −73%			
	Aspen	−50% to −85%			
	Douglas fir	−77% to −90%			Chang et al. (2014)
	Lodgepole pine	−68% to −80%			Clark et al. (2017)
	Engelmann spruce	−84% to −97%			
	Subalpine fir				
	Whitebark pine	−44% to +8%		L	
		−60% to +12%	Yellowstone Plateau		
	Forest cover		Historic to 2050	L	
	Basal area				

(Table 2. Continued.)

Category and Level 1 vital sign	Level II and Level III vital signs	Trend and magnitude	Spatial/temporal extent	Trend and level of confidence	Source
Large mammals	Grizzly bear	N = 136 in 1975	GYE	Increasing	YNP (2017)
		N = 690 in 2016	1975–2016	H	
		+>50% area occupied			
		31 introduced in 1995/96			
		N = 528 in 2015			
	Gray wolf		1996–2015		
		N = 23 in 1902			
		N = 5500 in 2016			
	Bison				
			1902–2016		
Fish	Westslope cutthroat trout			Decreasing	
	Population distribution				
		Declining	Historic to present	I	YNP (2017)
	Summer fish growth rate		1980–1999 to 2050–2069		
		<−10% in August at 23% of occupied sites and 42% of extirpated sites		L	Al-Chokhachy et al. (2013)
	Arctic grayling	Fluvial Grayling extinct in YNP	Historic to present	Decreasing I	Yellowstone National Park (2017)
	Native salmonids	Status by % of watersheds:	Historic to present	Decreasing	Van Kirk and Benjamin (2001)
		Good—20%		L	
		Fair—10%			
		Poor—70%			

Note: GYE, Greater Yellowstone Ecosystem.

repeated surveys with unknown accuracy; and still others were based largely on expert opinion. The varying quality of these data prohibits a statistically valid analysis of trends in condition across the suite of vital signs.

We performed original analyses of population density, housing density, land use change, ski area use, and river integrity. US census data for population density and housing density were acquired for the 20 counties that the mapped GYE lays within for 1970–2015. Trends were quantified with linear regression analyses. The resulting growth rates were used to represent one scenario of possible future population and housing density to 2050. Change in land use was evaluated using the Spatially Explicit Regional Growth Model (SERGoM; Theobald 2005, Bierwagen et al. 2010). The SERGoM model first removes areas where homes are unlikely to be built: specifically, public lands and areas of water. Homes were then dispersed using a weighted distribution based on: census data for housing units per block, counts of groundwater well permits, and road densities at a 100-m spatial resolution. The data extend from 1940 to 2000 and are calculated decadally at a 100-m resolution. We used the SERGoM outputs for 1970–2010, summarized in four land use classes: undeveloped/very low density (0–0.031 housing units/ha), rural (≥0.031–0.063 units/ha), exurban (≥0.063–1.45 units/ha), and urban/suburban (>1.45 units/ha).

We additionally used the disturbance zone approach (Theobald et al. 1997) to define developed area. This approach is based on a functional relationship between effect on habitat and distance from development. Many studies have found that roads, rural homes, and other types of human development degrade habitat quality some distance beyond the actual location of the human infrastructure. Mapping the cumulative disturbance zone among land use types is an index of the proportion of a wildland ecosystem that has been degraded by human development. To derive a developed area layer for the GYE, we first mapped exurban residential housing based on groundwater well data and county assessor tax data. For seven counties in eastern Idaho, tax assessor records were used to identify the number of homes in each quarter section. For all other counties, domestic wells data were used to represent rural homes. In Montana, these data were provided by the Montana Bureau of Mines and Geology, and in Wyoming, data were provided by the State Engineer's office. Data for urban, suburban, and agricultural lands were derived from the US Geological Survey's National Land Cover 2011 edition data set (NLCD; Jin et al. 2013). Road data from US Census Bureau Tiger/Line files included primary and secondary roads (Feature class codes A11 to A41; US Census Bureau 2014). Because NLCD classifies areas that are close to all roads as developed, we masked this NLCD developed class within public lands if there was no other evidence of human modification based on visual interpretation and other data sets. The distance of the disturbance zone around each land use type was estimated based on previous studies (see references in Hansen and Phillips 2016). We buffered all rural homes and wells by 1 km, NLCD classes by 500 m, and roads by 100 m, consistent with Gude et al. (2007).

Trends in ski area use for five or more years were provided by three of the seven commercial ski areas in the GYE.

Human modification of streams and rivers in the United States was quantified by the Center for American Progress (https://disappearingwest.org/rivers.html#big_picture) and summarized in their report by Harrison-Atlas et al. (2017). This index incorporated an index of flow alteration and an index of floodplain modification. The combined river modification index ranged from 0 to 1. Threshold values were derived based on the index value along protected sections of rivers and streams. Reaches with index scores above the threshold value were considered altered by human activities. This approach assumes that the protected stream reaches are in a condition of high ecological integrity and have not been degraded by human use, climate change, and atmospheric deposition. The percent of rivers and stream length labeled as altered was key metric reported in the river modification summary. We estimated mean standard deviation for this metric in the GYE study area by river size (1) headwater (<6 cfs mean annual flow), (2) streams and smaller rivers (6–163 cfs), and major rivers (>163 cfs) and by land allocation type.

We also summarized ecological forecasts to 2100 for climate change scenarios for a subset of vital signs under Intergovernmental Panel on Climate Change (IPCC 2013). These results are from our previous work and are summarized in Hansen et al. (2016*b*). The forecasts were done for ecological processes (Melton et al. 2016) and habitat suitability for plant species or communities (Chang et al. 2014, Piekielek et al. 2015). We additionally drew from the published literature for forecasts of hydrologic flows, stream temperature, and fish growth rates.

The direction of change in the condition of ecological vital signs is best established through explicit quantitative thresholds in their trends (Parks Canada Agency 2008). Such thresholds in vital signs have largely not been established in the GYE. In place of designated thresholds, we summarized the sign (increasing/decreasing) and magnitude of change in the stressors and vital signs. We classified confidence in these trends as high (statistically significant trend), intermediate (spatial extrapolations from point data without statistical analysis), or low (simulation model results or expert opinion without estimates of uncertainty). The period of analysis is 1970–present and we report longer time periods when data allow or for shorter time periods if data are limited.

We report trends for the vital signs in narrative and tabular form. The trends for vital signs were also summarized as 10 Level I management-relevant vital signs with a color-coded WHI Scorecard. Each vital sign was rated as deteriorating, possibly deteriorating, relatively stable, or improving by land allocation type. The assignment of trend classes was based on the direction and magnitude of change from analyses and expert opinion. For some vital signs with adequate data, trends were summarized by land allocation type. This was done to make the results most useful to the agencies and entities responsible for the management of these jurisdictional units. Ultimately, assignment of trend classes requires some subjectivity and conclusions may differ among experts. Our presentation of the WHI Scorecard is meant to generate discussion among GYE experts, increase research and monitoring efforts, lead to improved quantitative analysis, and provide a basis for applications of the approach to other ecosystems both nationally and internationally.

RESULTS

The vital signs with adequate data for analysis are listed in Table 2. Provided within the table are trends, spatial and temporal extent, interpretation of trend, level of confidence, and citations. The results below refer to entries in Table 2 and references from the table are not repeated in the text, except where needed for clarity. More detail on results for some of the vital signs is reported in tables or figures.

Human pressure

The population across the 20 counties of the GYE more than doubled during 1970–2015 (111.6% increase) to the current population of about 472,575 (Fig. 3). Approximately 4300 people per year were added to the population during 2011–2015. Extrapolating forward to 2050 at the average annual growth rate for 1970–2015 of 0.0168 results in a projected population of 846,146. The number of homes in the GYE counties more than tripled from 79,128 in 1970 to 227,687 in 2015 (Fig. 3). During 2010–2015, an average of 4837 homes was added per year. With the average annual growth rate of 0.0238 from 1970 to 2015, some 503,465 homes would in GYE by 2050.

