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Forests to Faucets 2.0

Connecting Forests, Water, and Communities

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Abstract

The Forest to Faucets version 2.0 (F2FV2) assessment uses geospatial modeling at the 12-digit hydrologic unit code (HUC12) scale in the conterminous United States to identify watersheds that are most important to surface drinking water, the ability to produce clean water, forest ownership (public or private), and potential threats to water yield from insects and diseases, wildfire, land use or climate change. F2FV2 updates a 2011 version of the project (Forests to Faucets version 1.0). Results, presented by regions administered by the U.S. Department of Agriculture, Forest Service, indicate that watersheds in the Eastern, Southern, and Pacific Southwest regions were most important for surface drinking water. Watersheds in the Southern, Pacific Northwest, and Pacific Southwest regions had the highest ability to produce clean water based on the five biophysical characteristics evaluated. The Pacific Southwest, Pacific Northwest, and Northern regions had the most watersheds at the highest threat of wildfire as well as the most watersheds at the highest threat of insects and disease. For all future climate and population growth scenarios, the Southern, Pacific Southwest, and Eastern regions had the most watersheds at the highest threat of land use change, while the Pacific Northwest and Southern regions had the most watersheds at the highest threat of decreases in water yield because of climate change. F2FV2 provides a user-friendly tool and relatively high spatial resolution benchmark dataset that forest managers can use to evaluate the effect of their management on the water supply, and that water consumers can use for considering potential threats upstream.

Keywords: climate change, drinking water, forest, insects and disease, land use change, surface water, water, water demand, watershed, wildfire

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Contents

Introduction

Forests are an important source of clean drinking water for over 150 million people in the United States (Caldwell et al. 2014; Liu et al. 2020). The 749 million acres of forested lands provide more than half of the national water yield from lands in the lower 48 States (Liu et al. 2021; Sun et al. 2015). Approximately 74 percent of total drinking water withdrawals originates from surface water sources, such as streams, ponds, and reservoirs (Dieter et al. 2018). However, there are increasing concerns about the quantity and quality of both ground water and surface water supplies because of climate change, population growth, changes in land use, and increased water demand (Sun et al. 2008).

Threats to Surface Drinking Water

Disturbances that interrupt core aspects of the hydrologic cycle pose threats to surface drinking water. In particular, land use change, insects and disease, wind events, and wildfire can reduce or eliminate vegetative cover (i.e., trees and shrubs) and ground cover (i.e., litter, impervious surfaces). The loss of vegetation reduces rainfall interception, water infiltration, and evapotranspiration, which can increase the amount of overland flow, stormflow, and streamflow, respectively, and can also alter the timing of that flow. Land use change and increases in flow can lead to a decrease in water quality from non-point source pollutants through increased nutrient and sediment loads and often toxins, heavy metals, and other chemicals (e.g., from towns and cities, farming practices, fire retardant, and burned infrastructure). When the core aspects of the hydrologic cycle are altered, the overall status of the watershed condition degrades (Hallema et al. 2018, 2019; Neary et al. 2005; Sun and Caldwell 2015).

Similarly, changes in climate can alter the magnitude, timing, and quality of surface water supplies. Temperature and precipitation are the two key climatic variables that control water yield (i.e., runoff). Changes in these variables—specifically higher temperatures and increased variability of precipitation—threaten forests directly by changing their structure and functions, and key ecosystem services such as clean water supply. Indirect threats to forests related to climate change include more frequent and intense wildfires and insect and disease outbreaks under prolonged drought stress and high temperatures (Koch and Coulston 2020; Vose et al. 2012, 2018; Westerling et al. 2006) that affect watershed health and water quantity and quality.

Fall colors reflect on Lake Rabideau in the Chippewa National Forest. USDA Forest Service photo.

"Forests to Faucets" Assessments

Land and water resource managers need comprehensive data and tools for planning and management of watersheds threatened by land use change, climate change, wildfire, and insects and disease. In response to these needs, the U.S. Department of Agriculture, Forest Service, State and Private Forestry completed the "From the Forest to the Faucet: Drinking Water and Forests in the U.S." version 1.0 (F2FV1) assessment (Weidner and Todd 2011). The F2FV1 assessment had multiple objectives that served land managers on a broad scale, including (Weidner and Todd 2011):

1. Using geospatial analysis at the 12-digit hydrologic unit code (HUC12) scale to identify watersheds in the conterminous United States that are most important to surface drinking water, the forests protecting surface drinking water in those watersheds, and forested areas that face threats from increased housing density insects and disease, and the frequency and severity of wildfires.
2. Creating a dataset that can be useful for identifying priority areas for protecting the quality of surface drinking water and can incorporate into broad-scale planning efforts or existing decision support tools.
3. Identifying watersheds that could be targeted in a payment-for-watershed-services project.
4. Creating an educational tool that highlights the role of forests in providing an ecosystem service of surface drinking water.

For the F2FV1 assessment, Weidner and Todd (2011) used four geospatial models:

1. Index of importance to surface drinking water (IMP) model.
2. Drinking water protection (PR) model.
3. Index of forest importance to surface drinking water (FIMP) model.
4. Index of threats to forest importance to surface drinking water model.

The assessment found that many watersheds in the Eastern United States had higher importance to surface drinking water than those in the West and Midwest. The assessment also showed how forests—often privately owned—in watersheds of high importance were key to the production of surface drinking water, but the threat assessment of water quality showed that the ability of forests in these watersheds to sustain important surface drinking water supplies was at threat. The results of the assessment were informative and produced multiple map layers that stakeholders could easily integrate into decision support tools (Weidner and Todd 2011). For example, the State of Vermont incorporated the F2FV1 assessment into its 2017 forest action plan to show areas of the highest priority for protecting and conserving public drinking water supplies (Vermont Department of Forests, Parks, and Recreation 2017).

