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Forest Vulnerability Assessments—Integrating Social and Ecological Indicators and Scores

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Abstract

This guide builds on existing frameworks to link ecological and socio-economic vulnerability. Vulnerability assessments use spatially explicit ecological and economic data to describe the exposure, sensitivity, and adaptive capacity of forest resources and local communities to potential hazards. This work describes ways to measure each aspect of vulnerability and ways to aggregate data that makes for more straightforward analysis. Knowledge about the relative vulnerability of natural resources and the communities that depend on them can help prioritize and inform management and guide adaptation strategies. In the context of national forest management, vulnerability results can inform land management planning (e.g., assessments, public communication, plan objectives), as well as landscape or project–level decisions (e.g., forest restoration, allotment management plans), to increase the resiliency of national forests and grasslands. Examples in this guide focus on climate change, but the framework can be applied to other hazards such as insects, disease, invasive species, and drought.

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WHY CONSIDER INTEGRATED VULNERABILITY INDICES?

Knowledge about the relative vulnerability of forested and rangeland areas at risk from climate change and other hazards is needed to help prioritize and inform management efforts and strategies. Vulnerability assessments contribute to this knowledge by using spatially explicit ecological and economic data to describe the exposure, sensitivity, and adaptive capacity of forest resources and local communities to potential hazards. Vulnerability assessment results can be used to help design adaptation strategies that enhance ecological and social resiliency in areas of greatest risk. In the context of national forest management, vulnerability results can inform land management planning (e.g., assessments, public communication, plan objectives), as well as landscape or project–level decisions (e.g., forest restoration, allotment management plans), to increase the resiliency of national forests and grasslands. When available data are limited and uncertainty is high, the results from vulnerability assessments can also serve to focus and stratify monitoring strategies and data collection efforts.

Vulnerability is a function of a given resource's exposure, sensitivity, and capacity to adapt to a hazard. When many variables are involved, the process of drawing conclusions about vulnerability can be challenging. Aggregating variables into one or more vulnerability indices or scores can facilitate that process. In addition to the condition and health of the resource itself, people and communities often want to understand more about their own exposure, sensitivity, and capacity to adapt to potential changes in vulnerable resources. Indices for social vulnerability can therefore be considered in combination with ecological indices to provide a more comprehensive picture of overall vulnerability.

HOW ARE VULNERABILITY INDICES DEVELOPED?

Descriptions of frameworks and methodologies for ecological and social vulnerability assessments are available in other reports or studies.[1] This guide builds on existing frameworks by using the concept of forest goods and services to anchor the links between ecological vulnerability and socio-economic vulnerability. Examples in this guide focus on climate change, but the framework can be applied to other hazards such as insects, disease, invasive species, and drought.

Figure 1 shows a sequence of steps for developing vulnerability scores for a given hazard, resource, and socio-economic impact area. Figures 2 and 3 show examples of rangeland (grazing) and water resource (drinking water supply) vulnerability to climate change.

[1]For socio-economic vulnerability, see: Hand, Michael S.; Eichman, Henry; Triepke, F. Jack; Jaworski, Delilah. 2018. Socioeconomic vulnerability to ecological changes to National Forests and Grasslands in the Southwest. Gen. Tech. Rep. RMRS-GTR-383. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 100 p. For ecological vulnerability, see: Glick, Patty; Stein, Bruce A.; Edelson, Naomi A., eds. 2011. Scanning the conservation horizon: a guide to climate change vulnerability assessment. Washington, D.C.: National Wildlife Federation. 168 p. Other studies are cited in: Halofsky, Jessica E.; Peterson, David L.; Ho, Joanne J.; Little, Natalie, J.; Joyce, Linda A., eds. Climate change vulnerability and adaptation in the Intermountain Region [Parts 1 and 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 513 p.

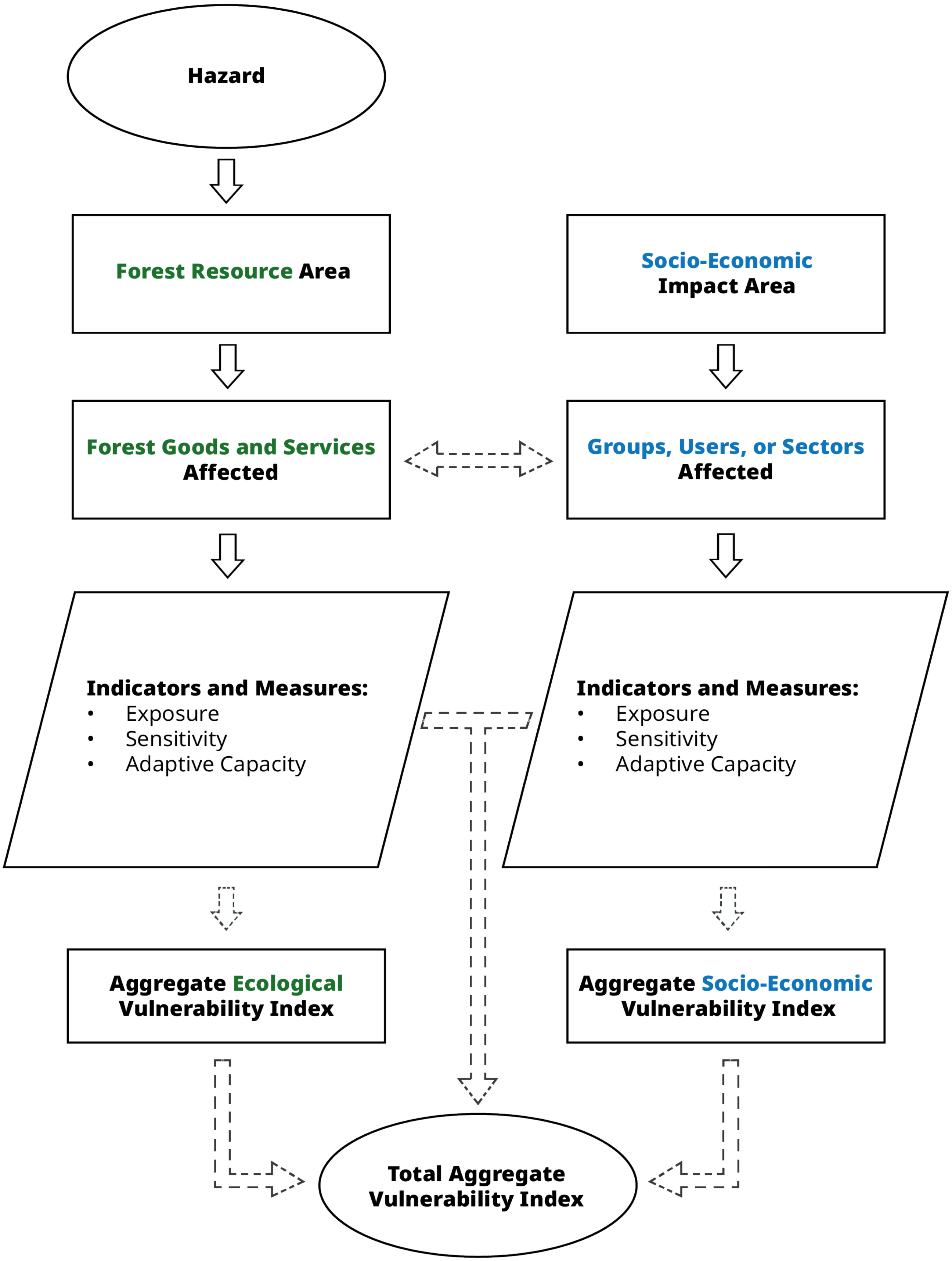

Figure 1—Framework for ecological and social/economic vulnerability indices.

The general steps for developing vulnerability indices are presented in figure 1 and can be summarized as follows:

1. Identify the hazard: The examples presented in this report focus on natural hazards like climate change, pests, and wildfire, but the methods could just as easily apply to human based hazards like disease outbreak and economic recession.

2. For ecological vulnerability, identify the following:

    a. Forest resource, including the geographic boundary and area units affected by the hazard (e.g., rangelands and range vegetation within a U.S. Forest Service region or grazing allotment).

    b. Goods and services (e.g., provisioning, recreation/cultural, regulating, and support services) derived or "flowing" from the forest resource (e.g., fo age and water for livestock).

    c. Indicators and measures[2] for each of the three components of vulnerability:

        i. Exposure: The likelihood or degree to which the good or service is exposed to the hazard (e.g., projected change in rangeland forage productivity from climate change).

        ii. Sensitivity: The degree to which the good or service responds to exposure to the hazard (e.g., current condition and productivity of rangeland forage; what are baseline conditions?).

        iii. Adaptive capacity: The ability of the good or service to adjust to or cope with the hazard (e.g., fire regime condition of angeland).

3. For socio-economic vulnerability, identify the following:

    a. Social/economic impact area or population, including units for describing subsets of areas or populations subject to socio-economic vulnerability (e.g., counties, population served).

    b. Socio-economic groups, users, or sectors directly affected by changes in forest goods and services (e.g., business or economic sectors; population of consumers). Socio-economic groups or sectors may be equal to, or subsets of, people or businesses in the social/economic impact area.

    c. Indicators and measures for each of the three components of vulnerability:

        i. Exposure: The degree to which groups or sectors use or rely on the affected goods and services (e.g., the amount of forage on forest lands used by the livestock industry).

        ii. Sensitivity: The degree to which communities or economies depend on, or are impacted by, changes in goods and services (e.g., the percentage of regional employment in the livestock sector).

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[2] A single measure for exposure, sensitivity, or adaptive capacity may include multiple indicators or variables.

iii. Adaptive capacity: The ability of communities, groups, or sectors to adjust to changes in goods and services (e.g., access to capital or credit; availability of substitutes; economic diversity and access to alternative sources of income).

4. Estimate total final vulne ability using different options for aggregating ecological and socio-economic indicators and measures, including:

    a. Creating separate ecological and socio-economic vulnerability indices using respective indicators and measures of exposure, sensitivity, and adaptive capacity, then combine ecological and socio-economic vulnerability indices to create a total vulnerability index (see fig. 2 and Attachment A for example). This approach provides opportunities to apply different weights to ecological and socio-economic components, and illustrates the relative importance of ecological and socio-economic factors in total vulnerability; or

    b. Combining socio-economic and ecological indicators to create aggregate measures of exposure, sensitivity, and adaptive capacity, then combine the three measures to create a total vulnerability index (see fig. 3 and Attachment B for example). This approach can be easier to implement and present when ecological and socio-economic indicators are hard to differentiate.