This growth in population and home density was associated with land use intensification. During 1970–2010, the proportion of private lands classified as undeveloped steadily declined, while the proportion classified as rural, exurban, and suburban/urban increased (Fig. 4). Developed lands (agriculture, exurban, suburban/urban, commercial/industrial, roads, and buffers) covered 31% of the GYE in 2016 (Fig. 5).

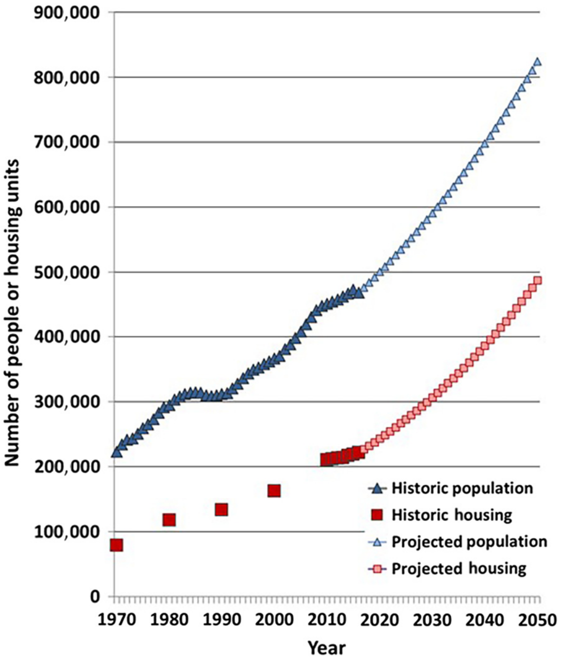


Fig. 3. Change in human population and housing units for the twenty counties of the Greater Yellowstone Ecosystem for a historic period and projected to 2050. Data are from the US Census Bureau.

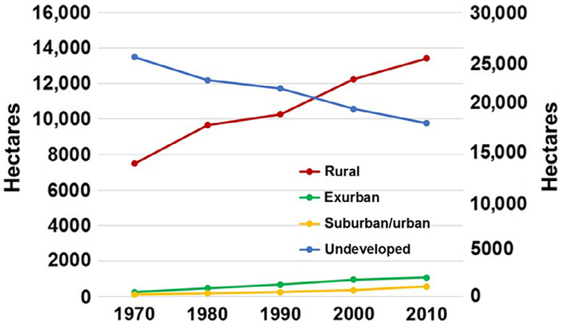


Fig. 4. Change in the aerial coverage of housing density classes across the Greater Yellowstone Ecosystem. Density classes are rural exurban suburban/urban undeveloped. The undeveloped class values are on the right axis. Data are from Theobald (2013).

Among types of outdoor recreation, visitation to Yellowstone National Park (YNP) has increased by 85% during 1970–2016 (Fig. 6). More than 4 million people entered the park during 2015 and 2016, and GTNP has similar trends. Skier days have risen by 69, 57, and 5% per yr in the three commercial ski areas for which trend data were available. The growth in the GYE human population suggests increases in fishing, hunting, hiking, backcountry skiing,

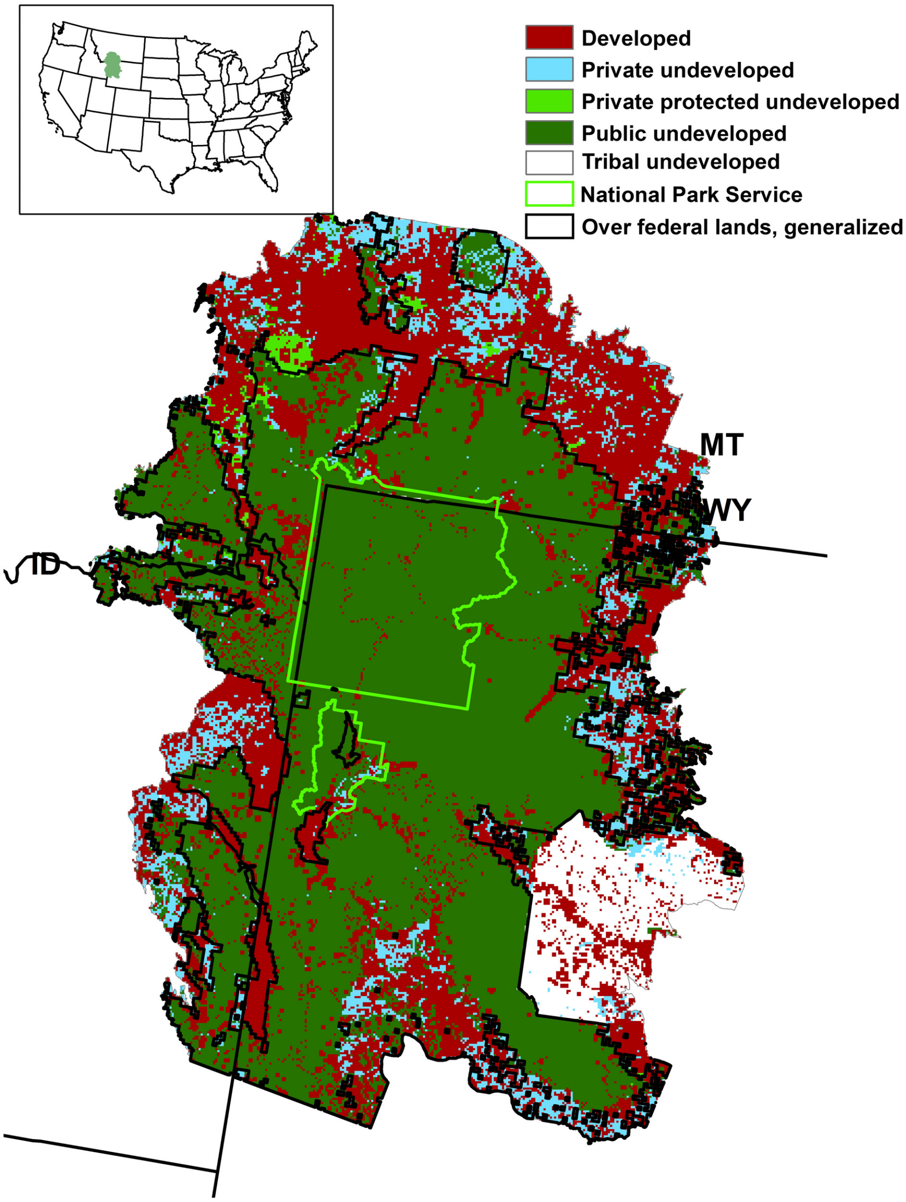


Fig. 5. Locations within the Greater Yellowstone Ecosystem that are considered "developed" (red), defined as in Fig. 4. Also shown are various public and private land allocation classes. Data are from Hansen and Phillips (2016).

mountain biking, and off-road vehicle use; however, data on these forms of outdoor recreation are currently unavailable at spatial resolutions relevant to the GYE. In the upper Madison River, for example, angler days increased from 51,000 in 1984 to 178,000 in 2016, and increase of 250% and Montana Fish Wildlife and Parks has proposed restricting use to protect the fishery (MFWP 2018).