Forests to Faucets version 2.0 (F2FV2) expands on the F2FV1 assessment, with updates to the methodology and input data. The F2FV2 project had multiple objectives and new features, including:

1. Using geospatial analysis at the HUC12 scale for the conterminous United States to determine watersheds most important to surface drinking water; type of forest ownership; and where they are threatened by insects and disease, wildfire, land use change, or climate change that decreases water yield.
2. Identifying watersheds with the natural ability to produce clean water under current land use conditions.
3. Developing an interactive tool for stakeholders to access and use the results of this work.

This report focuses on the methods the authors of this document used for completing the assessment and provides an overview of the results, which can be downloaded or viewed from the Forests to Faucets website: https://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml.

Methods

Extent and Scale of Analysis

The F2FV2 study focused on watershed characteristics and water supply and demand for the conterminous United States at the HUC12 resolution (10,000 to 40,000 acres, or about 40 km^2 to 160 km^2).[1] The 2019 version of the Watershed Boundary Dataset (WBD) (U.S. Department of Agriculture, Natural Resources Conservation Service 2019) provided the HUC12 vector delineation for the analysis and the watershed connectivity. This project considered 83,314 HUC12s within the conterminous United States. The results are summarized by Forest Service administrative regions (fig. 1):

- Northern Region
- Rocky Mountain Region
- Southwestern Region
- Intermountain Region
- Pacific Southwest Region
- Pacific Northwest Region
- Southern Region
- Eastern Region

Most of the data used for the conterminous U.S. analysis of F2FV2 were not available for Alaska, Hawaii, and the territories of Puerto Rico, the U.S. Virgin Islands, Guam, the Mariana Islands, and

1 A hydrologic unit is "a topographically defined set of drainage areas organized in a nested hierarchy by size and number of divisions per nested level" (U.S. Department of the Interior, Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service 2013).

Figure 1.—The administrative regions of the Forest Service within the conterminous United States.

American Samoa. However, land cover and the U.S. Environmental Protection Agency (EPA) Safe Drinking Water Information System (SDWIS) intake data were available and used to calculate the threat-based drinking water protection (PR) model for these areas. Outputs are available to download from the Forests to Faucets website: https://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml.

Models

The authors used four models in the development of F2FV2: the IMP model, the PR model, the ability to produce clean water (APCW) index model, and the threats to surface drinking water (THREAT) model (table 1). The F2FV2 assessment used the same model equations from the F2FV1 assessment, with updated input data, to calculate the IMP and PR indices. Weidner and Todd (2011) did not use the APCW model in the F2FV1 assessment; Barnes et al. (2009) describe the foundation of this model. This assessment uses a modified version of the APCW model that included five attributes to characterize the biophysical conditions within a watershed. The F2FV2 THREAT model differs from the index of threats to forest importance to surface drinking water model that Weidner and Todd (2011) used in the F2FV1 assessment; F2FV2 used a different equation to calculate threats and added climate change to the list of threats assessed.

Table 1.—Models used in the Forests to Faucets version 2.0 assessment

Model	Equation	Parameters
Index of importance to surface drinking water (IMP) model	$IMP_n = Q_n \times PR_n$	Q_n is average annual water yield (mm/yr) PR_n is the drinking water protection model
Drinking water protection (PR) model	$PR_n = \Sigma(W_i \times P_i)$	W_i is a proportional weighting P_i is the total population served by intakes in the *i*th watershed downstream from watershed *n*
Ability to produce clean water (APCW) index model	$APCW = (N + A + I + R) \times Q$	*N* is percentage of natural cover *A* is percentage of agricultural land *I* is percentage of impervious surface *R* is percentage of riparian natural cover *Q* is average annual water yield (mm/yr)
Threats to surface drinking water (THREAT) model	$THREAT = (IMP \times APCW \times PT) / 10{,}000$	*IMP* is the index of importance to surface drinking water model *APCW* is the ability to produce clean water index model *PT* is percentage of a watershed that is threatened from a contamination to surface water. *PT* is defined differently for each threat: climate change that decreases water yield (PT_{YIELD}); land use change (PT_{LUC}); insects and disease (PT_{ID}); or wildfire potential (PT_{WFP}).

Index of Importance to Surface Drinking Water (IMP) Model and Drinking Water Protection (PR) Model

The authors compiled water yield (i.e., water supply) and the population served by surface water intakes (water demand) to estimate the IMP index for watershed *n*.

IMP was calculated using equation (1):

$$IMP_n = Q_n \times PR_n \qquad (1)$$

where

Q_n = the average annual water yield in mm/yr for each watershed *n*

PR_n = the drinking water protection model (water demand calculation for watershed *n*)

PR_n was determined using equation (2):

$$PR_n = \Sigma(W_i \times P_i) \qquad (2)$$

where

W_i = the proportional weighting

P_i = the total population served by intakes in the *i*th watershed downstream from watershed *n* (Weidner and Todd 2011) (fig. 2)

The PR model identifies the importance of a watershed's land area by using the downstream drinking water demand. Watersheds with the highest water demand are considered the most important. The population served by surface water intakes located within the watershed represents water demand in the model. Through watershed connectivity, the model accounts for water demand within the source watershed, plus a fraction of water demand for all watersheds downstream of the source watershed. The proportional weighting, W_i, expressed by an exponential decay relationship, represents the fraction of water demand from the downstream watersheds that contribute to the importance of the source watershed.