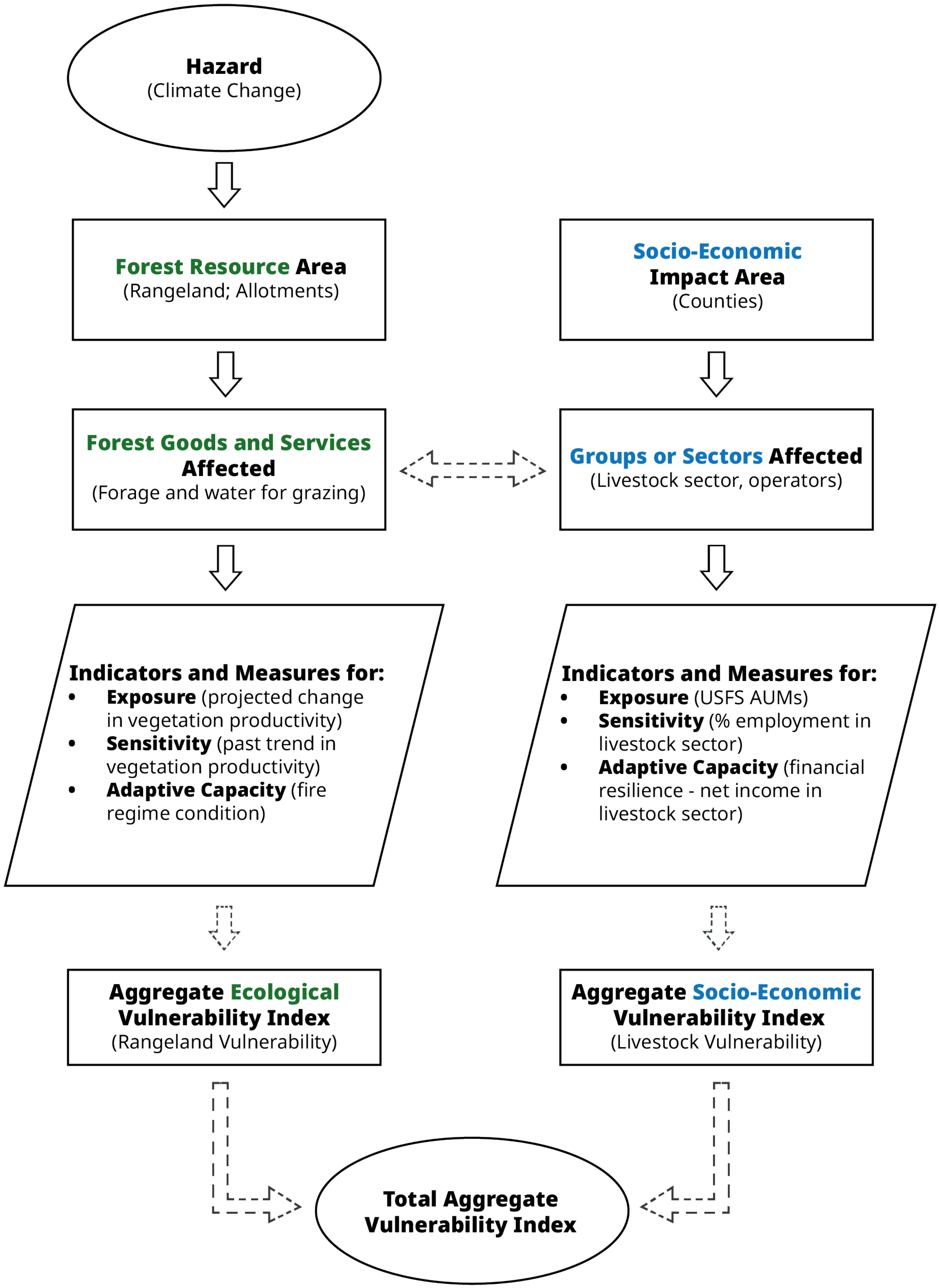

Figure 2—Example of vulnerability index: rangeland and grazing.

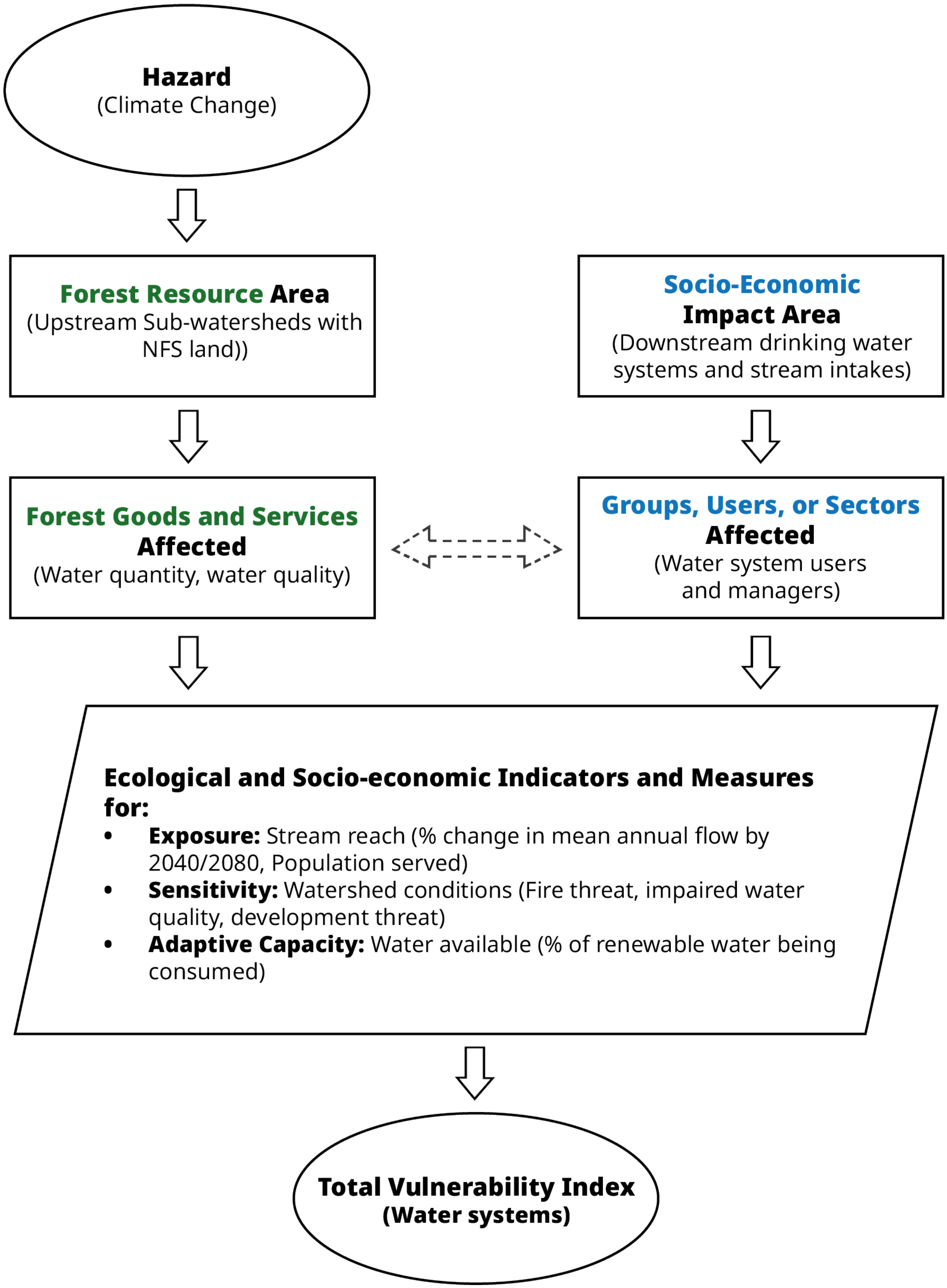

Figure 3—Example of vulnerability index: drinking water systems.

WHAT ARE SOME CONSIDERATIONS IN DEVELOPING VULNERABILITY INDICES?

Analysts have a great deal of flexibility when determining the number and types of indicators to use in measuring components of vulnerability, as well as the functions and assumptions used to aggregate indicators into component measures and vulnerability index scores.

Indicators and Measures

Indicators should be selected that can describe, directly or through proxy, the following components of vulnerability:

- **Exposure:** Projected changes in the resource conditions or flows of key goods or services caused by the hazard. For example, higher exposure might occur when forage productivity is projected to decrease and greater numbers of grazing permits depend on that forage.
- **Sensitivity:** Current or future conditions, including stressors or disturbances that affect how a resource or community responds to a hazard. For example, higher sensitivity might occur when current forage productivity is low and greater percentages of local jobs rely on livestock and agriculture.
- **Adaptive capacity:** Current or future conditions that affect how a resource or community can adapt or transition to new conditions and still provide ecological and socio-economic support. For example, higher adaptive capacity might result from greater biodiversity in the resource and greater business profitability and access to credit in communities using the resource.

Indicators should be quantitative, or capable of being converted into a quantitative rank or scale, and spatially explicit so information can be linked to resource management units, communities, or other socio-economic groups within a study area. Selecting the spatial unit of vulnerability assessment (e.g., allotment, county, district, sub-watershed) depends on the formats of available data as well as the final audience. Broader units (e.g., counties, national forests, districts) may be appropriate for public communication and outreach purposes, while more refined units (e.g., allotments, stands, sub-watersheds) m y be necessary to inform decisions about locations for management action and monitoring. Analysis of smaller spatial units can inform exposure and sensitivity to hazards, but it is important to note that vulnerability is inherently a community and landscape-scale measure.

Index Calculations and Assumptions

The assumptions and calculations used to combine indicators and measures into vulnerability indices will range in complexity and reflect the quality of available data, as well as perceptions about local resource and socio-economic needs. There are advantages to adopting simple and standardized assumptions (e.g., allows more direct comparisons of results across study areas), yet there may be local conditions that affect calculations (e.g., weighting of indicators to reflect local concerns). Calculation considerations include (1) function complexity and aggregation; (2) weights for measures of exposure, sensitivity, and adaptative capacity; and (3) standardizing data.

Functions for Aggregating Indicators, Measures, and Indices: There is no single best specification for vulnerability index functions, but indices should be increasing functions of exposure and sensitivity measures, and decreasing functions of adaptive capacity (e.g., Vulnerability = Exposure + Sensitivity - Adaptive Capacity). The calculations should strive to be mathematically and intuitively simple, and reproducible (e.g., simple summations or subtractions of measures).

The process of aggregating indicators and measures into indices may be an iterative process. For example, when many indicators are used, it may be easiest to merge indicators into separate measures of exposure, sensitivity, and adaptive capacity. Component measures can be combined into separate ecological and economic vulnerability indices that can then be merged into a final vulnerability index. Separate indices can be estimated for each good or service (e.g., forage and water for grazing), then merged into a single index of ecological vulnerability.

Weights and Sensitivity Analysis: To preserve mathematical simplicity, indicators and measures of exposure, sensitivity, and adaptive capacity can be assigned equal weighting in calculations (e.g., simply sum measures and indicators). However, analysts have the option of assigning different weights to measures or indicators to reflect the perceived level of importance of each variable in assessing vulnerability. Indicators can also be weighted by the total number of indicators. Otherwise, vulnerability measures will increase simply because the number of indicators increase, rather than due to any real change in vulnerability.[3]

The effect of different weights, as well as the importance of retaining individual indicators or variables, can be tested by conducting sensitivity analysis using different vulnerability index specifications, as well as ranges of indicator values. Effort should be made to minimize the number of indicators that have little influence on component measures or over all vulnerability results; some indicators may be highly correlated with other indicators and therefore of little use (e.g., a single indicator may capture the effects of multiple indicators).

Standardizing Measures and Indices; Identifying Outliers: Different indicators often have very different levels and ranges of data values. This creates the potential for some indicators to dominate calculation results. A solution is to standardize indicators, as well as component measures and index values to a mean of zero and a standard deviation of one. The advantage of standardization is that resulting vulnerability index scores for each unit of analysis (e.g., sub-watershed, county) can be easily interpreted relative to the average vulnerability score for the broader study area (e.g., region). The disadvantages of standardization include potentially losing important information from indicators or measures with naturally high variability, and the inability to compare standardized vulnerability scores across different study areas or regions. However, the advantages of standardizing often outweigh the disadvantages when magnitudes of values differ substantially across indicators or measures. As an alternative to standardization, analysts can transform data so that magnitudes of values are more consistent across indicators (e.g., divide by 1,000, or use log transformations).[4]

[3] Tate, E. 2012. Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis. Natural Hazards. 63(2): 325–347.
[4] Cutter, S.L.; Boruff, B.J.; Shirley, W.L. 2012. Social vulnerability to environmental hazards. Social Science Quarterly. 84(2): 242-261.