Climate

The GYE has warmed during 1950–2009 with mean annual minimum temperature increasing 0.78°C and mean annual maximum temperature increasing 0.89°C (Fig. 7). Most of the temperature increases have occurred since 1980, and rapid increases in temperature are projected for the coming century. The representative concentration pathway (RCP) 4.5 projects the ensemble average rate

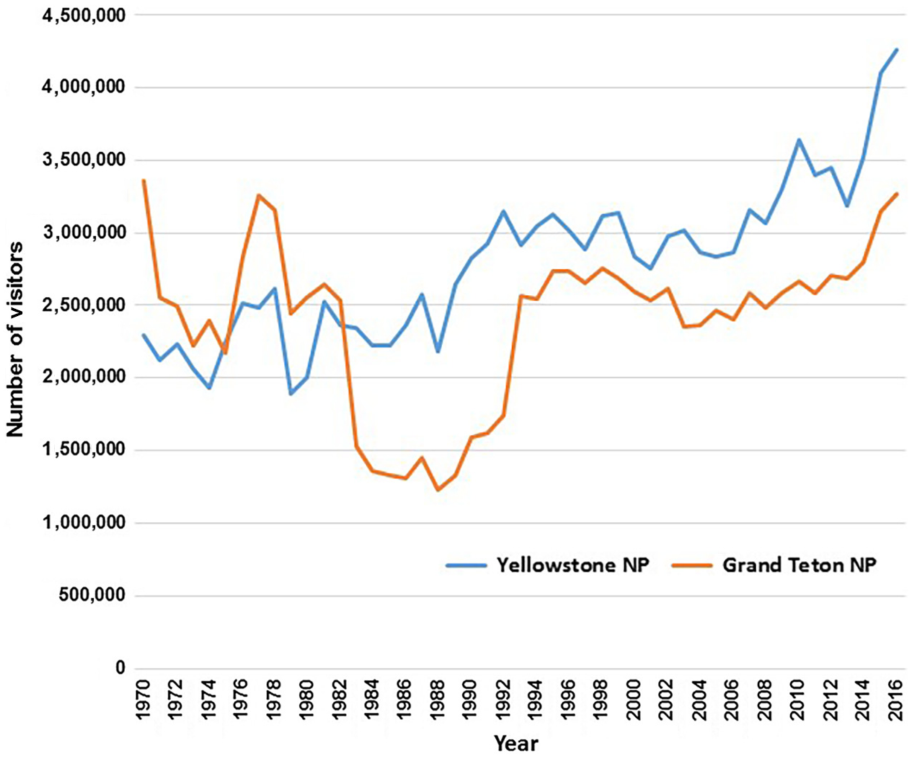


Fig. 6. Visitation rates to Yellowstone and Grand Teton national parks since 1970 (Data from https://irma.nps.gov/Stats/Reports/Park).

of increase of 2.5°C by 2100 and the RCP 8.5 projects the ensemble average rate of increase of 5.3°C by end of century. Precipitation decreased only slightly since 1980 and is projected to increase by 8% under RCP 4.5 and by 16% under RCP 8.5. Aridity (the ratio of PET to PPT) is, however, projected to increase in the coming century owing to greater evapotranspiration (Chang 2015).

More meaningful to plants and wildlife than annual average climate condition are thresholds based on daily climate (Table 3). Comparing climate metrics from the 1950s with those projected for 2100, the number of hot days (>32°C) is projected to increase dramatically, particularly at lower elevations where the projected increase is more than 4 weeks by 2100. Annual growing degree days more than double in all vegetation communities. The number of days below freezing is projected to decline by 32% by 2100.

Snow

The observed warming described above has reduced snowpack. Snow water equivalent (SWE) for April 1 is currently 20% lower than the average for the period 1200–2000 AD. Moreover, 1900–2000 represents the longest period of below-average snowpack in the 800-yr record, and the decade of the 1990s was among the lowest in the century. An analysis in YNP found that 70% of sites had statistically significant declines in April 1 SWE. Sites with significant declines tended to be warmer than sites without declines, suggesting snowpack is declining most rapidly in the lower elevation snow transition zones. Projections for the coming century suggest more precipitation as rain rather than snow, which will have substantial impacts to snowpack across the GYE. The net balance of the projected increases in temperature and precipitation results in a 36% reduction of the average total annual snowpack during 2070–2099 relative to 1970–1999 under RCP 4.5, and a 66% reduction under RCP 8.5.

Water

River flows have declined in the GYE, at accelerating rates since 1970. Despite high interannual

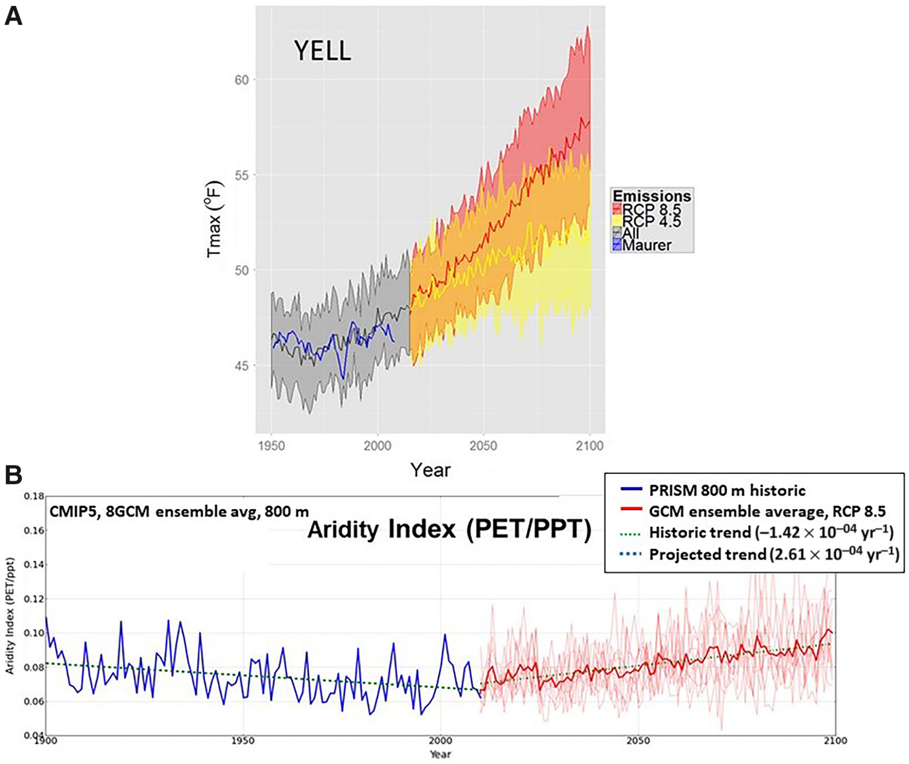


Fig. 7. (A) Projected average annual temperatures for the Yellowstone PACE for a higher-emissions pathway (RCP 8.5) and a lower-emissions pathway (RCP 4.5) for an ensemble of global climate models. Shaded zones are ±1 standard deviation. "Maurer" in the key represents historical data. Data are from Gross et al. (2016). (B) Historic and projected change in aridity estimated as potential evapotranspiration/precipitation under RCP 8.5. Data are from Chang (2015). RCP, representative concentration pathway.

variation, strong statistically significant trends in stream flow were found across the GYE during 1970–2015. Peak discharge shifted 7.5 d earlier, summer minimum flows declined by 27.5% and total annual volume declined by 15.6% (Al-Chokhachy et al. 2017). Projected changes in annual runoff in the coming century across GYE indicate increases at higher elevations and decreases at lower elevations but little change summed across the ecosystem (Melton et al. 2016). Large changes are projected, however, in the seasonality of hydrologic fluxes. Runoff is projected to experience large increases in the fall and winter seasons, with corresponding decreases in the spring and summer.

Stream temperatures have warmed across the region by ≥1°C over the past century (Al-Chokhachy et al. 2013). Stream warming during 2000–2009 exceeded that of the Great Dustbowl of the 1930s and represented the greatest rate of change over the past century. Stream temperatures are projected to increase by 1 to >3°C by 2069.

Most rivers in the GYE have impoundments or water withdraws for human use. These human alterations influence peak flows, water temperature, stream sediment, channel morphology, and habitat structure. Floodplains have also been altered by human land use. Consequently, the river integrity index of Harrison-Atlas et al. 2017 reveals that streams and rivers on private lands have been altered from the benchmark condition along 19–27% of their lengths (Table 4) and some major rivers in GYE are >70% altered (Fig. 8). In National parks and wilderness areas, in contrast, stream alteration was 4–9% (Harrison-Atlas et al. 2017).