W_i was calculated using equation (3):

$$W_i = (1-0.01)^d \qquad (3)$$

where

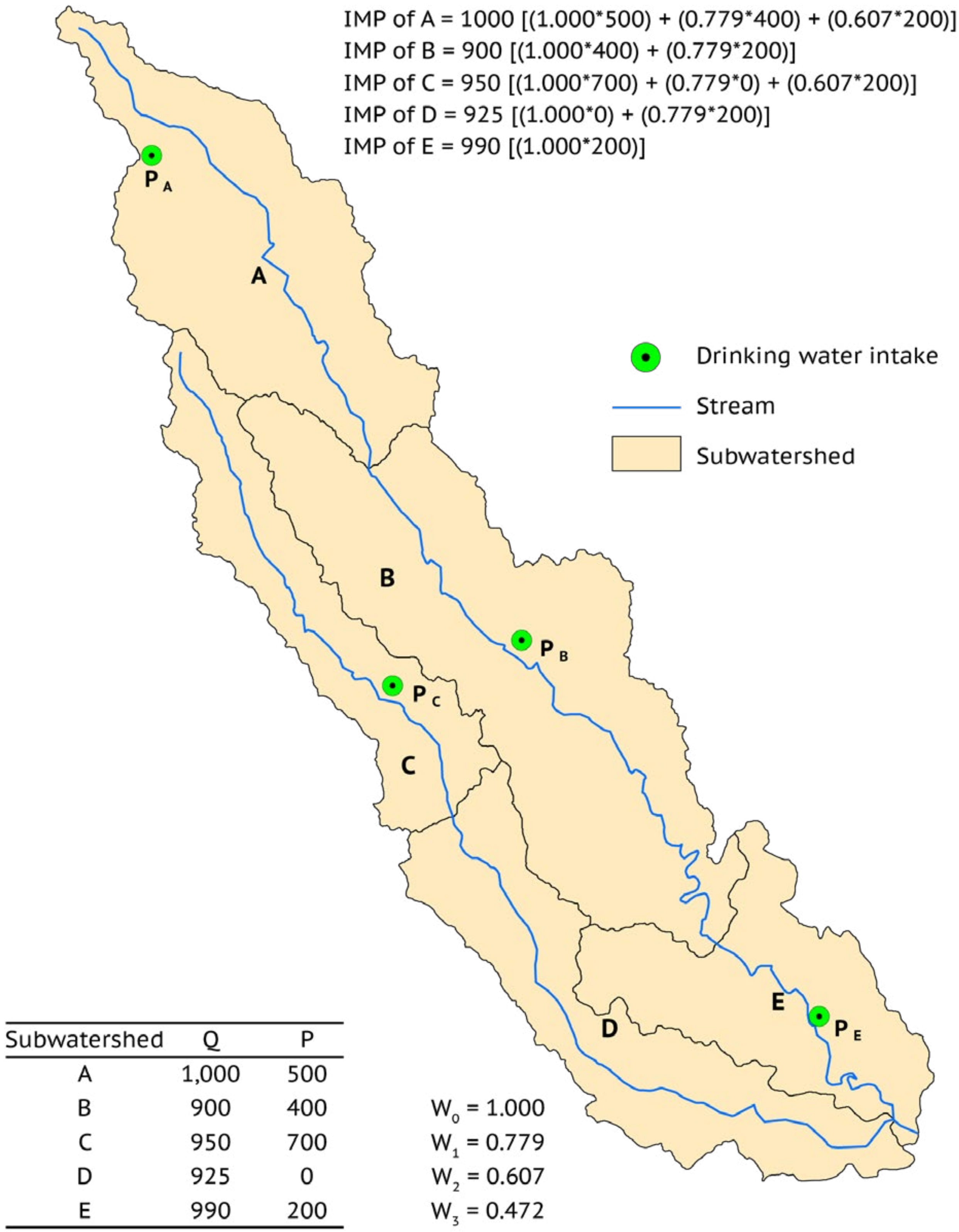
d = the distance, assumed to be 25 km in stream length, between the source watershed and a downstream watershed containing an intake (table 2) (Weidner and Todd 2011)

Interbasin transfers and water diversions were not incorporated into the model.

In the F2FV1 assessment, Weidner and Todd (2011) derived the exponential decay relationship equation after reviewing literature about decay curves from a variety of contaminants and consulting with a science advisory team. The equation is meant to represent, in a generalized way, the decay of contaminants in a stream or river (Weidner and Todd 2011). The final IMP value was divided into 10 quantiles and mapped on a 0 to 100 scale.

Table 2.—Proportional weight values used in the index of importance to surface drinking water (IMP) model

*i*th down-stream HUC	Distance down-stream *(d)* km	Proportional weight *(W_i)*
0	0	1.000
1	25	0.779
2	50	0.607
3	75	0.472
4	100	0.368
5	125	0.287
6	150	0.223
7	175	0.174
8	200	0.135
9	225	0.105
10	250	0.082



Subwatershed	Q	P
A	1,000	500
B	900	400
C	950	700
D	925	0
E	990	200

Figure 2.—Schematic diagram illustrating the calculation of importance to drinking water index where *Q* is average annual runoff (mm/year), P_i is population being served by the drinking water intake (green dot), and W_i is the proportional weight, which represents the fraction of water demand from the downstream watersheds that contribute to the importance of the source watershed and is expressed by an exponential decay relationship.

Ability to Produce Clean Water (APCW) Index Model

This assessment used land cover and water yield datasets to calculate the APCW index, a water quality index that reflects watershed integrity by incorporating the conditions of five attributes. APCW characterizes the biophysical conditions that relate to the ability to provide clean water in each watershed.

APCW was calculated using equation (4):

$$APCW = (N + A + I + R) \times Q \qquad (4)$$

where

N = percentage of natural cover (ranking points)

A = percentage of agricultural land (ranking points)

I = percentage of impervious surface (ranking points)