Even after standardizing values, there is potential for some vulnerability results to be unexpectedly or abnormally high or low, due to combinations of extreme measures or indicator values for a given unit within the study area. Outliers have the potential to skew the vulnerability results, as well as study area averages, but may also contain valuable information. Best practices suggest consulting with a statistician about suspected outliers and discussing whether removing them from the data analysis makes sense. As an example, very high amounts of Forest Service animal unit months (AUM) in a few counties may skew standardized indicators of exposure that can in turn skew distributions of socio-economic vulnerability to the high side, and limit the ability to describe variation across counties on the low vulnerability side of the distribution.

CONCLUSIONS

The vulnerability assessment framework presented in this note is tailored to inform forest management and decision-making, demonstrating how vulnerability assessments can account for both ecological and socio-economic factors, using readily accessible spatial data. Though the range of vulnerability assessments for forest resources is expected to vary in scope and complexity from what is presented in the examples, the same concepts and steps are expected to apply. Data sources, methods, tools, and theory will continue to evolve within the fields of natural resource and environmental management, as well as other areas of management that face risks and uncertainty. As a consequence, modifications and expansions of this framework are encouraged. Examples include the incorporation of methods to account for risk, such as Monte Carlo analysis, and customizing frameworks that dovetail with adaptive management.

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ATTACHMENT A—VULNERABILITY EXAMPLE: RANGELAND

This attachment summarizes the application of the vulnerability index methodology to rangelands and grazing on national forests in the Intermountain Region (Region 4). The results presented here are for demonstration purposes and should not be cited; additional input from staff specialists is needed to refine variables and data selected for final vulnerability analysis. The methodology can easily accommodate alternative vulnerability specifications. For more details about the methods, data, and results in this example, see "Vulnerability to Climate-Induced Changes in Grazing Services on National Forest Land in the Intermountain West" (Elmer 2018)[5].

This demonstration considers the impacts of climate change on rangeland vegetation and hydrology, as well as the ripple effects on forage and water supplies from rangelands that local livestock operators rely on. Spatially explicit data describing current and projected range conditions, accounting for climate change, are used to characterize the ecological vulnerability of rangelands (i.e., "rangeland vulnerability"). Economic data for the livestock sector are used to assess the economic vulnerability of producers and communities at the county level (i.e., "livestock vulnerability"). Rangeland and livestock vulnerability are added to estimate total vulnerability that accounts for ecological and economic factors.

Vulnerability is assumed to be the sum of measures of exposure and sensitivity, minus adaptive capacity, where each vulnerability component is a composite of underlying variables:

a. Vulnerability (V) = Exposure + Sensitivity - Adaptive Capacity

i. Exposure (E) = $E1 + E2 + \ldots + EN$

ii. Sensitivity (S) = $S1 + S2 + \ldots + SM$

iii. Adaptive capacity (AC) = $A1 + A2 + \ldots + AK$

Rangeland (ecological) vulnerability is the sum of forage and water supply vulnerabilities, using existing ecological data and climate change projections on Forest Service grazing allotments.

b. $V_{Rangeland} = V_{Forage} + V_{Water}$, where

i. $V_{Forage} = E_{Forage} + S_{Forage} - AC_{Forage}$

ii. $V_{Water} = E_{Water} + S_{Water} - AC_{Water}$

Livestock (economic) vulnerability utilizes county-level economic data for the livestock sector.

c. $V_{Livestock} = E_{Livestock} + S_{Livestock} - AC_{Livestock}$

[5] See Chapter 3 in: Elmer, M. 2019. Essays on natural disturbances and the provision of ecosystem services: Monetizing impacts, assessing management tradeoffs, and measuring vulnerability. Fort Collins, CO: Colorado State University. Dissertation for Degree of Doctor of Philosophy, Department of Economics.

Final or aggregate vulnerability is the sum of Rangeland and Livestock vulnerabilities.

d. $V_{Final} = V_{Rangeland} + V_{Livestock}$

Rangeland vulnerability identifies allotments where climate-driven changes in fo age and water pose a risk to grazing opportunities. Livestock vulnerability identifies counties where livestock operators and local economies may be at risk from reductions in forage and grazing services on Forest Service lands. Final vulnerability scores require consistent units for rangeland and livestock vulnerabilities, so the average of rangeland vulnerability across allotments within a county is adopted as the county-level rangeland vulnerability score.

All underlying variables, component measures, and final vulne ability scores are standardized to a mean of zero and a standard deviation of one. This demonstration evaluates 1,426 grazing allotments in Region 4, spanning 67 of the 85 counties in the Region. Table A1 provides a list of variables used in the vulnerability calculations for this demonstration. The effects and robustness of these implicit weighting assumptions associated with the calculations can be tested using sensitivity analysis.

Table A1—Component measures, variables, and data sources.

Vulnerability	Component measure	Variables	Source
Rangeland forage vulnerability (ecological)	Forage exposure	Projected change in net primary production based on A1B 2080 climate projections[1]	Reeves and Lankston 2018
		Projected change in variability of net primary production (A1B 2080) as a proxy for uncertainty	Reeves and Lankston 2018
	Forage sensitivity	IAP nonforested vegetation climate change sensitivity score, reflecting resistance to climate change	Halofsky et al. 2018
		Trend of net primary production, 2000–2015	Reeves and Lankston 2018
		Coefficient of variation of net primary production, 2000–2015	Reeves and Lankston 2018
		Drought resistance, 2000–2015	Palmer Drought Index
		Forage appropriation rate, 2014–2016 average, reflecting % of NPP used by livestock	Forest Service/Region 4 data; NRM Matt Reeves 2017
	Forage adaptive capacity	IAP nonforested vegetation climate change adaptive capacity score, reflecting species composition, landscape condition, and invasive species	Halofsky et al. 2018
		Rangeland vegetation condition—native and nonnative plants.	USDA WCC 2010
		Fire regime condition, reflecting departure from historic range	USDA WCC 2010
		Terrestrial invasive species condition	USDA WCC 2010

Table A1 continued.

Vulnerability	Component measure	Variables	Source
Rangeland water vulnerability (ecological)	Water exposure	Projected change in mean summer streamflow based on A1B 2080 climate projections, reflecting seasonal water availability	USDA Stream flow metric
		Projected change in runoff timing, A1B 2080, reflecting potential for seasonal stress	USDA Stream flow metric
	Water sensitivity	Water quantity condition for watershed	USDA WCC 2010
		Water quality condition for watershed	USDA WCC 2010
	Water adaptive capacity	Riparian and wetland vegetation condition for watershed	USDA WCC 2010
		Soil condition for watershed	USDA WCC 2010
		Projected change in mean annual streamflow, A1B 2080, reflecting change in overall water supply	USDA Stream flow metric
Livestock vulnerability (socio-economic)	Livestock exposure	Authorized AUMs on Forest Service rangelands in the county, 2014–2016 average, reflecting level of livestock use	USFS/Region 4 data; NRM
		Forest Service fraction of total AUMs in the county, 2014–2016 average, reflecting relative importance of Forest Service lands	USDA NASS
	Livestock sensitivity	Livestock employment location quotient, 2015, reflecting importance of livestock in the community[2]	USDA NASS
		Livestock earnings concentration, 2015, reflecting importance in the community[3]	USDA NASS
		Total employment in the livestock industry, 2015, reflecting importance in the community	USDA NASS
		Proprietor income, reflecting importance of livestock to business ownership[4]	USDA NASS
		Land in grazing, reflecting community commitment to livestock	USDA NASS
		NPP on Forest Service rangelands relative to NPP on private rangelands, reflecting livestock reliance on NFS lands	Reeves and Lankston 2018
	Livestock adaptive capacity	Livestock income per worker, as proxy for financial capacity	USDA NASS
		Livestock business net income—proxy for financial capacity	USDA NASS
		NPP on Forest Service rangelands relative to NPP on non-Forest Service public rangelands, reflecting alternative fo age supplies	Reeves and Lankston 2018

[1] AIB 2080 refers to the A1B climate change projection out to the year 2080. Data for other climate change projections are available.
[2] Location quotient is concentration (%) of labor in livestock sector, relative to entire United States.
[3] Earnings concentration is concentration of labor income from livestock, relative to total earnings in the county.
[4] Income received by sole proprietors and partnerships in livestock, excluding corporate farms.
NASS = National Agricultural Statistics Service; WCC = Watershed Condition Classification; IAP = Intermountain Adaptation Partnership. Reeves, M.C.; Lankston, R. 2018. The Rangeland Production Monitoring Service (RPMS). Available at: https://www.fuelcast.net/rpms-product.

Definitions of Vulnerability and Underlying Variables

Rangeland Vulnerability identifies Forest Service grazing allotments where grazing opportunities are vulnerable to climate-induced reductions in forage and/or water supplies. It is a function of:

- **Rangeland Exposure**, measuring the degree to which climate change is expected to impact forage and water supplies, and therefore grazing services;
- **Rangeland Sensitivity**, measuring the degree to which rangeland forage and water supplies respond to climate change based on current allotment conditions and use; and
- **Rangeland Adaptive Capacity**, measuring the ability of rangeland forage and water supplies to adjust to, or cope with climate change, based on existing rangeland ecological conditions on each allotment.

Livestock Vulnerability identifies livestock operators and counties that are vulnerable to reductions in grazing services as a result of climate change. It is a function of:

- **Livestock Exposure**, measuring the degree to which livestock operators depend on Forest Service grazing services in each county;
- **Livestock Sensitivity**, measuring the degree to which livestock operators and counties respond to changes in grazing services, based on existing livestock sector economic conditions in each county; and
- **Livestock Adaptive Capacity**, measuring the ability of the livestock industry and county to adapt to, or cope with, reductions in grazing services, based on existing livestock sector economic conditions in each county.

Classifying Vulnerability

All composite indicators (exposure, sensitivity, adaptive capacity, and vulnerability) are standardized to a mean of zero and a standard deviation of one so that the results for each allotment/county can be interpreted relative to the average in the Region. Due to varying numbers of variables within component indicators, variables are not necessarily given equal weight in final vulne ability scores. The cutoffs for classifying indicators and vulnerability scores are based on standard deviations (SD) as shown in figure A1, assuming a normal distribution.

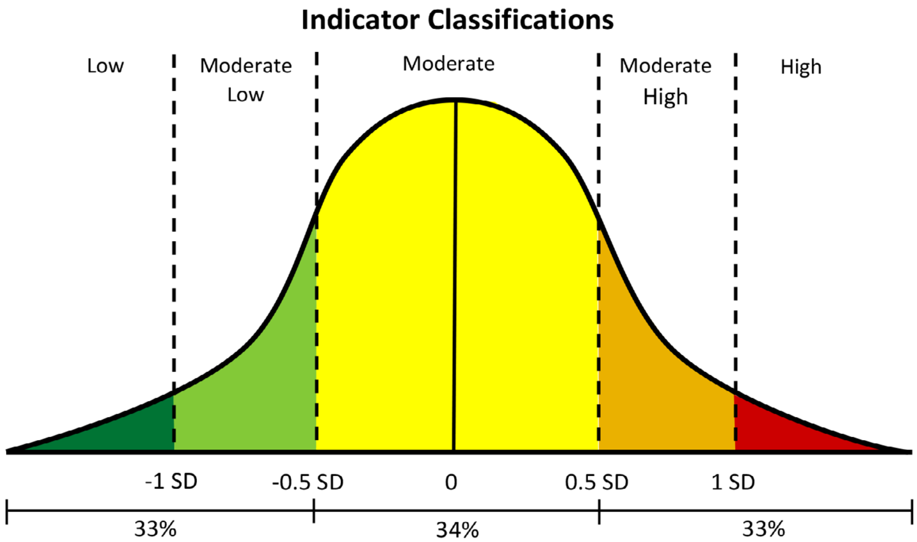


Figure A1—Indicator classifications and cutoffs for vulnerability scores.