Disturbance

A consequence of the recent warming trend has been an outbreak of forest pests and forest

Table 3. Climate metrics calculated from daily climate variables for GYE PACE, by vegetation type and decadal periods for RCP 8.5. Data are from Gross et al. (2016).

Park/veg. Type	Metric	Period			
		1950–1959	2000–2009	2050–2059	2090–2099
Montane sage	Above 32°C	1	4	15	34
	AGDD 0°C	3379	3854	4943	6317
	Below 0°C	246	229	195	160
	Period > −2°C	86	101	125	158
	Period > 0°C	58	73	99	133
	Days < −22°C	14	10	6	3
Alpine	Above 32°C	0	0	0	7
	AGDD 0°C	2081	2465	3376	4575
	Below 0°C	280	263	230	195
	Period > −2°C	62	77	101	131
	Period > 0°C	40	53	79	108
	Days < −22°C	19	15	8	5
Lodgepole pine	Above 32°C	0	1	8	27
	AGDD 0°C	2962	3422	4469	5800
	Below 0°C	260	242	208	173
	Period > −2°C	75	92	117	148
	Period > 0°C	50	66	93	122
	Days < −22°C	15	12	7	4
Spruce-fir	Above 32°C	0	0	2	15
	AGDD 0°C	2471	2899	3863	5122
	Below 0°C	271	254	221	185
	Period > −2°C	67	85	109	139
	Period > 0°C	44	59	85	114
	Days < −22°C	18	14	7	4

Notes: GYE, Greater Yellowstone Ecosystem; RCP, representative concentration pathway. Metrics are above 32°C = number of days per year above 32°C; AGDD 35°C = growing degree days with 0°C growth threshold; days < 0°C = number of days per year below 0°C; period > −2°C = consecutive days with Tmin above −2°C; period > 0°C = consecutive days with Tmin above 0°C; days < −22°C = days per year below −22°C.

Table 4. Alteration streams and rivers by human activities across land allocation types as a function of stream size in the Greater Yellowstone Ecosystem.

River size	Land allocation		
	NPS/Wildness	Other federal	Private
Headwaters	8.5 (7.4)	7.7 (9.1)	19.0 (18.6)
Streams and smaller rivers	5.3 (5.5)	8.8 (8.9)	22.7 (18.1)
Major rivers	4.2 (5.7)	15.4 (14.0)	27.1 (13.0)

Notes: Data are the mean (and standard deviation) percent alteration of stream flows and floodplains by human structures, consumption, and land use. Data are from Harrison-Atlas et al. (2017).

die-off. Milder temperatures lead to higher populations and lethality of mountain pine beetle (*Dendroctonus ponderosae*), the major pest of pine (*Pinus* spp.) trees in GYE (Logan et al. 2010). From 1998 to 2010, an eruptive outbreak resulted in moderate to severe mortality of overstory whitebark pine (*Pinus albicaulis*) across 82% of its range in GYE. This 2000–2010 outbreak was estimated to be twice the total area of the previous large outbreak in 1960–1969 and had an expanded elevational range that included the core whitebark pine habitat. The projected future warming is expected to increase suitability for beetle survival and development. The proportion of years with temperatures suitable for outbreaks was projected to increase from 0.56 during the 2000–2010 outbreak to 0.94 in 2070–2099. As a result of tree mortality due to the beetle, there is a shift to smaller trees which may now be more susceptible to blister rust (Shanahan et al. 2016).

Fire occurrence at lower elevations in the GYE is thought to have been reduced through human fire exclusion during the century prior to 1988 (Littell 2002), but has expanded since then. A fire reconstruction on the mid-elevation Yellowstone Plateau for 1700–1989 found that area burned

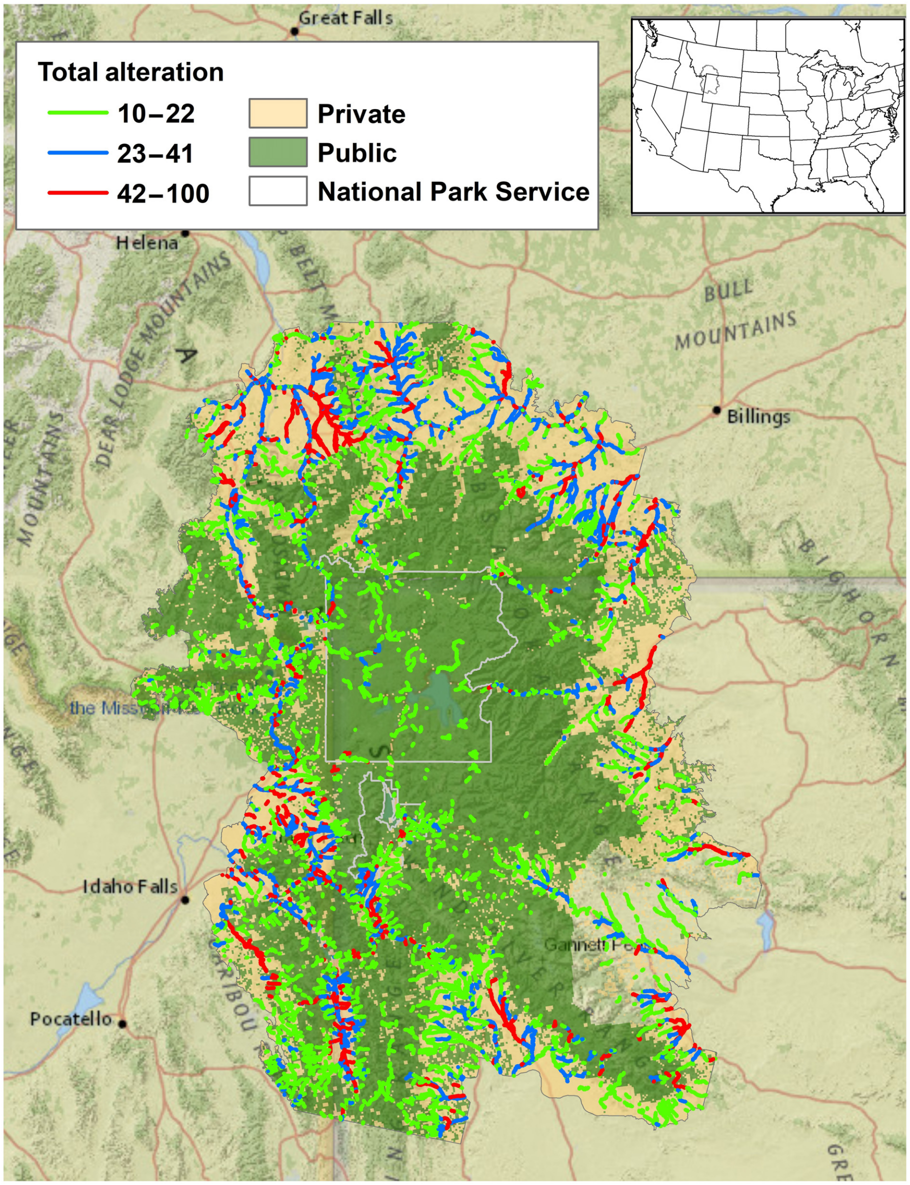


Fig. 8. Alteration of streams and rivers by human activities across land allocation types in the Greater Yellowstone Ecosystem. The stream alteration metric is scaled from 0 (unaltered) to 1 (highly altered). Data are from Harrison-Atlas et al. (2017).

during 1910–1980 was very low (Romme and Despain 1989). Similarly, Littell (2002) found evidence of frequent low-intensity fire for the lower elevation forests prior to 1880, but virtually no fires during 1880–2000. Data on area burned for 1984–2015 indicate that since the very large fires in 1988, relatively large fires occurred in 2000, 2006, and 2012, including at lower elevations (Fig. 9). While fire data for 2016 are not yet available for the GYE, that year had the largest area burned in Yellowstone National Park since 1988 (www.nps.gov/yell/learn/news/16068.htm). Collectively, these studies suggest a major shift in fire regime in GYE at all elevation zones, from relatively little fire prior to 1988 to periodic large fires thereafter. Projections of fire into the future,