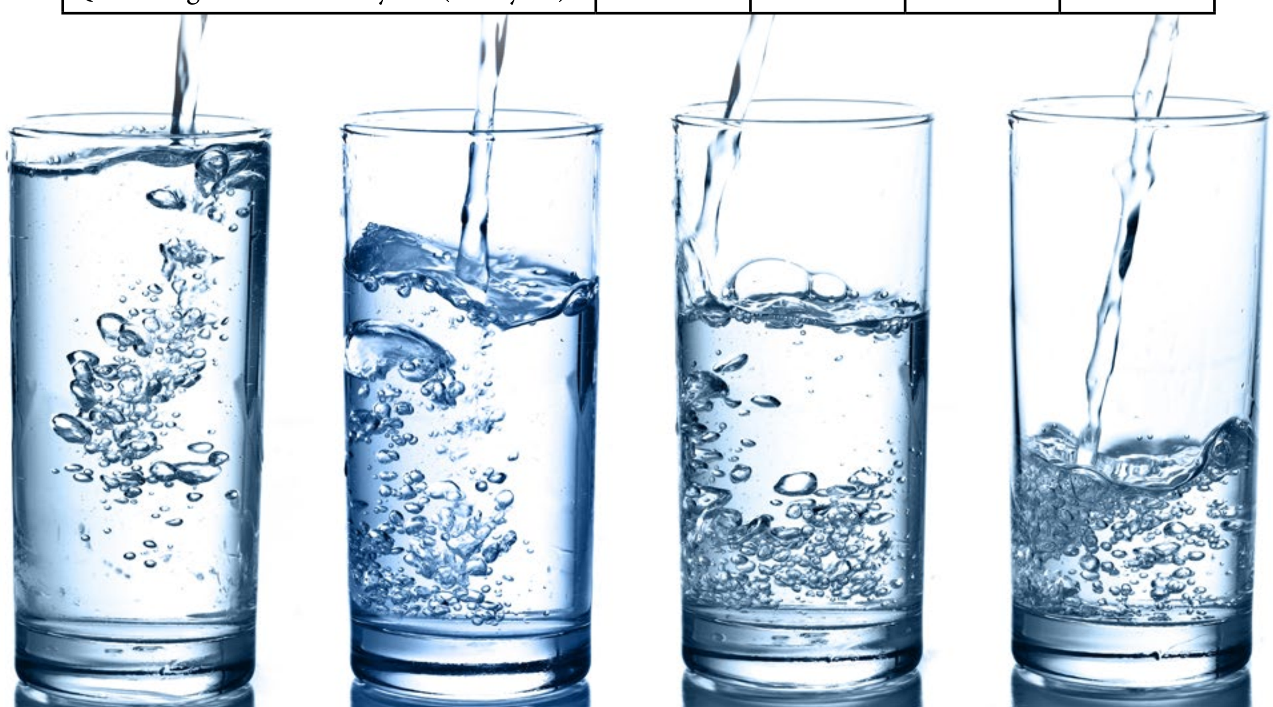
R = percentage of riparian area that is natural cover (ranking points)

Q = the average annual water yield in mm/yr (ranking points)

This assessment ranks the attributes from low to very high, based on the percentage of that attribute in a watershed, and valued the attributes at 1 to 4 points, respectively, based on accepted standards in the scientific literature (Barnes et al. 2009). Point values of the four attributes were summed and multiplied by the ranked average annual water yield (table 3). The APCW index was determined by dividing the results by the maximum score of 64. APCW values were divided into 10 quantiles and mapped on a 0 to 100 scale.

Table 3.—The ability to produce clean water index model attribute ranking system

Attribute	Very high (4 points)	High (3 points)	Moderate (2 points)	Low (1 point)
N = percentage of natural cover	>75	51–75	25–50	<25
A = percentage of agricultural land	<10	10–20	21–30	>30
I = percentage of impervious surface	0–1	2–5	6–10	>10
R = percentage of riparian natural cover	>70	51–70	30–50	<30
Q = average annual water yield (mm/year)	>800	401–800	201–400	0–200



Threats to Surface Drinking Water (THREAT) Model

Combining the IMP and APCW indices with each surface drinking water potential threat (PT) produced the THREAT index for each watershed.

THREAT, an environmental threat index, was calculated using equation (5):

$$THREAT = (IMP \times APCW \times PT)/10{,}000 \quad (5)$$

where

IMP = index of importance to surface drinking water model

APCW = ability to produce clean water index model

PT = percentage of a watershed that is threatened from a contamination to surface water

PT is defined differently for each threat: climate change that decreases water yield (PT_{YIELD}); land use change (PT_{LUC}); insects and disease (PT_{ID}); and wildfire potential (PT_{WFP}). Storm events, such as hurricanes, tornadoes, and straight-line winds were considered but were not used because no national coverage dataset was available.

THREAT values were divided by 10,000 to maintain a 0 to 100 index.

PT_{YIELD} was calculated for low emissions and high emissions future climate scenarios and for future years 2040 and 2090 using equations (6–9):

$$PT_{YIELD(LOW40)} = [(\{Yield2010 - Yield2040low\}/\{Yield2010\}) \times 100] \quad (6)$$

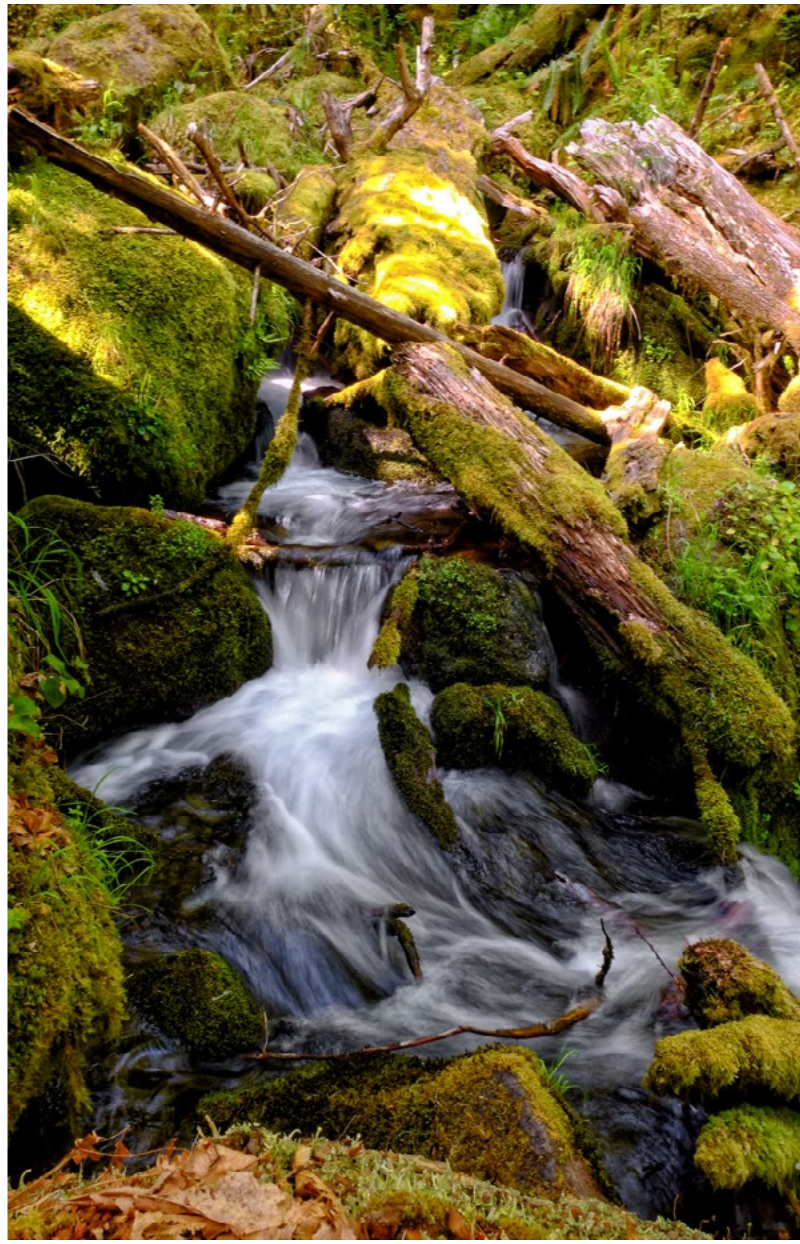
$$PT_{YIELD(LOW90)} = [(\{Yield2010 - Yield2090low\}/\{Yield2010\}) \times 100] \quad (7)$$