The “moderate” category is intended to capture the middle third of the distribution, while the remaining third in each tail is divided into two categories of vulnerability. This approach identifies only the scores that reasonably diverge from the mean. Each standardized indicator is bounded between [-3, 3] so that outliers do not bias final vulne ability scores.

Demonstration Results: Rangeland and Livestock Vulnerability

The maps in figures A2 to A7 show the locations of potentially vulne able Forest Service grazing allotments and livestock sectors (at the county level). Recall that livestock sector (economic) vulnerability is measured at the county level, while rangeland (ecological) vulnerability is measured at the allotment level. County–level rangeland vulnerability is the average of rangeland vulnerability across allotments within a county. Following the maps is table A2a-d, which lists the vulnerability scores by county. Included in table A2a-d is the average annual AUMs authorized on Forest Service allotments in each county, highlighting the level of grazing services linked to vulnerability.

The drivers for vulnerability vary across Region 4 and by State. Grazing allotments in Nevada are projected to be highly exposed to climate–induced stress on both forage and water supplies (see figs. A2 and A3), and therefore have high angeland (ecological) vulnerability (table A2a-d). In contrast, vulnerability in Utah and Idaho counties tends to be influenced more by livestock (socio-economic) vulnerability, driven by higher livestock sensitivity (see figs. A4 and A5). Livestock vulne ability also tends to be somewhat higher in Wyoming counties, but it is driven more by low livestock adaptive capacity (fig. A5)

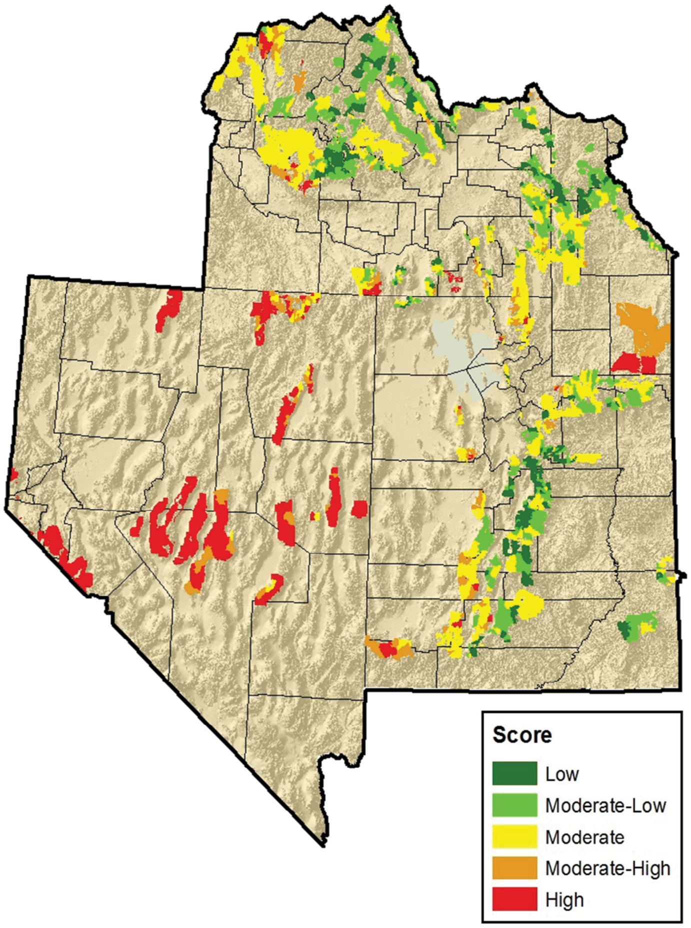
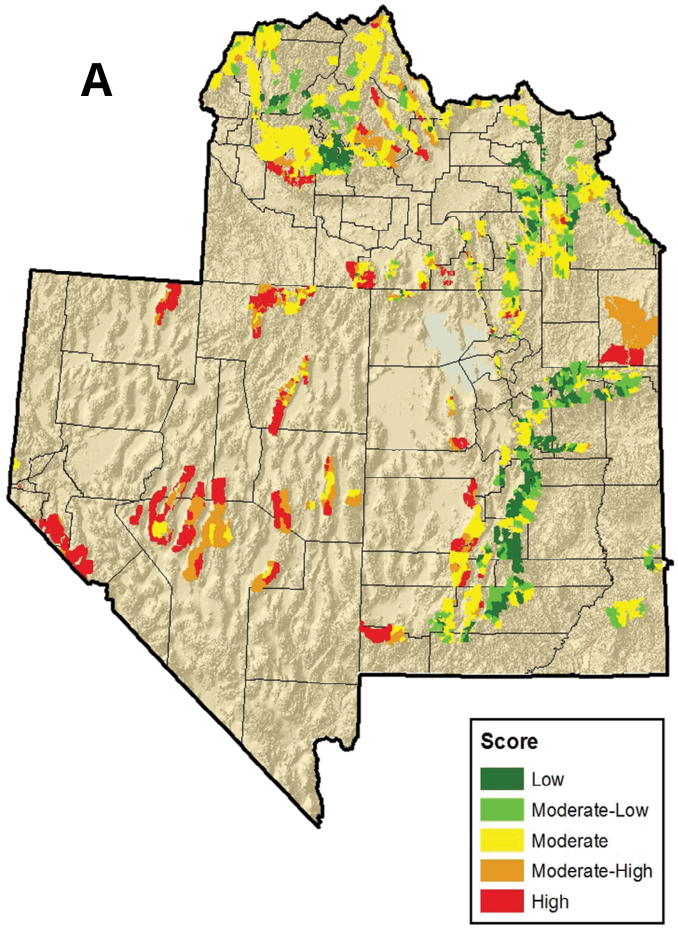


Figure A2—Rangeland (ecological) vulnerability (forage and water) for allotments.



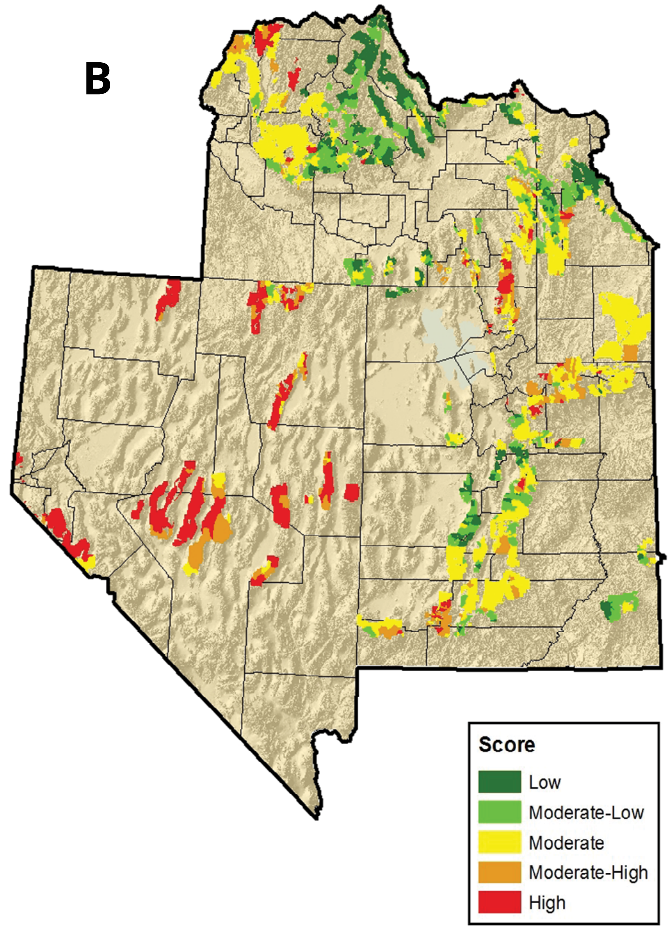


Figure A3—Separate forage vulnerability **(A)** and water vulnerability **(B)**.

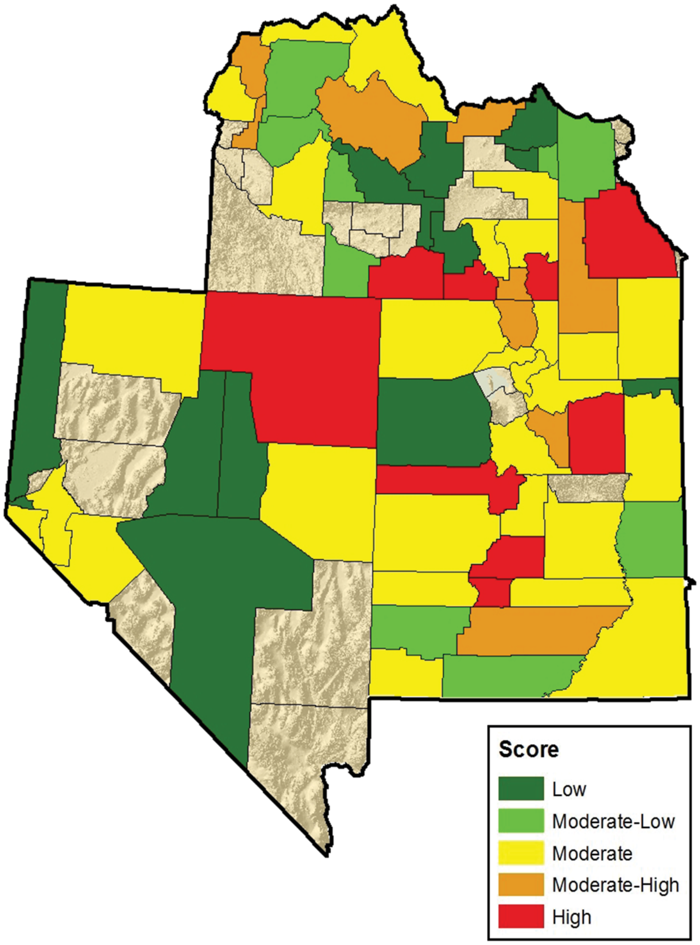


Figure A4—Livestock (socio-economic) vulnerability, by county.