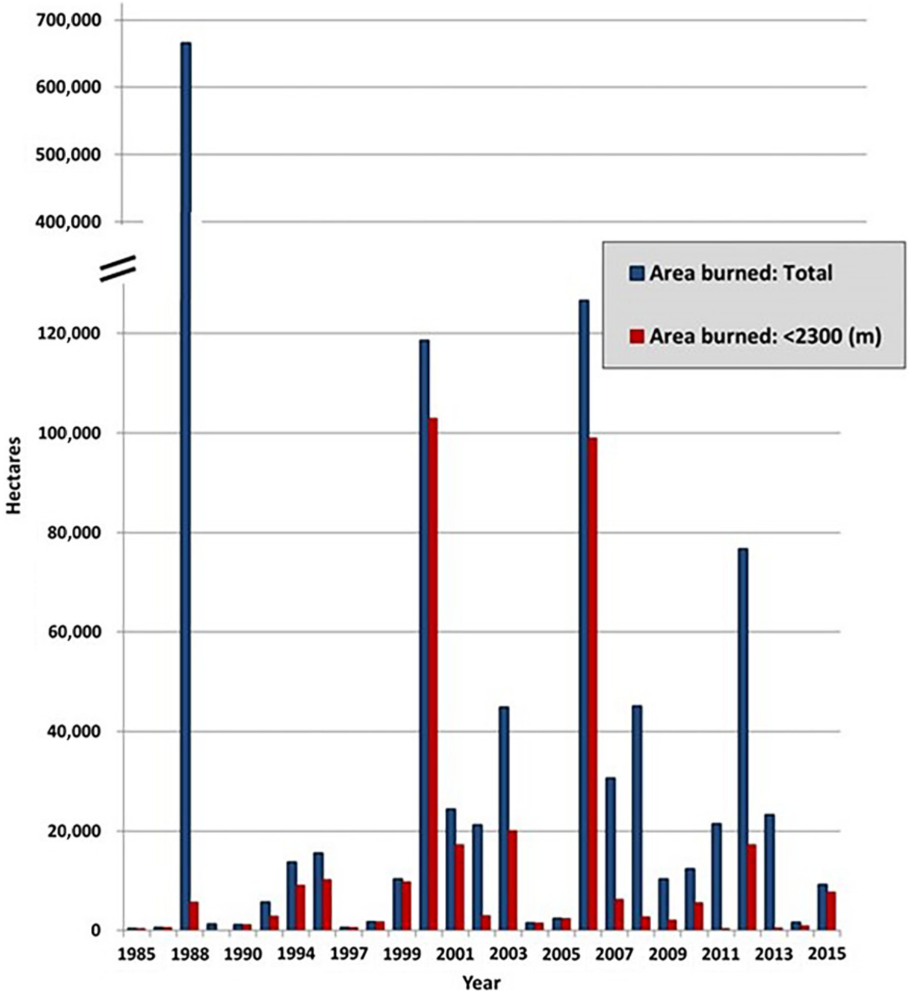


Fig. 9. Area burned across the Greater Yellowstone Ecosystem for elevations less than 2300 m. Data are from the National Monitoring Trends in Burn Severity database.

based on fire/climate relationships, suggest substantial increases in fire by midcentury, with fire rotation reduced to <30 yr from the historical 100–300 yr for most of the GYE (Westerling et al. 2011). By 2075, potential annual area burned was projected to regularly exceed the signature 1988 event. Similarly, a mechanistic modeling study that simulated fire/climate/vegetation interactions projected a 24–414% increase in area burned from a historic period to 2100 (Clark et al. 2017).

Habitat intactness

Habitats for several vegetation communities and wildlife species have been mapped across GYE. Overlaying developed areas on these vegetation and wildlife habitat types provides an approximation of habitat fragmentation (Gude et al. 2007). Analyses by Hansen and Phillips (2016) revealed that loss of aerial extent of habitat types to development since pre-EuroAmerican settlement times on higher elevations and on public lands has been (10–13% for subalpine coniferous forests and grizzly bear, *Ursus arctos horribilis*; Table 5). Habitat loss was higher (25–32%) for vegetation types at mid-elevations (Douglas fir, aspen, upland deciduous forests) and for elk habitats. Habitat types most reduced (39–57%) were those overlapping lower elevations and private lands, including sagebrush/grasslands, bird hot

Table 5. Habitat intactness for several vegetation types and wildlife species across the GYE based on patterns of human land development (from Hansen and Phillips 2016).

Habitat type	Definition	% of habitat type classified as developed	
		Private lands	All lands
Aspen	Stands dominated by aspen	56	27
Riparian habitat	Rivers buffered by 256 m and adjacent deciduous habitat	89	57
Sage/grassland	Nonforest vegetation dominated by sagebrush and grassland communities	68	39
Upland woody deciduous	Forests dominated by aspen and deciduous shrubs	63	32
Douglas fir forest	Forests dominated by Douglas fir, which occurs in the productive lower treeline to mid-elevation portion of the GYE	50	25
Subalpine coniferous forest	Coniferous forests dominated by lodgepole pine, subalpine fir, Engelmann spruce, or whitebark pine	50	10
Bird hot spots	Areas of >70% of maximum bird diversity and abundance	65	41
Pronghorn	Habitat suitability; expert opinion	66	51
Moose	Habitat suitability; expert opinion	64	44
Grizzly bear	Edge of composite polygon of fixed-kernel ranges from all grizzly locations (1990–2000)	61	13
Elk winter	Habitat suitability; expert opinion	56	30

Note: GYE, Greater Yellowstone Ecosystem.

spots, moose habitat, pronghorn habitat, and large river riparian zones. Within private lands, habitat loss was ≥50% for all habitat types and 89% for large river riparian zones.

Forest cover

During the fire exclusion period in the 1900s, some vegetation types in GYE underwent directional change. Conifer forest increased in density and expanded into low-elevation sage/juniper and grassland communities. Of locations that were not recently burned or logged, 38% of aerial photo samples increased in conifer cover between 1971 and 1999. At lower elevations, 48% of samples increased in conifer cover. A satellite-based analysis across the GYE found that the total area of conifer cover increase during 1985–1999 was more than twice that of conifer cover decrease due to fire and logging, including the area burned in 1988 (Powell et al. 2008). Quaking aspen (*Populus tremuloides*) cover declined by an average 10% across aerial photo plots during 1956–2001 with 34% of plots losing ≥20% of aspen cover. The expansion of conifer and reduction of aspen are likely results of the reduction in fire in GYE during the 1900s (Gallant et al. 2003). The influence of the expanded fire regime in lower elevation conifer and aspen forests since 2000 has not been quantified but is likely tending toward pre-fire exclusion vegetation patterns.

Projected future climate change may have large impacts on GYE vegetation. While data are not available on change in aerial extent of vegetation types during the recent period of warming (since 1980, a study based on species distribution modeling, Piekielek et al. 2015 found that subalpine tree species declined dramatically in projected area of suitable habitat by 2099 under RCP 4.5 [50–77% decrease] and RCP 8.5 [80–90% decrease]). The montane species aspen, Douglas fir (*Pseudotsuga menziesii*), and Lodgepole pine (*Pinus contorta*) also showed substantial decreases in suitable habitat area with decreases of 10–53% under RCP 4.5 and decreases of 60–85% under RCP 8.5. Some lower treeline communities were projected to increase substantially in suitable habitat. The juniper (*Juniperus*) community type was projected to increase 32% and 55% in suitable habitat area under RCP 4.5 and RCP 8.5, respectively. The sagebrush community was projected to increase 31% and 40% in suitable area under the two scenarios. Whitebark pine was found to be most vulnerable to climate change with projected suitable climate area estimates in 2100 averaged 16.5% and 3% of the 2010 baseline for RCP 4.5 and 8.5, respectively (Chang et al. 2014). In total, the proportion of GYE with climate suitable to support forest is projected to drop substantially under future climate scenarios. Similarly, a process modeling study (Clark et al. 2017) that considered forest dynamics under climate, disturbance, species interactions, and dispersal projected statistically significant decreases in forest cover (34–44%) and reductions in basal area (51–60%) by 2050 under scenarios with warming of 2.7°C and 4.0°C.