$$PT_{YIELD(HIGH40)} = [(\{Yield2010 - Yield2040high\}/\{Yield2010\}) \times 100 \quad (8)$$

$$PT_{YIELD(HIGH90)} = [(\{Yield2010 - Yield2090high\}/\{Yield2010\}) \times 100] \quad (9)$$

where

Yield2010, Yield2040, and *Yield2090* are the water yield as calculated by the Water Supply Stress Index (WaSSI) model for the years 2010, 2040, and 2090, respectively, by a 20-year average around the year of interest



A waterfall on the Umpqua National Forest. USDA Forest Service photo by Richard Krieger.

This study only considered watersheds that saw a decrease in water yield as potential threat from climate change. While the duration and timing of precipitation events can pose threats to watersheds with no water yield change and infrastructure can be potentially threatened by increases in water yield, detailed examinations of these factors were not considered in this analysis. Refer to the data section for a detailed description of the climate datasets and the WaSSI model.

PT_{LUC} was calculated for a low emissions and high emissions future climate scenarios and for future years 2040 and 2090 using equations (10–13):

$$PT_{LUC(LOW40)} = (LUC2010 - LUC2040low)/Total\_HUC12 \quad (10)$$

$$PT_{LUC(LOW90)} = (LUC2010 - LUC2090low)/Total\_HUC12 \quad (11)$$

$$PT_{LUC(HIGH40)} = (LUC2010 - LUC2040high)/Total\_HUC12 \quad (12)$$

$$PT_{LUC(HIGH90)} = (LUC2010 - LUC2090high)/Total\_HUC12 \quad (13)$$

where

LUC2010, LUC2040, and *LUC2090* are the land use as calculated by the Integrated Climate and Land-Use Scenarios (ICLUS) for the years 2010, 2040, and 2090, and *Total_HUC12* is the total HUC12 area for the HUC12 of interest. The change that occurred was one direction, i.e., from a nonurban land use classification to an urban classification. Refer to the data section for a detailed description of the land use datasets.

PT_{ID} was calculated using equation (14):

$$PT_{ID} = (At\_Risk/TOTAL\_ID) \times 100 \quad (14)$$

where

At_Risk is the treed area having National Insect and Disease Risk Map (NIDRM)-modeled "risk" and *TOTAL_ID* is the sum of the treed area having NIDRM-modelled "risk" and "not at risk." Refer to the data section for a description of the insect and disease dataset.

PT_{WFP} was calculated using equation (15):

$$PT_{WFP} = (Total\_H\_VH/TOTAL\_WFP) \times 100 \quad (15)$$

where

Total_H_VH is the sum of the watershed area in the wildfire potential classes of high and very high; *TOTAL_WFP* is the sum of watershed area in all the other classes present in wildfire potential dataset. Refer to the data section for a description of the wildfire potential dataset.

Data

Inputs for the IMP, APCW, and THREAT models (table 4) used a variety of national scale data. The authors rescaled the data used in the assessment models from their native resolution to the HUC12 boundaries.

Population and Surface Drinking Water Intakes

This study used the EPA's SDWIS dataset (U.S. Environmental Protection Agency 2018) to identify drinking water intake locations and the population served by those intakes for the IMP model. SDWIS contains basic, violation, and enforcement information on water systems in the United States. The States self-report the data contained in SDWIS to the EPA, and the EPA aggregates these to a national dataset as submitted (without correction). The authors used basic information from SDWIS, including the water system identification (ID), the latitude and longitude of the water system intake, the population served by the water system, and the source water type (surface water, ground water, etc.). This analysis omitted intakes with erroneous location information and only considered intakes with a source water type code of surface water or ground water under the direct influence of surface water. The population served by each water intake was calculated by summing the population within a water system and dividing it by the total number of intakes within that water system.[2] The analysis included a total of 16,811 water intakes within the conterminous United States; the total population served by those intakes was 124,835,279. The IMP model used these data as inputs.

2 The Great Lakes present a special case in that there are a large number of drinking water intakes found offshore. To maintain a similar weighting scenario using the population served by each water intake, the authors assigned offshore intakes to the subwatershed within 25 km of the intake and used them together with all the on-land intakes in the drinking water protection (PR) model. Because intakes are located offshore, all areas bordering the Great Lakes affect the water quality of the offshore intakes, not just the nearest subwatersheds where they were assigned.