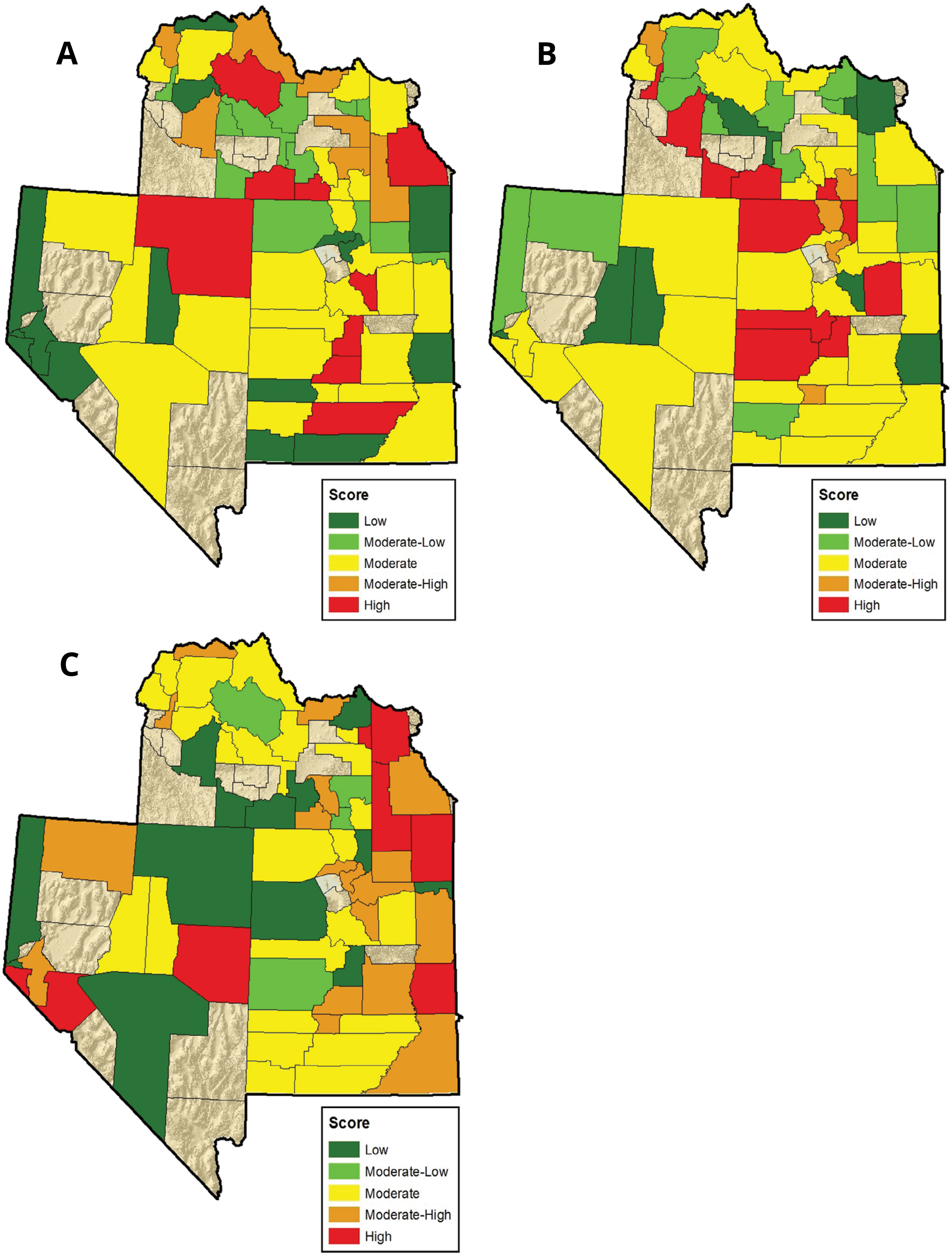


Figure A5—Livestock exposure **(A)**, sensitivity **(B)**, and adaptive capacity **(C)**, by county.

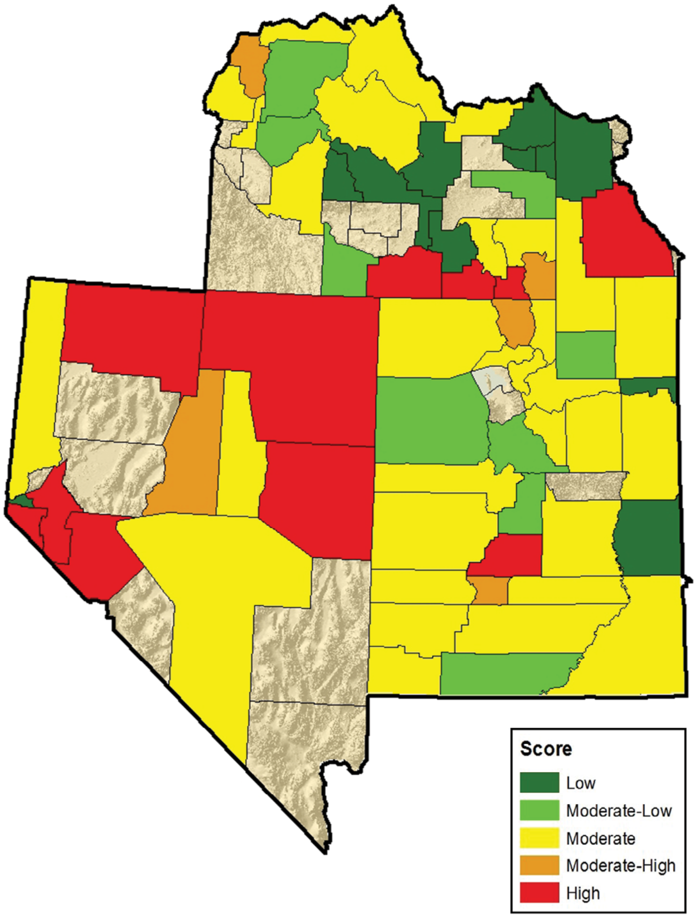


Figure A6—Final aggregate rangeland and livestock vulnerability score, by county.

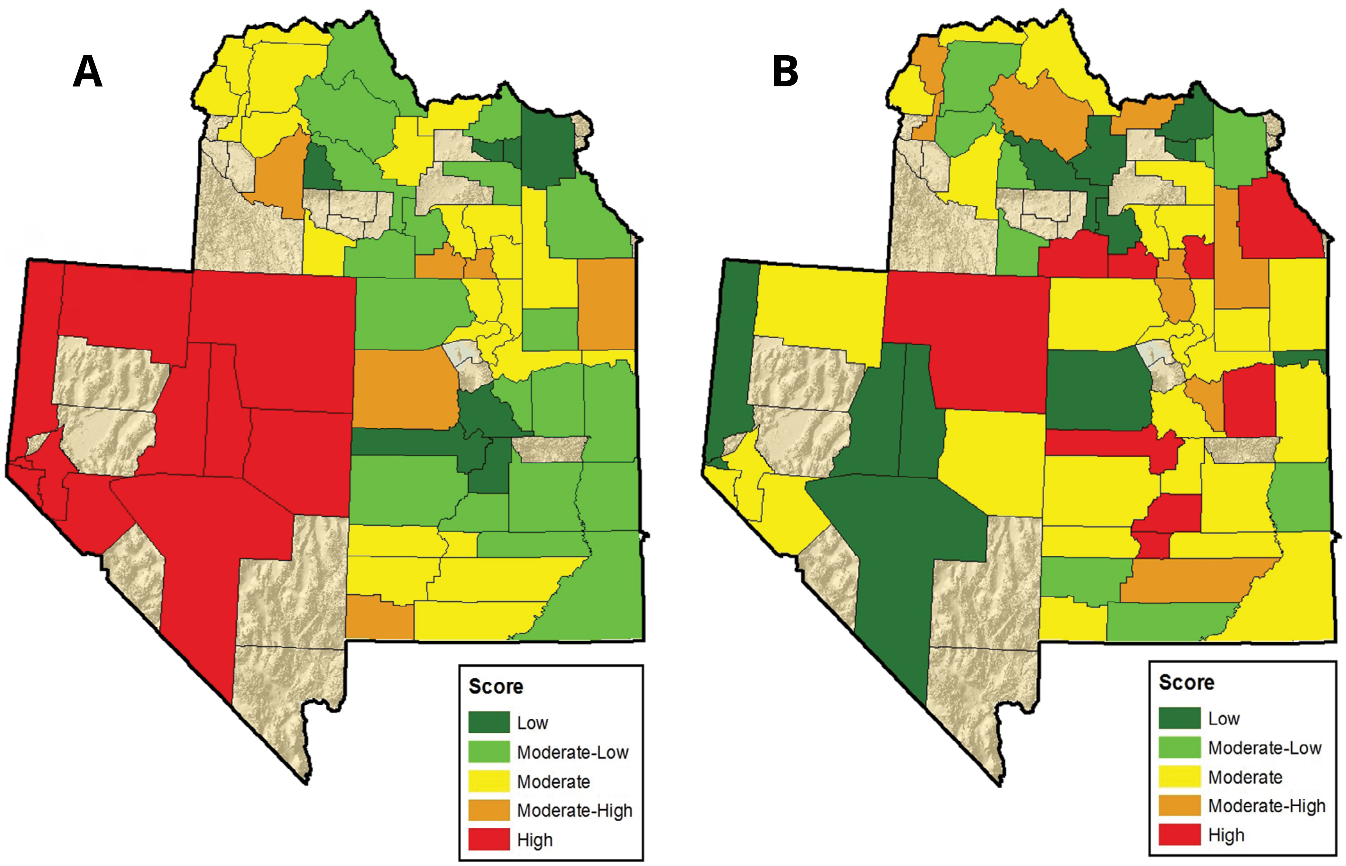


Figure A7—Rangeland vulnerability **(A)** and livestock vulnerability **(B)**, by county.

Table A2a—Vulnerability by county for the state of Idaho.

County[1]	Rangeland vulnerability[2]	Livestock vulnerability	Final vulnerability	Authorized AUMs
Adams	M	MH	MH	38,786
Bannock	M	M	M	31,861
Bear Lake	M	H	MH	29,752
Blaine	ML	L	L	6,632
Boise	M	ML	ML	2,738
Bonneville	ML	M	ML	38,486
Butte	M	L	L	6,630
Camas	L	ML	L	7,796
Caribou	M	M	M	46,131
Cassia	ML	H	H	59,933
Clark	M	MH	M	38,629
Custer	ML	MH	M	62,919
Elmore	MH	M	M	38,394
Franklin	MH	MH	H	11,503
Fremont	ML	L	L	26,054
Gem	M	MH	M	9,301
Idaho	M	M	M	207
Lemhi	ML	M	M	35,113
Madison	L	L	L	5,528
Oneida	MH	H	H	46,914
Power	ML	L	L	6,953
Teton	L	ML	L	7,640
Twin Falls	M	ML	ML	7,472
Valley	M	ML	ML	14,215
Washington	M	M	M	15,512

[1] Only counties in Region 4 with active or vacant Forest Service grazing allotments are assessed.
[2] Rangeland vulnerability is the average of rangeland vulnerability scores on allotments in the county.

Table A2b—Vulnerability by county for the state of Nevada.

County[1]	Rangeland vulnerability[2]	Livestock vulnerability	Final vulnerability	Authorized AUMs
Carson City	H	L	L	1,730
Douglas	H	M	H	2,710
Elko	H	H	H	126,243
Eureka	H	L	M	2,924
Humboldt	H	M	H	32,409
Lander	H	L	MH	11,129
Lyon	H	M	H	4,097
Mineral	H	M	H	3,235
Nye	H	L	M	22,725
Washoe	H	L	M	1,628
White Pine	H	M	H	23,681

[1] Only counties in Region 4 with active or vacant Forest Service grazing allotments are assessed.
[2] Rangeland vulnerability is the average of rangeland vulnerability scores on allotments in the county.

Table A2c—Vulnerability by county for the state of Utah.

County[1]	Rangeland vulnerability[2]	Livestock vulnerability	Final vulnerability	Authorized AUMs
Beaver	M	M	M	4,097
Box Elder	ML	M	M	9,122
Cache	M	MH	MH	33,055
Daggett	M	L	L	9,262
Duchesne	ML	H	M	23,433
Emery	ML	M	M	15,698
Garfiel	M	MH	M	52,417
Grand	ML	ML	L	3,858
Iron	M	ML	M	12,608
Juab	L	H	M	13,779
Kane	M	ML	ML	3,437
Millard	ML	M	M	19,388
Morgan	M	M	M	597
Piute	M	H	MH	21,588
Rich	M	M	M	8,693
San Juan	ML	M	M	23,428
Sanpete	L	M	ML	48,485

Table A2c continued.

County[1]	Rangeland vulnerability[2]	Livestock vulnerability	Final vulnerability	Authorized AUMs
Sevier	ML	H	H	90,238
Summit	M	M	M	17,215
Tooele	MH	L	ML	16,305
Uintah	ML	M	M	19,252
Utah	L	M	ML	26,629
Wasatch	ML	MH	M	57,055
Washington	MH	M	M	352
Wayne	ML	M	M	14,135
Weber	M	M	M	2,254

[1] Only counties in Region 4 with active or vacant Forest Service grazing allotments are assessed.
[2] Rangeland vulnerability is the average of rangeland vulnerability scores on allotments in the county.