Large mammals

The GYE is the center of the major large mammal restoration in the northern Rockies following the period of overhunting in the late 1800s (Picton and Lonner 2008). The gray wolf (*Canis lupus*) was regionally extirpated, and only small populations of bison (*Bison bison*) and grizzly bear persisted. Focused conservation efforts have allowed these populations to grow and flourish so that the GYE is now a major source area for large mammals that are currently repopulating other parts of the western United States. Grizzly bears were federally listed in the lower 48 states as a threatened species in 1975 when the GYE population was estimated as 136 (Yellowstone National Park 2017). The current population size is around 700 (Fig. 10), and occupied habitats have expanded by >50%. Consequently, the Yellowstone grizzly was removed from the threatened species list in 2017. The GYE bison population grew from 23 individuals in 1902 to about 5500 in 2016 and has expanded its migratory range to lower elevation grasslands outside of YNP. Since the gray wolf was reintroduced into GYE in 1995, the population has grown to an estimated 528 individuals in 2015 and the population range has expanded dramatically, with individuals wandering as far as Oregon, Colorado, and Arizona (YNP 2017).

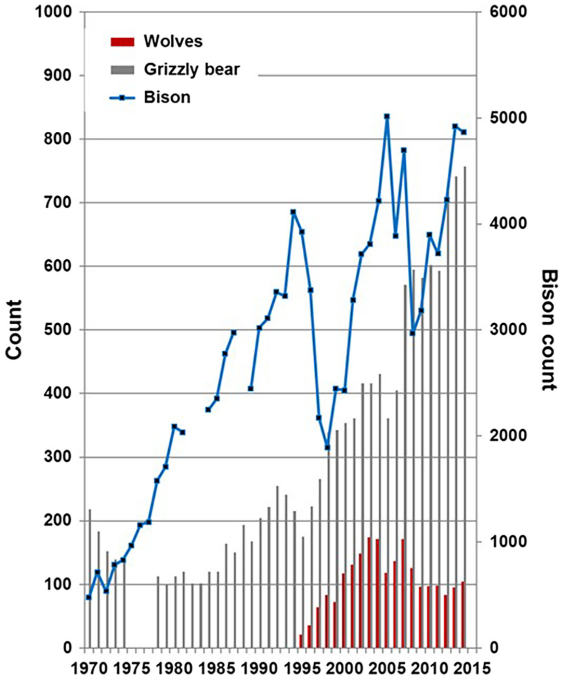


Fig. 10. Population sizes of select large mammals in the Greater Yellowstone Ecosystem since 1970. Data are from Yellowstone National Park (2017).

Fish

In contrast to large mammals, native fish in the GYE have been declining in recent decades. All four subspecies of cutthroat trout (*Oncorhynchus clarkii*) native to the GYE, as well as the native Montana grayling (*Thymallus arcticus montanus*), were suggested by conservation organizations for endangered species protection in the 1990s (Yellowstone National Park 2017). Genetically, pure Yellowstone cutthroat trout (YCT; *O. clarkii bouvieri*) populations have declined throughout their natural range in the Intermountain West, succumbing to competition with and predation by nonnative fish species, a loss of genetic integrity through hybridization, habitat degradation, predation, and angling harvest (Yellowstone National Park 2017). Restoration efforts are underway in several locations in the GYE. Fluvial grayling were eliminated from their entire native range within YNP during the 1900s. An important threat to these native fish is exotic fishes. The nonnative brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), and brook trout (*Salvelinus fontinalis*) are now widespread throughout the GYE, and lake trout are found in many GYE lakes and reservoirs, including Yellowstone and Jackson lakes. More recently, eastern warm-water species have moved upstream into the GYE with warming temperatures, including smallmouth bass (*Micropterus dolomieu*) and northern pike (*Esox Lucius*; Al-Chokhachy et al. 2013).

Projections of Yellowstone cutthroat trout growth rates to 2069 under future climate scenarios indicate that high-elevation sites will have increased growth rates in the future, and lower elevation sites will display a reduction in growth rates between June and August (Al-Chokhachy et al. 2013). End-of-season body mass was projected to increase at all high-elevation sites and decrease at two of the three low-elevation sites. Any benefits of enhanced growth for the species are likely to be offset, however, by the interspecific effects of corresponding growth of sympatric, nonnative trout species.

The status of native salmonids was assessed across the GYE based on current distribution relative to historic distribution. They ranked the status of native salmonids as good in 20% of watersheds (41 in total), fair in 10%, and poor in the remaining 70% of watersheds (Van Kirk and Benjamin 2001). All watersheds in which native salmonid status were either good or fair occurred at higher elevations on public lands. Watersheds with poor status were in lower watersheds on both private and public lands.

Discussion

An overarching question in natural resource management is: How well are we sustaining entire ecosystems under climate and land use change? Various approaches have emerged for addressing this question including historic range of variation (Landres et al. 1999), resilience theory (Walker et al. 2002), ecological integrity (Parks Canada Agency 2008), novel ecosystems (Radeloff et al. 2015), and planetary boundaries (Rockstrom et al. 2009). These approaches tend to converge on core steps. These steps include identifying indicators of ecosystem health, evaluating trends to determine risk of surpassing critical ecosystem thresholds, and recommending strategies to avoid or adapt to ecosystem disruption. The Planetary Boundary Framework, for example, aims to define a safe operating space for human societies to develop and thrive. By combining improved scientific understanding of Earth's functioning with the precautionary principle, the framework identifies levels of anthropogenic perturbations below which the risk of destabilization of the Earth system is likely to remain low—a safe operating space for global societal development.

Consistent with these frameworks, the WHI is designed to aid in the evaluation of regional scale wildland ecosystems. It is deliberately designed in context of the widely used conservation planning cycle (Fig. 1) to emphasize that evaluation of ecosystem function, structure, and composition required for effective conservation planning. It is the interactive effects of stressors, ecosystem processes, biodiversity, and the multiple management strategies employed across natural resources that determine the ecological condition of an ecosystem (Parks Canada Agency 2008). For example, in the GYE climate warming has elevated stream temperature, reducing native fish growth, favoring nonnative fish that negatively influence native fish, and requiring nuanced management strategies to restore native species. Monitoring each of these components is required to understand how they interact to influence ecosystem integrity. The WHI also emphasizes that ecosystem evaluation and management should be done at ecologically relevant spatial scales, which are often larger than individual protected areas or management jurisdictions.

Unfortunately, evaluating ecological integrity across entire wildland ecosystems is seldom done, and methods for doing so and for communicating results to stakeholders are underdeveloped. Consequently, we often do not know whether ecosystems are approaching tipping points at which additional small changes in stressors could result in large reductions in ecosystem services (Scheffer et al. 2015). Yet, if stakeholders had such information, they might factor it into their personal-, business-, and governmental-level decision making in ways that could further sustain ecological condition and services.