Table 4.—Input datasets for the Forests to Faucets version 2.0 assessment

Data	Parameter	Source	Resolution	Time period	Model(s)
Watershed boundary	Watershed area	Watershed Boundary Dataset (WBD) (USGS and USDA NRCS 2013) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset)	HUC12	2019	IMP, APCW, THREAT
Population and surface drinking water intakes	Water intake, population served	Safe Drinking Water Information System (SDWIS) database (EPA 2017) (https://www.epa.gov/enviro/sdwis-search)	Aggregated to the HUC12 watershed	2017	IMP
Historical climate	Monthly total precipitation, mean temperature	Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Daly et al. 1994) (https://prism.oregonstate.edu/)	4 km x 4 km	1960–2015	Used to estimate water yield for IMP, APCW, THREAT
Future climate	Monthly total precipitation, mean temperature	Multivariate Adaptive Constructed Analogs (MACA) datasets (Taylor et al. 2012) (https://climate.northwestknowledge.net/MACA/index.php)	6 km x 6 km	1961–2099	Used to estimate water yield for IMP, APCW, THREAT
Water yield	Average annual water yield, percent change in average annual water yield	Water Supply Stress Index (WaSSI) model (Caldwell et al. 2012; Lockaby et al. 2013; Marion et al. 2013; Sun et al. 2008, 2011a, 2011b, 2013; Tavernia et al. 2013) (https://forestthreats.org/research/tools/WaSSI/)	HUC12	1960–2099	IMP, APCW, THREAT
Land cover	Developed; forest area; percentage of agriculture, impervious, and natural cover	National Land Cover Database (NLCD) (USGS 2019) (https://www.mrlc.gov/data)	30 m x 30 m	2016	APCW
Riparian area	Natural cover	National riparian areas base map (Abood and Maclean 2012; Abood et al. 2012) (https://www.riparian.solutions/story-map)	10 m x 10 m	2019	APCW
Land use change	Future land use	Integrated Climate and Land Use Scenarios (ICLUS) version 2.1 (EPA 2017) (https://iclus.epa.gov/)	90 m x 90 m	2000–2100	THREAT
Insects and disease	Insect/disease risk area	National Insect and Disease Risk Map (Krist et al. 2014) (https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/national-risk-maps.shtml)	240 m x 240 m	2012	THREAT
Wildfire	Wildfire hazard area	Forest Service wildfire hazard potential (WHP) dataset (Dillon 2018) (https://www.firelab.org/project/wildfire-hazard-potential)	270 m x 270 m	2018	THREAT
Forest ownership	Forest ownership	National Conservation Easement Database (NCED) version 3 (https://databasin.org/datasets/)	Parcel	2013	None. Ancillary layer available in online tool for filtering

APCW = ability to produce clean water index model; IMP = index of importance to surface drinking water model; THREAT = threats to surface drinking water model

Water Yield

This study used the Water Supply Stress Index (WaSSI) model to create the water yield (runoff) dataset by quantifying the amount of water produced within a HUC12 watershed under various climate scenarios. The Forest Service developed WaSSI to assess the potential impacts of changes in population, climate, and land use on water availability and ecosystem productivity at the conterminous U.S. scale (Caldwell et al. 2012; Lockaby et al. 2013; Marion et al. 2013; Sun et al. 2008, 2011a, 2011b, 2013; Tavernia et al. 2013). WaSSI runs at the monthly time step and comprises water balance, ecosystem productivity, and water supply and demand modules.

The authors averaged baseline water yield as annual water yield for a historical time period (1961–2015) and estimated future water yield for two future time periods (2040, an average of the years 2030–2049; and 2090, an average of the years 2080–2099). The Parameter-elevation Regression On Independent Slopes Model (PRISM) was the source of the historical climate data (Daly et al. 1994). The HadGEM2-ES365 general circulation model using representative concentration pathways (RCP) greenhouse gas emissions scenarios 4.5 and 8.5 was the source of the future climate data (Taylor et al. 2012). The RCP 4.5 emissions scenario is considered a less warming scenario, and RCP 8.5 is considered a higher warming scenario (Hayhoe et al. 2018). This assessment calculated the percent change in water yield by subtracting the average annual water yield for the historical time period from the future time period and dividing by the historical water yield for each scenario. Inputs for the IMP and APCW models used the average annual water yield; THREAT model inputs used the percent change in average annual water yield.

Land Cover

Every 5 years, the Multi-Resolution Land Characteristics (MRLC) Consortium produces the National Land Cover Database (NLCD), which was used to estimate land cover for the APCW model. The NLCD includes 30- x 30-m resolution land cover, percentage of developed imperviousness, and land cover change products for the United States. The MRLC uses the Landsat 5 thematic mapper (TM) as the source for the land cover classification; Homer et al. (2015); the U.S. Department of the Interior, Geological Survey (2019); and Yang et al. (2018) categorized the United States into 16 classes. The 2016 version of the NLCD provided inputs for the following APCW modeling parameters under baseline conditions: percentage of natural cover, percentage of agricultural land, percentage of impervious surface, and percentage of riparian natural cover. The dataset also provided forest cover input for forest ownership. This study grouped together classes of NLCD land cover to delineate these input parameters (table 5).

Table 5.—Crosswalk of National Land Cover Database (NLCD) land use class grouping to input parameters for the Forests to Faucets version 2.0 (F2FV2) assessment

Input parameter	Forest to Faucets definition (NLCD class grouping)	Model
Forest ownership	41, 42, 43, 90	Used as a filter in the F2FV2 online tool
Percentage of agricultural land	81, 82	APCW
Percentage of impervious surface	NLCD percent developed imperviousness dataset	APCW
Percentage of natural cover	11, 12, 41, 42, 43, 51, 52, 71, 90, 95	APCW
Percentage of riparian cover (natural or developed and agriculture)	21, 22, 23, 24, 31, 81, 82	APCW

The Fremont River meanders through the Fishlake National Forest. USDA Forest Service photo.