Table A2d—Vulnerability by county for the state of Wyoming.

County[1]	Rangeland vulnerability[2]	Livestock vulnerability	Final vulnerability	Authorized AUMs
Lincoln	M	MH	M	43,517
Sublette	ML	H	H	79,428
Sweetwater	MH	M	M	1,154
Teton	L	ML	L	11,175
Uinta	ML	M	ML	6,677

[1] Only counties in Region 4 with active or vacant Forest Service grazing allotments are assessed.
[2] Rangeland vulnerability is the average of rangeland vulnerability scores on allotments in the county.

ATTACHMENT B—VULNERABILITY EXAMPLE: WATER SUPPLIES

Municipal Drinking Water Vulnerability to Climate Change

Prepared for USDA Forest Service Intermountain Adaptation Partnership—Climate Change Vulnerability Assessment[6]

Introduction

Climate change is projected to alter water resources across the country's forest and grassland habitats, leading to changes in water–related ecosystem services that communities depend on. This analysis utilizes municipal drinking water intake locations and nearby spatial characteristics to identify drinking water vulnerability for users that depend on National Forest System (NFS) lands within the Forest Service's Intermountain Region[7]. Vulnerability measures are based on stream channel and sub-watershed characteristics and mapped at the water system and national forest levels. Each water system is analyzed based on the location of water intakes and the population served. The results presented here are for demonstration purposes; additional input from staff specialists is needed to refine variables and data selected for final vulne ability analysis. However, the results illustrate how these methods can be used to support local and regional climate change adaptation efforts through national forest and grassland management and land management planning.

Drinking water vulnerability is assessed for water systems (one or more intakes serving a common population) that rely on water resources located within one sub-watershed downstream of NFS lands. Vulnerability is measured based on measures of exposure, sensitivity, and adaptive capacity that account for a combination of ecological and socio-economic conditions. The sensitivity and adaptive capacity components are combined to create a single "sensitivity less adaptive capacity" component (SAC), due to the amount of overlap between these categories. Values for the exposure and SAC components, for each water supply system, are standardized to mean zero and a standard deviation of one. Standardized values for exposure and SAC are added for a final vulne ability score for each system, which is again standardized to mean zero and standard deviation of one so water systems can be easily compared within the Region. The vulnerably scores for water systems within a national forest are averaged to describe and map municipal drinking water vulnerability at the national forest level.

Effects of Climate Change on Water Resources and Public Supplies

Region 4's Intermountain Adaptation Partnership (IAP) completed an assessment of the vulnerability of national forests to climate change,[8] which includes a summary of impacts to water resources on NFS lands. Water yield, timing, and quality are particularly important for municipal drinking water suppliers and are expected to be uniquely impacted across Region 4 by climate–induced changes. Increased atmospheric temperatures and loss of vegetation along stream banks will raise the temperature of streams, impacting solubility and aquatic

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[6] http://adaptationpartners.org/iap/.
[7] Also referred to as Region 4, covering Nevada, Utah, southern Idaho, and western Wyoming.
[8] Halofsky, Jessica E.; Peterson, David L.; Ho, Joanne J.; Little, Natalie, J.; Joyce, Linda A., eds. Climate change vulnerability and adaptation in the Intermountain Region [Parts 1 and 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 513 p.

organisms. Increased number and severity of wildfires will deposit more sediment and debris into streams, lakes, and reservoirs, causing further concerns for water quality.

Changes in vegetation affect the rate of flow and influence the landscape's ability to filter and purify water. Riparian systems and vegetated areas are likely to be affected by changes in temperature, precipitation, evapotranspiration, flow, runoff timing, and extreme weather events. As surface water runoff is altered, riparian zones experience reduced abundance and diversity of many organisms including algae, invertebrates, amphibians, and fishes.

Stream runoff is expected to occur earlier in the year and summer flows are expected to be significantly lower for most users in the Region. In extreme cases, the median flow date is over a month and a half earlier and summer flows are projected to decline over 90 percent. Total water yield, measured by mean annual flow, is expected to slightly increase on average in the northern part of the Region but decline over 10 percent in the warmer southern and western parts of the Region.

Groundwater levels and recharge rates are also impacted by climate change. During the summer, high water demand coupled with low water supply already forces many municipal water suppliers to utilize groundwater intakes in order to meet local water demand. Changes in temperature and population growth will create additional pressure on demand for water and stress water supplies.

Any resulting reductions in water quality will lead to increased treatment costs, compounded by increased frequency and severity of wildfires that lead to increased sediment delivery. Extreme weather and increased rain rather than snow can also increase runoff from agricultural fields and add pesticides and fertilizers to streams. Changes in timing and summer flow are expected to cause shortages of surface water in ma y regions, especially during the warm summer months when demand is high. Many municipal systems will likely experience increased treatment costs and greater dependence on groundwater intakes in order to meet demand.

Sensitivity to Climatic Variability and Change

The most sensitive watersheds are those which are already impaired or at–risk, based on vegetation, soil, and habitat conditions. Watersheds that have a high threat of wildfire or plant disease or are heavily developed are more sensitive to climate change. Many of the Region's sub-watersheds are already impaired or at–risk (table B1). Riparian and wetland vegetation conditions are impaired for nearly all of Nevada, while Utah and parts of Idaho and Wyoming have a mix of well-functioning and at-risk riparian systems. Soil condition is poor in Nevada, but also a concern for much of Utah. Aquatic habitat is impaired in much of Nevada and in Utah where development is prevalent. Many of the watersheds are also at risk for wildfire

Vulnerability Estimation

Vulnerability is traditionally defined as a function of measures for (1) exposure, (2) sensitivity, and (3) adaptive capacity; increasing in exposure and sensitivity; and decreasing in adaptive capacity. A linear summation of these three components is the simplest approach and gives no weighted preference to any of the three components (each component is a function of multiple variables):

Vulnerability = Exposure + Sensitivity - Adaptive Capacity

As noted above, vulnerability in this analysis is assessed for individual drinking water systems. Variables for exposure are based on conditions for stream reaches' nearest intake locations. Many watershed conditions variables can serve as proxies for both sensitivity and adaptive capacity. As a result, sensitivity (positive "+" for higher sensitivity) and adaptive capacity (negative "-" for higher adaptive capacity) are merged into a single measure SAC, representing "sensitivity less adaptive capacity" or sensitivity adjusted for adaptive capacity. Vulnerability scores are therefore estimated as:

Vulnerability (water system) = Exposure (stream reach) + SAC (sub-watershed),

where exposure and SAC include both ecological and socio-economic indicators. Final vulnerability results are mapped to system locations as circles that vary by (i) color, representing magnitude of the calculated vulnerability index and (ii) size, representing population served (see fig. B4)

A water system is defined as any unique supplier of municipal drinking water. Many small systems only have a single water intake, while larger systems sometimes have upwards of 20 intakes. "Municipal drinking water use" is defined as serving water to the same population year around (i.e., community water systems). Each water system is analyzed based on the location of its water intakes and the population served. Variables used to describe exposure, sensitivity and adaptive capacity are shown in table B2a-b.

Exposure is measured according to projected changes in annual stream flow (figures B2 B3), summer stream flow, runoff timing, and stream temperature from climate projection scenarios for the 2040s (2030–2059) and the 2080s (2070–2099) at the streamline or stream segment level. The stream segment closest to an intake is used to describe exposure for that intake. By including both mean annual and summer flows, the most exposed users are those that experience declines in both. Changes in summer flow are significant in some areas but not well represented in annual flow changes since low summer flow can be offset by high flows during earlier seasons. For some systems, mean annual flow and mean summer flow trend in opposite directions. Runoff timing has varying impacts on flow as well. Earlier runoff can lead to lower summer flows, but it can also be correlated with higher mean annual flows Summary statistics for exposure variables are provided in table B3. Exposure variables are summed to estimate an aggregate exposure measure for each water system; aggregate exposure measures are standardized to mean zero and a standard deviation of one. Total exposure values are in figure B3.

Sensitivity and adaptive capacity are measured primarily at the HUC-12 watershed scale using 21 sub-watershed characteristics or variables (table B2a-b). Summary statistics for SAC variables are shown in table B4a-c. Factor Analysis is used to narrow the 21 variables down to seven "factors" that explain most of the variation (97 percent) across all water systems in the Region. The first factor broadly captures watershed and forest health, the second captures ecological sensitivity and adaptive capacity, the third factor captures human development and use, and the fourth factor water sustainability. The remaining factors encompass a mix of variables with lower correlations. The factor "loadings" or values for a sub-watershed are applied to each water system with intakes in the sub-watershed. The seven factor loadings are summed for each system to get a final measure of SAC, which is then standardized to mean zero and a standard deviation of one. Final SAC measures, as well as populations served, are mapped in figure B1; large red circles represent water systems that service large populations with high SAC. Weighted average factor loadings are estimated for water systems with intakes that span multiple sub-watersheds.

Average water system vulnerability measures are estimated at the National Forest level (fig. B5, table B5). Final vulnerability is estimated to be very high or high for five National Forest units with populations served ranging from 170 (Payette National Forest) to 1.3 million (Wasatch National Forest). Vulnerability is very low or low for five National Forest units with populations served ranging from 10,000 to 66,000. Vulnerability is moderate for the remaining six National Forest units. More details about water system vulnerability results are provided in Chapter 13 of Region 4's IAP assessment of climate change vulnerability.[9]

[9] Halofsky, Jessica E.; Peterson, David L.; Ho, Joanne J.; Little, Natalie, J.; Joyce, Linda A., eds. Climate change vulnerability and adaptation in the Intermountain Region [Parts 1 and 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