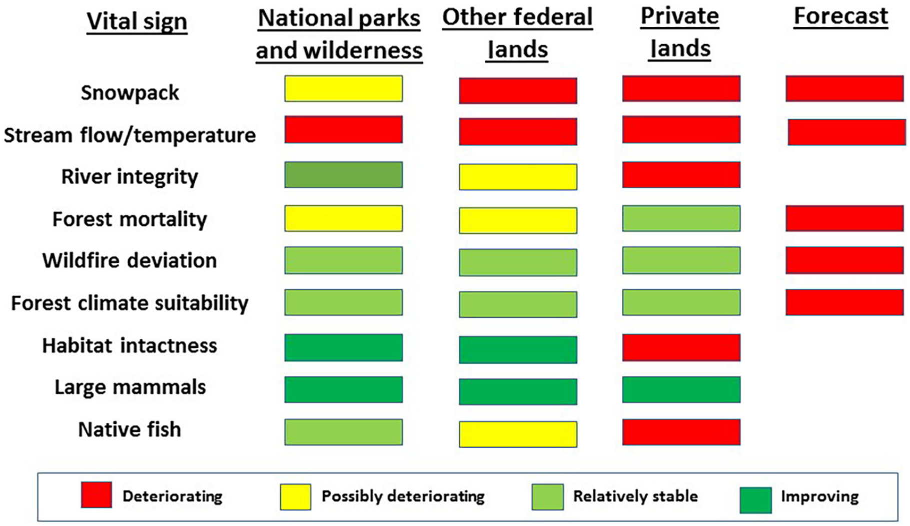
Synthesis of results: Wildland Health Index Scorecard

Potential stressors on the GYE have intensified dramatically in recent decades. The natural amenities, high quality of life, and other attributes of the region have attracted large numbers of new residents (Quammen 2017). Human population growth in some of the GYE counties is among the highest in the nation, resulting in a doubling of the GYE population and tripling of housing density since 1970. Population and home density are forecasted to double again in the next 30 yr under a scenario of future growth rates being the same as past rates. Developed lands now cover about one-third of the GYE. Rates of visitation to national parks and most ski areas have reached record levels. Trends in other types of outdoor recreation have largely not been quantified, but local knowledge suggests that front- and backcountry recreation use is surging.

Climate has warmed substantially since 1980. Temperatures are projected to increase 3–5°C by 2100 creating conditions similar to Nevada and Utah today, leading to substantial increases in aridity. These climate changes, population growth, and land use pressures are strongly impacting some vital signs of ecological integrity.

The responses of the ecological vital signs to human pressure and climate change can be visualized in the context of the WHI Scorecard (Fig. 11). Climate change has led to deteriorating trends in snowpack, stream condition, and forest mortality across all land allocation types. Snowpack is at historic low levels relative to a millennial record, and most sites show declines since 1970. These declines are most pronounced at lower elevations where winter precipitation is more transitional, and hence, the two lower elevation land allocation types were placed in the likely deteriorating class. The reduced snowpack contributes to declines in stream flow. Since 1970, peak flows are occurring earlier in the spring, total annual volume has declined, and most importantly for native fish, summer low flows have dropped by 28%. Stream temperatures have increased, and these trends in stream flow and temperature are projected to become more extreme in the future. Recent forest pest outbreaks and impacts on forests were more pronounced than in previous natural pest cycles, representing a possibly deteriorating condition for forest mortality. Fire regimes may be returning to pre-settlement levels after a century of human fire exclusions. Projections for coming century indicate likely deteriorating trends for snowpack, streams, forest mortality, wildfire deviation, and forest climate suitability.

Vital signs most influenced by land use change, not surprisingly, show deteriorating condition primarily on private lands. A hydrologic integrity index based on impoundments, water withdrawals, and total consumptive use was found to be poor in the lower elevation watersheds, largely on private lands. Land use intensification on private lands has also led to more than half of each of 11 habitats being in or near developed human land uses. Particularly of concern are riparian habitats, of which only 11% remain undeveloped on private lands across the GYE. Exotic species, noxious weeds, and overabundant mesocarnivore native species dominate these developed lands and reduce the viability of native species (Hansen et al. 2002). In contrast to private lands, habitat intactness has been relatively stable on public lands. Native fish populations have been declining, particularly on private lands due to the land use change, climate impacts on streams, and invasive species described above. Thus, trends in hydrologic integrity, habitat intactness, and native fish were



Vital sign	National parks and wilderness	Other federal lands	Private lands	Forecast
Snowpack	🟨	🟥	🟥	🟥
Stream flow/temperature	🟥	🟥	🟥	🟥
River integrity	🟩	🟨	🟥	
Forest mortality	🟨	🟨	🟩	🟥
Wildfire deviation	🟩	🟩	🟩	🟥
Forest climate suitability	🟩	🟩	🟩	🟥
Habitat intactness	🟢	🟢	🟥	
Large mammals	🟢	🟢	🟢	
Native fish	🟩	🟨	🟥	

🟥 Deteriorating 🟨 Possibly deteriorating 🟩 Relatively stable 🟢 Improving

Fig. 11. A Wildland Health Index Scorecard for the Greater Yellowstone Ecosystem based on evaluation of condition and trend in vital signs of ecological integrity in this assessment. Modified from Hansen and Phillips (2016).

assigned as likely deteriorating on private lands and relatively stable or improving on some public lands. The population status of large mammals was scored as improving across all land allocation types. This is a result of the highly effective wildlife restoration efforts that have occurred across public and private lands.

In summary, the WHI Scorecard for GYE indicates that snowpack, stream flow and temperature, and forest mortality are deteriorating or possibly deteriorating across all land allocations now and they as well as wildfire deviation and forest climate suitability are projected to deteriorate in the future. Fluvial ecosystems and native aquatic communities on private lands are likely deteriorating, due to both climate change and land use intensification. Intactness of natural habitats is also likely deteriorating on private lands. Whether these systems are approaching or have reached tipping points of irreversible degradation unknown, but should be a high priority for research and adaptive management. The large native fish kill in the Yellowstone River and resulting economic losses during the record low flow in 2016 (Al-Chokhachy et al. 2017) illustrated the importance of addressing the issue.

Current assessment and reporting in the GYE

The information required to assess trends in ecological integrity of the GYE is far from complete (Table 6). The highest level of monitoring, analysis, and reporting is within the national parks. The National Park Service has developed a rigorous monitoring program nationwide

Table 6. Current level of monitoring, evaluation, and reporting of vital signs of ecological integrity for the GYE by land allocation type.

	Monitored				
Vital sign	National Parks	Other federal	Private	Trends systematically evaluated	Reported in media
Human density	X	X	X	NPS	Locally
Land use	X	X	X	NPS	
Visitation	X		NA	NPS, USFS	GYE
Backcountry visitor nights	X				
Hunting/fishing use	X			YNP	
Resort skiing	NA	X	X		
Motorized/nonmotorized backcountry use					
Temperature/precipitation	X	X	X	NPS	Locally
Invasive species	X			NPS	
Fish and wildlife disease	X	X	X	NPS	Locally
Air quality	X			NPS	
Snowwater equivalent (Apr 1)	X	X	X		
River discharge	X	X	X		
Water quality	X				
Stream temperature	X	X	X		
Hydrologic integrity					
Vegetation productivity	X	X	X		
Forest mortality	X	X	X		
Burned area	X	X	X		Locally
Forest structure/composition	X	X	X		
Habitat fragmentation					
Gray wolf, grizzly bear, bison populations	X	X	X	Interagency	GYE
Other large mammal populations	X			NPS	
Ungulate migrations	YNP	Wyoming	Wyoming		
Birds at risk	X			NPS	
Breeding birds, wintering birds	X	X	X		
Native fish	X			NPS	
Amphibians	X			NPS	

Notes: GYE, Greater Yellowstone Ecosystem. Cells with "X" indicate monitoring is performed. Cells with "NA" indicate the vital sign is not applicable.