Riparian Area

The Forest Service developed a 10- x 10-m resolution riparian areas base map dataset for the continental United States and delineated it to the 50-year flood height. This dataset is unique in that it integrates streams, lakes, watersheds, wetlands, soils, elevation, land cover, and hydrologic data to delineate a variable-width riparian area (Abood and Maclean 2012; Abood et al. 2012). The authors overlaid the riparian areas base map on the 2016 NLCD dataset with two classifications—natural cover and developed and agriculture (see table 5)—to determine the percentage of the riparian area with natural cover at 30- x 30-m resolution, which was input into the APCW model.

Land Use Change

The THREAT model used the EPA's ICLUS version 2.1 dataset to estimate the threat of land use change across the United States (U.S. Environmental Protection Agency 2017). The ICLUS dataset projects decadal population into the year 2100, based on the Intergovernmental Panel on Climate Change (IPCC) shared socioeconomic pathways (SSP), which affects fertility, mortality, and immigration. ICLUS uses a mathematical model to simulate population migration patterns at the county level to estimate housing demand. Finally, a statistical model predicts future impervious surface area from the housing demand estimate.

ICLUS creates land use scenarios by combining standard SSPs—possible future socioeconomic conditions with either no climate change for the year 2010 or a climate change projection identified by the IPCC standard RCPs. Climate change projections used two future time periods: 2040 (an average of the years 2030–2049) and 2090 (an average of the years 2080–2099). This study used six ICLUS datasets (table 6). The combination of SSP5 and RCP8.5 represents a higher emissions, higher population-growth scenario, and the combination of SSP2 and RCP4.5 represents a lower emissions, lower population-growth scenario (U.S. Environmental Protection Agency 2017).

Table 6.—The land use and climate scenarios from the Integrated Climate and Land-Use Scenarios (ICLUS) version 2.1 dataset used in the Forests to Faucets version 2.0 assessment

Shared socioeconomic pathways (SSP)	Climate change model	Year
SSP2	No climate change	2010
	HadGEM2-ES365 RCP 4.5	2040
	HadGEM2-ES365 RCP 4.5	2090
SSP5	No climate change	2010
	HadGEM2-ES365 RCP 8.5	2040
	HadGEM2-ES365 RCP 8.5	2090

The ICLUS dataset has a 90- x 90-m resolution and 19 land-use classes (table 7). The authors reclassified land-use classes 14 to 18 to the land-use class "urban." The assessment calculated the land area that changed to "developed" based on the SSP-RCP scenario for each future time period and also calculated the percentage of land changed to "developed" for HUC12 watersheds. The authors input the percentage of a watershed predicted to change to "developed" into the THREAT model for each of the climate emissions scenarios.

Table 7.—The Integrated Climate and Land-Use Scenarios (ICLUS) land use classification scheme

Code	Group	Class name	Forest to Faucets classification
0	Water	Natural water	Not reclassified
1		Reservoirs, canals	Not reclassified
2		Wetlands	Not reclassified
3	Protected	Recreation, conservation	Not reclassified
4	Working/ production	Timber	Not reclassified
5		Grazing	Not reclassified
6		Pasture	Not reclassified
7		Cropland	Not reclassified
8		Mining, barren land	Not reclassified
9	Developed	Parks, golf courses	Not reclassified
10		Exurban, low density	Not reclassified
11		Exurban, high density	Not reclassified
12		Suburban	Not reclassified
13		Urban, low density	Not reclassified
14		Urban, high density	Urban
15		Commercial	Urban
16		Industrial	Urban
17		Institutional	Urban
18		Transportation	Urban

Insects and Disease

This study used the 2012 version of the National Insect and Disease Risk Map (NIDRM) to estimate risk of insects and disease in the THREAT model. Every 5 years, the Forest Service, Forest Health Technology Enterprise Team produces the NIDRM for the United States. The NIDRM defines risk as "the expectation that, without remediation, at least 25 percent of standing live basal area greater than 1 inch in diameter will die over a 15-year timeframe (2013–2027) due to insects and diseases" (Krist et al. 2014). The dataset has a 240- x 240-m resolution, and the NIDRM modeled 1.2 billion acres of treed areas ("any areas where presence of trees was recorded" [Krist et al. 2014]), as opposed to forested areas obtained from a remotely sensed land cover map that identifies forest location. The authors tabulated the area of the two classes—risk and no risk—within each HUC12 at the 30- x 30-m resolution, and from that, calculated the percentage of HUC12 with NIDRM-modeled risk, which was incorporated into the THREAT model.

Wildfire

The 2018 wildfire hazard potential (WHP) dataset, developed by the Forest Service to "help inform evaluations of wildfire risk" (Dillon 2018), provided input for the wildfire hazard parameter. The raster dataset has a 270- x 270-m resolution and covers the conterminous United States. "Areas mapped with higher WHP values represent fuels and other landscape conditions with a higher probability of experiencing high-intensity fire with torching, crowning, and other forms of extreme wildfire behavior under conducive weather conditions" (Dillon et al. 2015). The dataset presents WHP in seven classes: very low, low, medium, high, very high, nonburnable, and water. The authors tabulated the area of each WHP class within HUC12 watersheds at the processing resolution for the project—30 m x 30 m—and calculated the percentage of the high and very high WHP classes for each HUC12 watershed. The resulting percentage map provided input for the THREAT model.