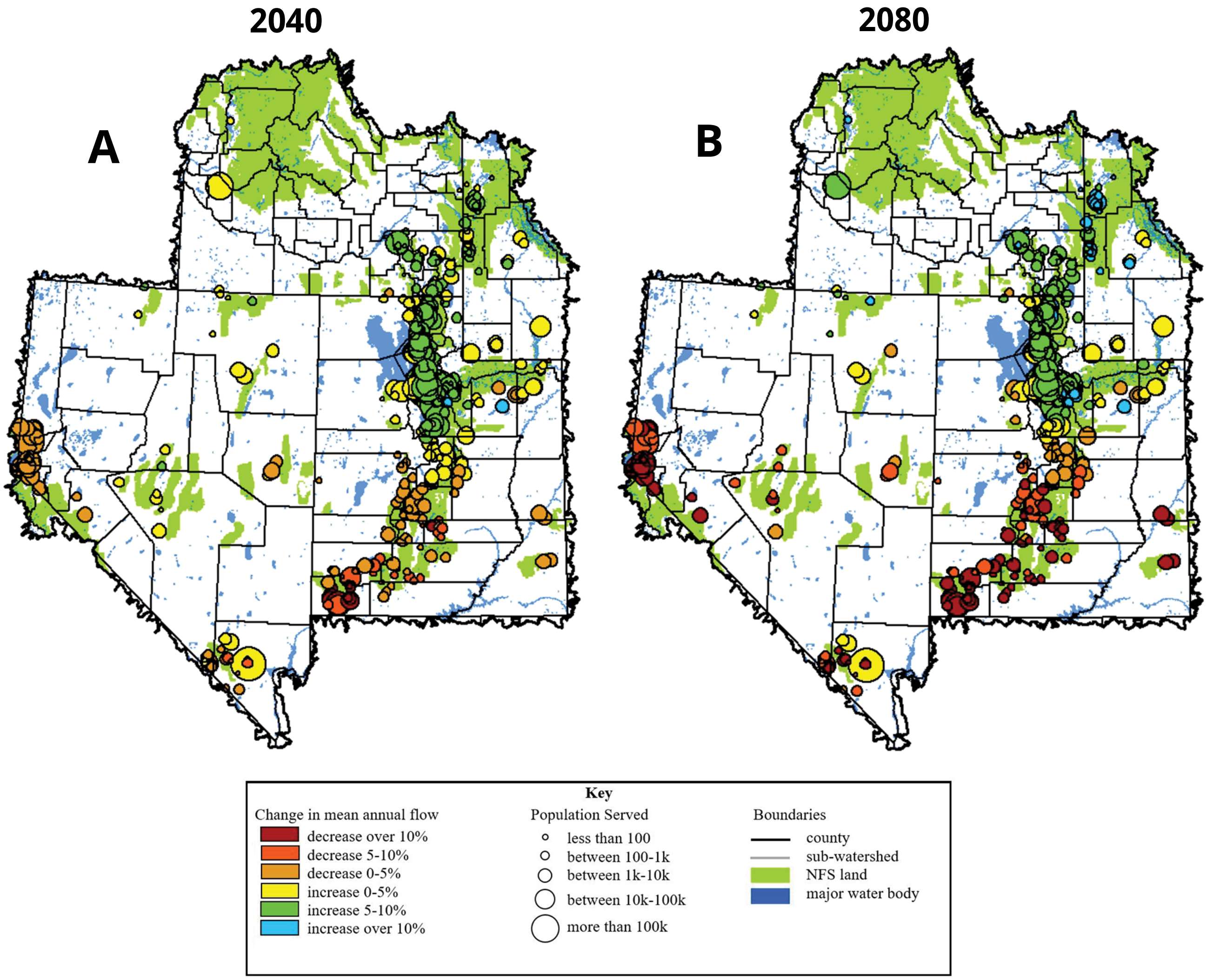

Figure B1— (A) Sensitivity less adaptive capacity (SAC) results for municipal water systems for the year 2040. **(B)** Sensitivity less adaptive capacity (SAC) results for municipal water systems for the year 2080.

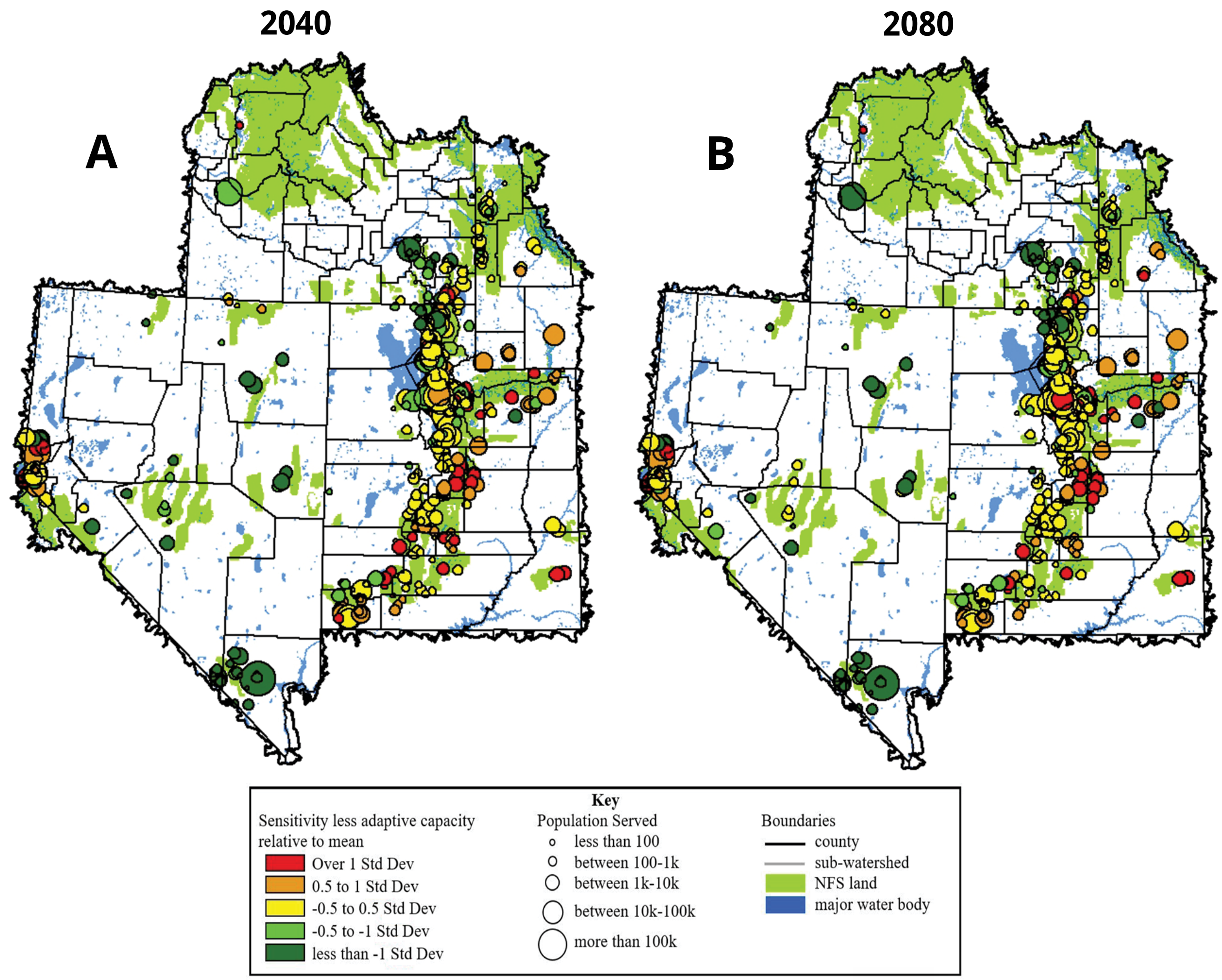

Figure B2—(A) Example of single variable: projected change in mean annual flow in the year 2040. **(B)** Example of single variable: projected change in mean annual flow in the year 2080.

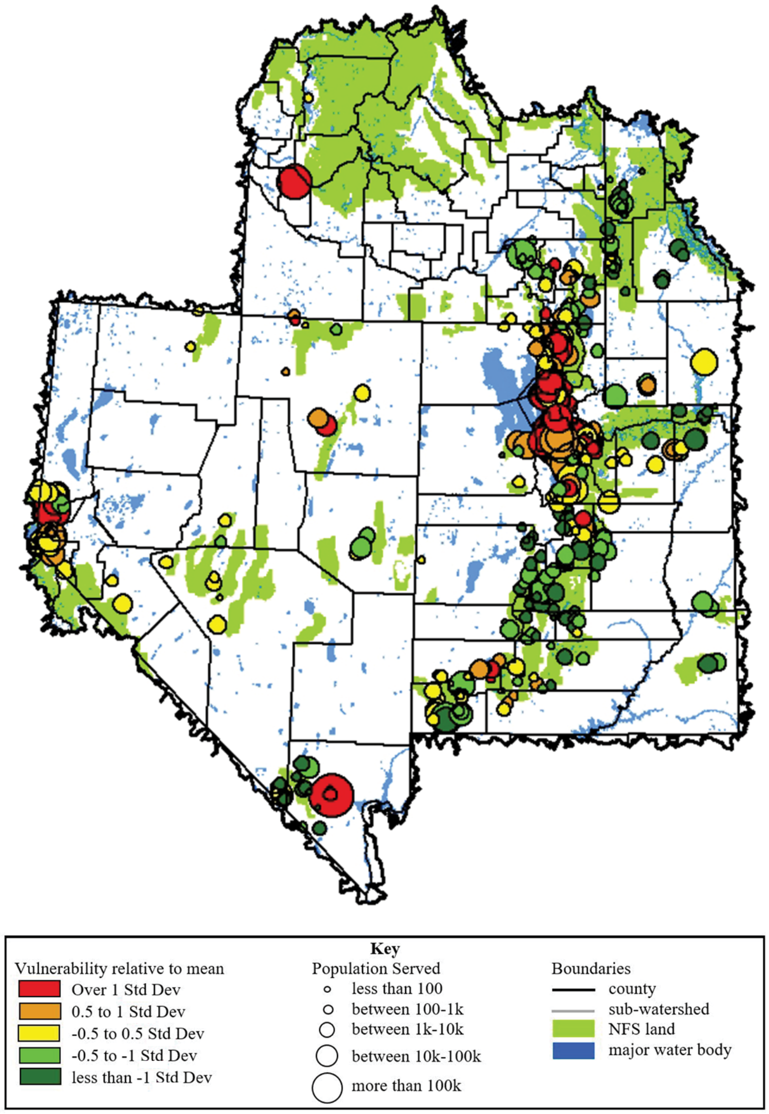

Figure B3—Exposure results for municipal water systems.

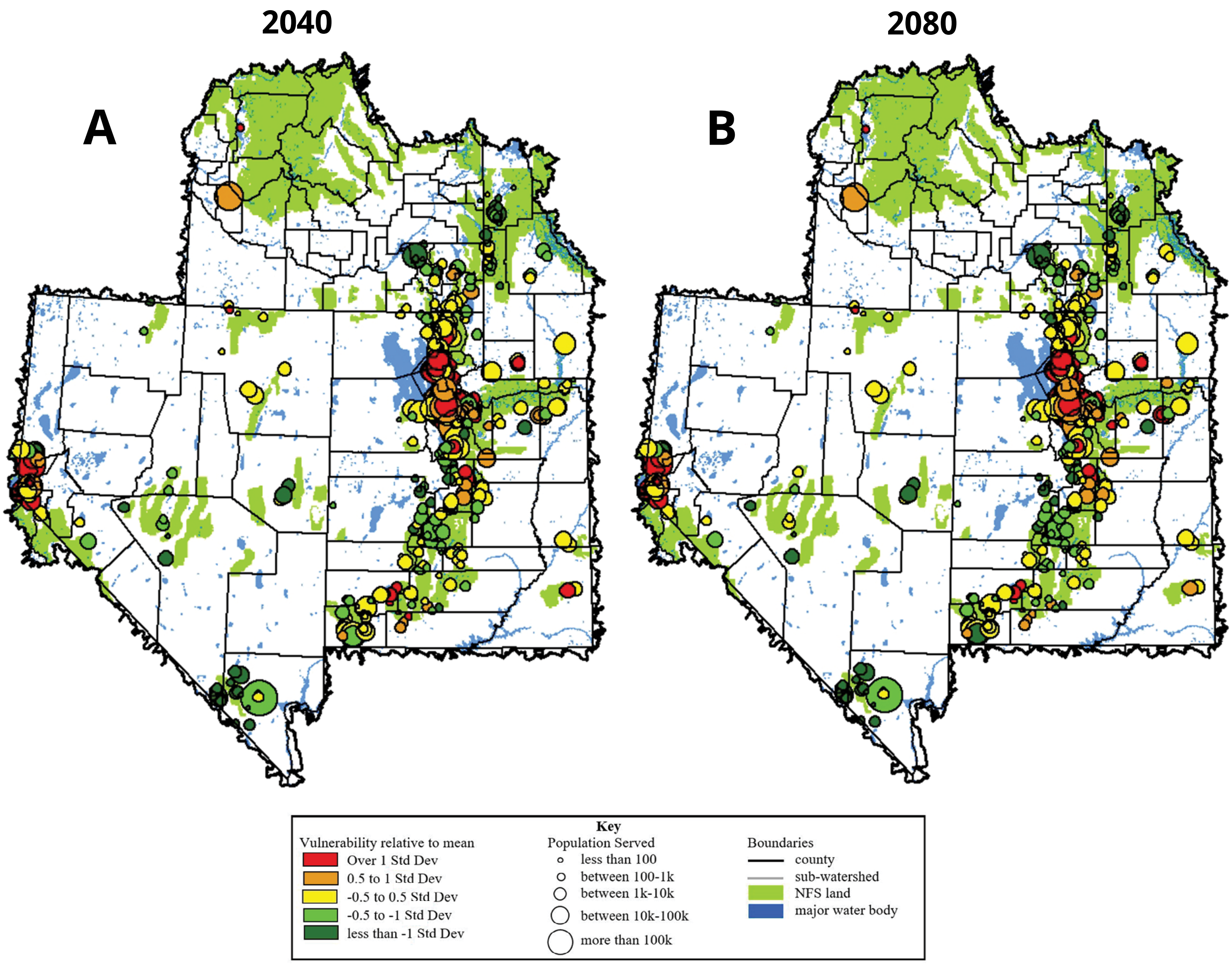

Figure B4—(A) Total vulnerability for municipal water systems in the year 2040. **(B)** Total vulnerability for municipal water systems in the year 2080.