(Fancy et al. 2009, Rodhouse et al. 2016), landscape-level data for individual parks are systematically evaluated by the central national program NPScape (Monahan et al. 2012), and both Yellowstone and GTNPs periodically evaluate trends in vital signs (YCR 2013, USDI 2017) and provide results online (www.nps.gov/yell/learn/management/vitalsigns.htm; www.nps.gov/grte/learn/nature/vital-signs.htm). Other federal agencies have important monitoring programs at the national scale such USGS stream and snow monitoring, USFWS Breeding Bird Survey, and the USFS Forest Inventory and Analysis Program. Unfortunately, results of these national monitoring efforts are not systematically evaluated by agencies within the GYE nor reported in the media. Monitoring on private lands is very limited. The only measures of ecological integrity that are regularly monitored across the private and public lands are those done by national programs noted above. Monitoring and reporting is done across the entire ecosystem primarily for high-profile mammal species that are largely restricted to public lands (e.g., grizzly bear, gray wolf, bison) and also whitebark pine across high-elevation public lands. Consequently, environmental decision makers, such as county commissioners, do not have the benefit of including impacts on GYE ecological integrity in the information they consider when evaluating development projects such as subdivision approvals.

Ecological health reporting in other wildland systems

Like the GYE, most large wildland ecosystems in the United States are not subject to evaluation of trends in ecological integrity (Hansen et al. 2014). Vital sign report card approaches have been used more widely for aquatic systems. Vital signs of ecosystem health are a core element of the Everglades Restoration Project, one of the most expensive in US history. Eleven system-wide indicators have been carefully selected to assess the progress of the restoration program from a system-wide perspective by showing how key ecological components respond comprehensively to implementation of restoration projects (Brandt et al. 2014). Similarly, the Chesapeake Bay Program (www.chesapeakebay.net/state) and Chesapeake Bay Foundation (www.cbf.org) issue State of the Bay reports covering the entire watershed, which spans six states. The reports examine the best available historical and current information for 13 indicators in three categories: pollution, habitat, and fisheries. Taken together, these indicators offer an assessment of the Chesapeake's health. Additionally, the University of Maryland Integration & Application Network's (IAN) (http://ian.umces.edu/) report card provides a transparent, timely, and geographically detailed annual assessment of Chesapeake Bay health. It rates 15 reporting regions of the bay using seven indicators that are combined into a single overarching index of health. Both the State of the Bay report and the IAN report card are widely covered in the national media.

The IAN has expanded its ecosystem assessment by developing the ECO HEALTH Report Card process. The process allows users to conceptualize values, measure indicators, define thresholds of health, calculate scores, and communicate results. The process has been applied to several watersheds across the United States and internationally. Connolly et al. (2013) review aquatic and marine ecosystem health reporting efforts globally. The success of these efforts for aquatic systems suggests high benefits for applications to terrestrial wildland systems.

Implications and recommendations

Our results reveal the importance of the selection of the area of analysis of GYE health. Extensive assessment of the spatial extent of species and ecological processes centered in the national parks and wilderness areas has led to consensus that the greater ecosystem includes the network of federal lands as well as surrounding state, tribal, and private lands (Keiter and Boyce 1991). We found that the differences in ecological integrity across the GYE largely coincide with land allocation. With regard to the impacts of land use, the public lands in GYE are arguably well managed due to the legal mandates and expertise and resources of federal and state agencies. This is a considerable achievement because these public land managers are challenged by the large spatial extent of the GYE and the complex mix of management jurisdictions.

It is, of course, the places where people live, work, and grow food that nature conservation is most challenged by land use intensification. In mountainous systems like the GYE, private lands and human endeavors are concentrated in the small portion of the system that is most important for native species and key ecosystem processes (Hansen et al. 2002). The locations with more favorable climate, better soils, surface water, and groundwater that attract people are also locations of high ecological productivity, native species diversity, key seasonal habitats, and higher demographic performance of wildlife. Consequently, the condition of these lower elevation private lands is vital to the ecological integrity of the broader ecosystem. Moreover, many invasive species and diseases gain entry into the ecosystem in the more heavily impacted private land component, with potential to then move upstream and upslope into the federal lands. Hence, monitoring, evaluation, and management on private lands are critically important to sustaining ecological integrity on public lands.

Climate change is a threat to the ecological integrity of both public and private lands of the GYE. This is evident in the observed changes in snowpack, runoff, and forest mortality in recent decades, and by the ecological forecasts suggesting strong negative impacts on ecological processes and vegetation and fish populations in coming decades. The federal agencies of the GYE are increasingly having to focus personnel, education programs, planning, and management on climate adaptation (Olliff and Hansen 2016).

We suggest that implementation of the WHI across the GYE is an important step in sustaining ecological integrity. Doing so would provide knowledge of recent past reference conditions, current trends and forecasts, vital signs most at risk of becoming destabilized, and a means of reporting to the GYE community. The key challenges regarding application of the WHI in GYE are continued enhancement of the monitoring and evaluation approach employed by the NPS I&M Program and the national park; and scaling the approach up to the full extent of the GYE.

The NPS I&M Program (https://www.nps.gov/im/gryn/index.htm) was designed based on state-of-the-art principles (Fancy et al. 2009) and has been increasingly embraced by the national parks in the GYE for monitoring the condition of ecological vital signs (YCR 2013, USDI 2017). NPS values and ecological objectives were used identify ecological targets for monitoring. Conceptual models of drivers, responses, and consequences of these ecological targets were developed that identify key vital signs of ecological health. Statistical sampling methods were used to design monitoring protocols. Monitoring was initiated for a subset of vital signs based on priority, feasibility, and capacity.

We suggest this impressive NPS program could be enhanced by more explicit evaluation of trends in condition based on objective thresholds (Mazzotti et al. 2009); employing ecological forecasting to place recent trends in vital signs in the context of potential future trends under alternative land use and climate scenarios (Hansen et al. 2016*a*, *b*, Thompson et al. 2016); and by more effectively communicating trends in the condition of vital signs through a WHI scorecard as illustrated in this paper.

The NPS I&M program should be scaled up to include all public and private lands in the GYE and integrated with other federal monitoring programs (e.g., USFS Inventory and Monitoring Program, USFWS Breeding Bird Survey, USGS National Streamflow Information Program), as well as state and local efforts. Such an effort would require: setting goals and identifying relevant vital signs based on the values and objectives of multiple stakeholders; expanding current monitoring efforts into a statistically sound, annually repeated, ecosystem-wide program; evaluating trends in condition relative to scientifically valid thresholds; and communicating results in ways that are compelling to the diverse stakeholders that make decisions that influence the health of the ecosystem.

Scaling up of scientific assessment of vital signs to the full GYE poses several challenges. Stakeholders include diverse public and private entities that may have differing values and objectives. No single entity is responsible for facilitating conservation across the system and network governance is likely needed. Monitoring costs would be high due to the large size of the GYE. Many of these challenges have been overcome, however, in other large landscapes such as the Everglades ecosystem and the Chesapeake Bay watershed (references above). We suggest a next step for the GYE is for federal and state agencies and private groups who are currently monitoring in the ecosystem to work toward integrating their efforts toward a comprehensive WHI approach. As a positive step in this direction, a panel discussion on this theme is scheduled for an upcoming Yellowstone Biannual Science Conference (https://www.nps.gov/yell/learn/scientificconferences.htm) and an issue of Yellowstone Science (https://www.nps.gov/yell/learn/yellowstone-science.htm) is focused on vital sign monitoring within the ecosystem.

Successful application of the WHI to the GYE would likely serve as an important demonstration of the approach and increase likelihood of applications to other wildland ecosystems across the United States and perhaps even other nations.

CONCLUSION

Like many other remaining wildland ecosystems across the world, the GYE is at a crossroad. The natural factors that inhibited human expansion here in the past are now major attractants for people and businesses that value access to high-quality nature. The resulting land use pressures on private lands and climate change stresses on public lands have degraded some vital signs of ecological integrity within the GYE. These forces are projected to increase in the coming decades, raising questions about the future for sustaining the GYE as a wildland ecosystem. If Yellowstone, as the first national park, inspired the creation of the global system of protected areas, can the GYE inspire progress toward more systematic evaluation and reporting of wildland ecological health? Systematic application of the WHI to GYE is an important step in the large landscape conservation planning approach that is ultimately needed to better sustain this and other iconic wildlands.

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