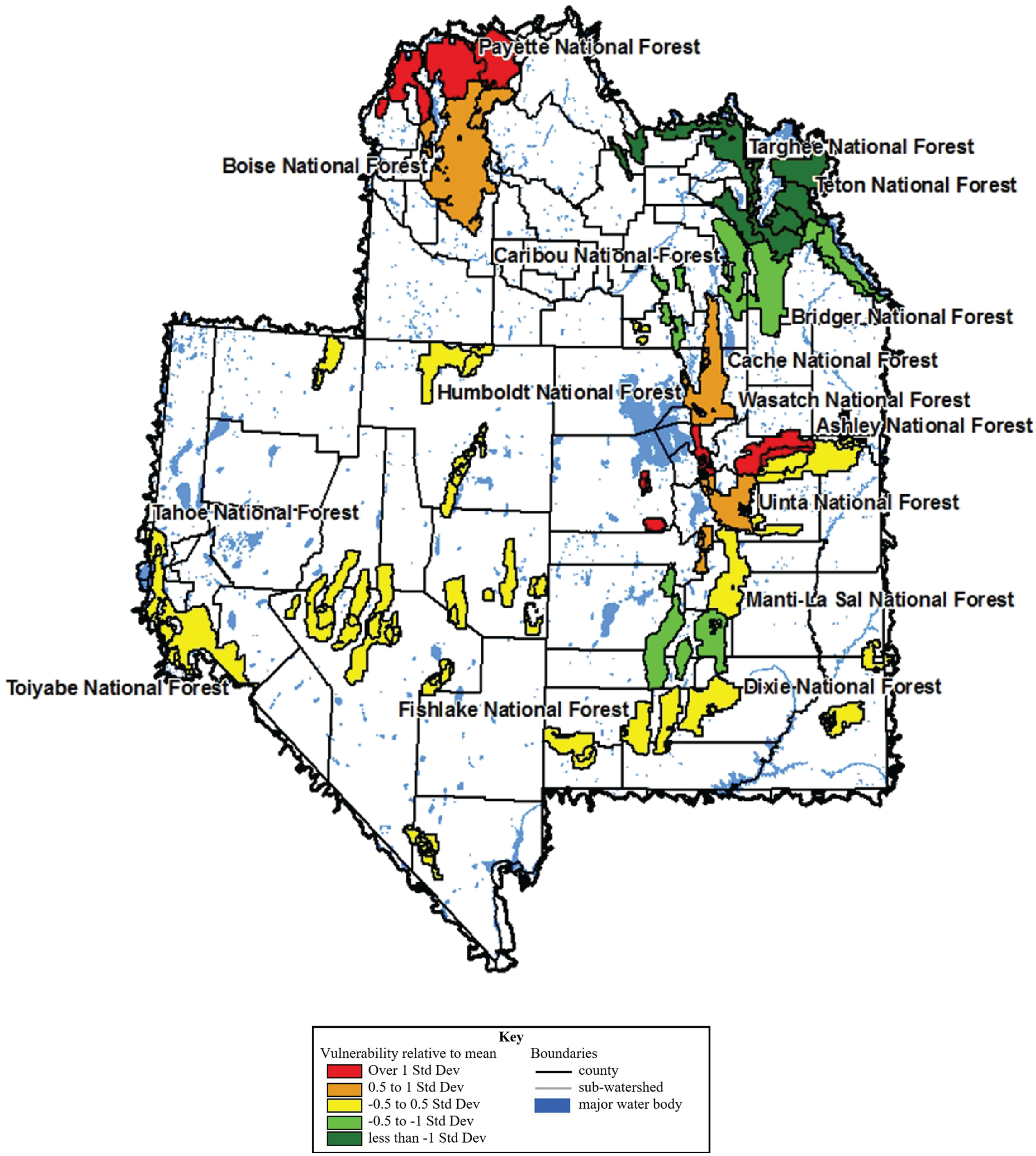

Figure B5—Water system vulnerability by National Forest.

Table B1—Region 4 sub-watershed conditions (HUC-12)[1]

Watershed indicator	Good (%)	At risk (%)	Impaired (%)
Water Quality	62.14	21.61	16.25
Water Quantity	55.14	32.55	12.32
Aquatic Habitat	49.82	26.09	24.09
Riparian/Wetland Vegetation	38.45	44.2	17.35
Rangeland Vegetation	69.26	29.36	1.38
Roads and Trails	23.65	43.96	32.39
Soils	56.0	34.16	9.84

[1]Represents all sub-watersheds in Region 4 with some fraction of NFS land. Sub-watersheds = 2,541.

Table B2a—Variables for estimating vulnerability: Exposure measures (demonstration only).

Variable	Description	Source
Mean annual flow Mean summer flow Runoff timing Water temperature	% change from historical	IAP Team Projections

The location of water system intakes and the population served comes from the USEPA-SDWIS.

“IAP Team Projections.” Source: Western U.S. Stream Flow Metrics. Available through USDA Forest Service Air, Water, and Aquatic Environments: https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml, as referenced in Halofsky, Jessica E.; Peterson, David L.; Ho, Joanne J.; Little, Natalie, J.; Joyce, Linda A., eds. Climate change vulnerability and adaptation in the Intermountain Region [Part 1]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Table B2b—Variables for estimating vulnerability: Sensitivity and adaptive capacity measures (demonstration only).

Variable	Description	Source
Fire threat Insect and disease threat Development threat Protected land* NFS land* Private land	% of sub-watershed	USFS-F2F (2016)
Agricultural land Developed (high, med, and low) Developed open space Water, snow, and ice-covered land* Forested land* Grassland * Wetland*	% of sub-watershed	USGS-NLCD (2016)
Water quality condition Water quantity condition Riparian/wetland vegetation condition Rangeland vegetation condition Aquatic habitat condition Roads and trails condition Soil condition	Sub-watershed: impaired, at risk, or good	USFS-WCC (2016)
Water depletion	Fraction of available renewable water consumptively used by human activities within a watershed	EarthStat (2016)

*The final measure of vulnerability is increasing in most variables but decreasing in some.

The location of water system intakes and the population served comes from the USEPA-SDWIS.

“USFS-F2F”: USDA Forest Service National Forests to Faucets 2.0, Assessment Database (2016) https://www.fs.usda.gov/research/products/dataandtools/tools/forests-faucets-2.0-connecting-forests-water-and-communities

“USGS-NLCD”: US Geological Survey, National Land Cover Database (2016).

“USFS-WCC”: USDA Forest Service Watershed Condition Classification (2016).

“EarthStat”: Earthstat.org, Water Depletion and WaterGap3 Basins (2016).

Table B3—Summary statistics of exposure projections (demonstration only).

Time Period	Variable	Average	Std Dev	Median	Min	Max
2040 (2040–2059)	Mean annual flow (% change	2.04	.34	3.62	-15.25	17.26
	Mean summer flow (% change	-20.85	22.08	-14.5	-90.37	21.11
	Median Flow date (change in days)	-11.34	6.27	-11.59	-28.14	2.21
	Water temperature (% change)	6.71	1.7	6.95	2.56	14
2080 (2070–2099)	Mean annual flow (% change	-0.58	10.51	3.1	-31.24	17.44
	Mean summer flow (% change	-25.69	27.86	-18.27	-92.37	33.11
	Median Flow date (change in days)	-19.14	10.86	-19.52	-47.09	4.1
	Water temperature (% change)	11.73	3.03	12.2	4.53	24.82

Table B4a—Summary statistics of sensitivity and adaptive capacity: Sub-watershed land use and cover (% of sub-watershed) (demonstration only).

Variable	Average	Std Dev	Median	Minimum	Maximum
Agricultural land	10.58	14.21	4.57	0	81.8
Developed (High, Med, and Low)	6.81	13.21	1.14	0	83.6
Developed open space	3.0	2.8	2.14	0	23.87
Private land	8.96	12.9	4.0	0	65.0
Protected land*	24.65	21.25	21.0	0	91.0
NFS land*	19.98	20.24	14.0	0	91.0
Forested land*	32.42	24.3	30.67	0	93.76
Grassland*	41.42	23.9	38.83	0.11	99.49
Wetland*	2.24	4.08	0.39	0	29.3
Water, snow, and ice–covered land	2.14	11.11	0.07	0	99.65

Measures of sensitivity and adaptive capacity are combined due to important overlap. The final measure of vulnerability is increasing in some variables and decreasing in others (*).

Table B4b—Summary statistics of sensitivity and adaptive capacity: Sub-watershed threats (% of sub-watershed) (demonstration only).

Variable	Average	Std Dev	Median	Minimum	Maximum
Fire threat	78.37	32.22	95.6	0	100
Insect and disease threat	5.99	15.05	0	0	100
Development threat	34.48	29.73	30.54	0	99.99
Water depletion (5% = 1, 100% = 6)	3.18	0.93	3	1	4

Table B4c—Summary statistics of sensitivity and adaptive capacity: Sub-watershed conditions (good = 1, at-risk = 2, impaired = 3) (demonstration only).

Variable	Average	Std Dev	Median	Minimum	Maximum
Water quality condition	1.64	0.85	1	1	3
Water quantity condition	1.88	0.72	2	1	3
Riparian/ wetland vegetation condition	1.75	0.72	2	1	3
Rangeland vegetation condition	1.28	0.5	1	1	3
Aquatic habitat condition	1.86	0.79	2	1	3
Roads and trails condition	2.17	0.75	2	1	3
Soil condition	1.59	0.61	2	1	3
Population served	9,136	62,064	500	25	1,276,091

The population served by each water system is not included in the estimate and is instead used to represent the size of each system on the maps. Water systems = 521, Population = 4,768,915.

Table B5—Summary average of Region 4 municipal water system vulnerability by nearby national forest.

National forest	Municipal systems	Population served	Exposure	Sensitivity less adaptive capacity	Vulnerability
Ashley	18	53,322	High	Low	Moderate
Boise	2	186,072	Very low	Very high	High
Bridger	23	10,782	Moderate	Low	Low
Cache	83	398,296	Moderate	Very high	High
Caribou	22	66,615	Very low	Moderate	Low
Curlew	2	449	Moderate	Moderate	Moderate
Dixie	50	148,365	Moderate	Moderate	Moderate
Fishlake	38	27,651	Moderate	Very low	Low
Humboldt	15	21,718	Low	High	Moderate
Manti-La Sal	24	38,934	Very high	Low	Moderate
Payette	1	170	Very high	Moderate	Very high
Targhee	4	245	Moderate	Very low	Very low
Teton	22	13,452	Low	Very low	Very low
Toiyabe	99	2,070,860	Moderate	Moderate	Moderate
Uinta	54	463,766	Moderate	High	High
Wasatch	64	1,268,218	Moderate	Very high	Very high

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