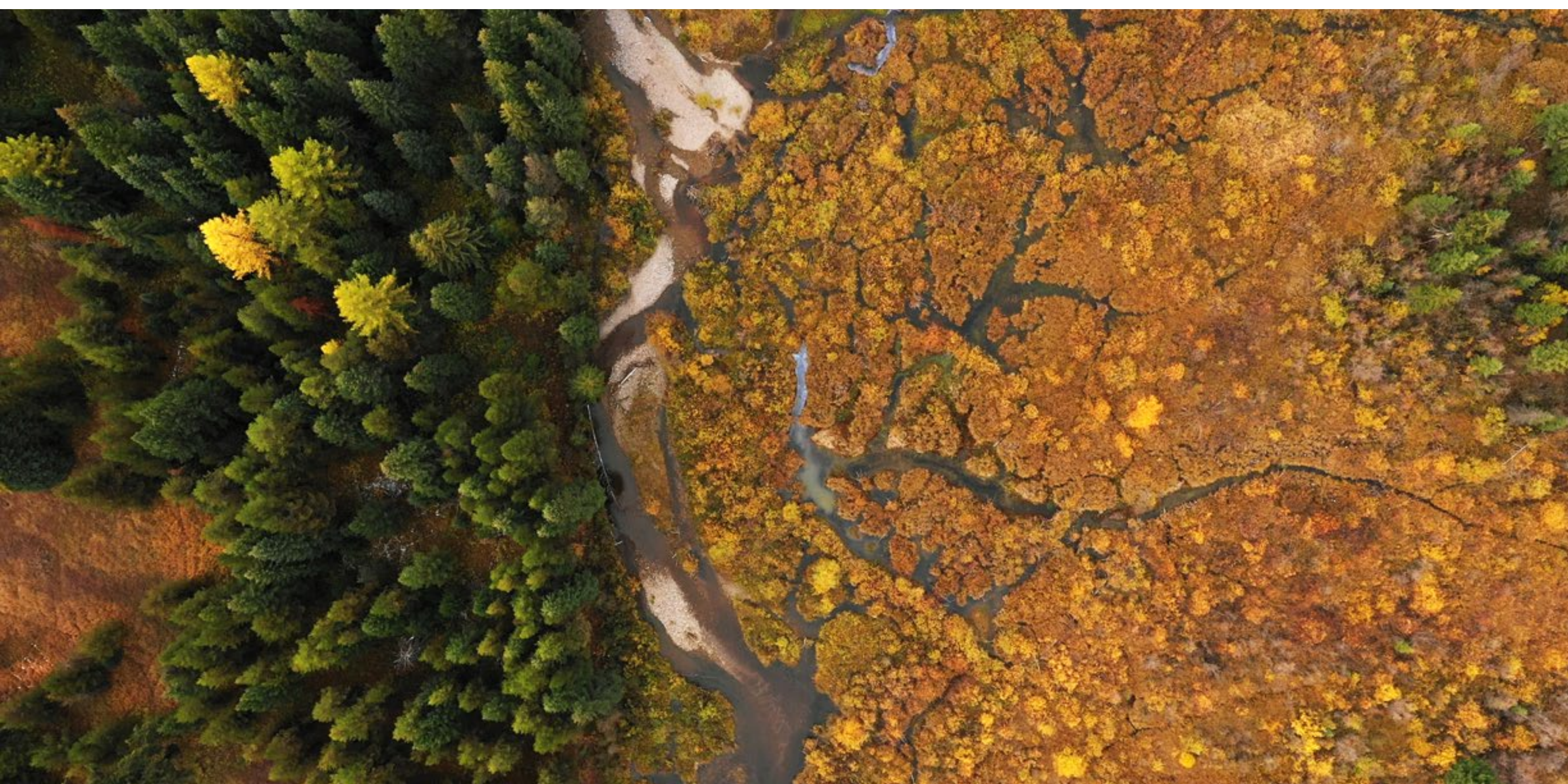
Forest Ownership

This study integrated the Conservation Biology Institute's Protected Areas Database of the United States (PAD-US) version 2.1, the National Conservation Easement Database (NCED) version 3, and NLCD forest land cover classes to determine forest ownership by HUC12 watershed. The timeframe of the forest ownership for the three datasets represents (approximately) 2016. The PAD-US identifies lands that are in fee simple ownership—"lands and water that [are] owned and legally designated to be set aside for the preservation of natural, cultural, or recreational resources" (Foster et al. 2014)—including national forest lands, for example. The NCED identifies lands that have permanent conservation easements—private lands voluntarily set aside by legal means between the owner and the Government, or a land trust for restricted use to protect the land's conservation value. The PAD-US and NCED account for approximately 990 million acres of land within the United States (Foster et al. 2014). The authors merged the PAD-US and NCED vector datasets together into a single dataset and grouped them into five categories (table 8). The dataset was then converted to a raster with a 30- x 30-m resolution. Next, the PAD-US and NCED layers were combined with the NLCD forest dataset (classes 41, 42, 43, and 90) to tabulate the area of forest ownership within the HUC12 watersheds. Finally, the assessment calculated the percentage of protected forested land per HUC12 as an ancillary layer for use in the web tool as a filter.

Table 8.—Crosswalk of Protected Areas Database of the United States (PAD-US)/National Conservation Easement Database (NCED) class to Forests to Faucets version 2.0 ownership class

Forests to Faucets class name	PAD-US/NCED class name
Other Federal forest, not national forest	Federal land
National forest	USDA Forest Service
Nonforest	Nonforest
Private forest	Private forest
Protected forest	NCED permanent, Native American land, joint ownership, local land, private conservation land, State land, unknown

Forests border a wetland area on the Flathead National Forest. USDA Forest Service photo.



Results

The following results summarize the F2FV2 model findings for the eight regions within the conterminous United States (see fig. 1).

Index of Importance to Surface Drinking Water (IMP)

The IMP index is an estimated value that integrates average annual runoff, population, and water intake data for the watersheds. This study maps the index on a scale of 0 to 100 and charted with five classes in 20-unit increments, ranging from very low to very high importance for surface drinking water. The IMP model results identified the Forest Service Eastern, Southern, and Pacific Southwest regions as those with the most watersheds with very high importance to surface drinking water supplies; the Southwestern and Intermountain regions had the most watersheds with very low importance to surface drinking water supplies (figs. 3 and 4). In general, the watersheds with very high importance to surface drinking water supplies are those that correspond to locations with large populations that rely on surface drinking water and have a higher water use. These results are consistent with the results from the F2FV1 assessment (Weidner and Todd 2011).

Trout Pond on the Apalachicola National Forest, FL. USDA Forest Service photo by Susan Blake.

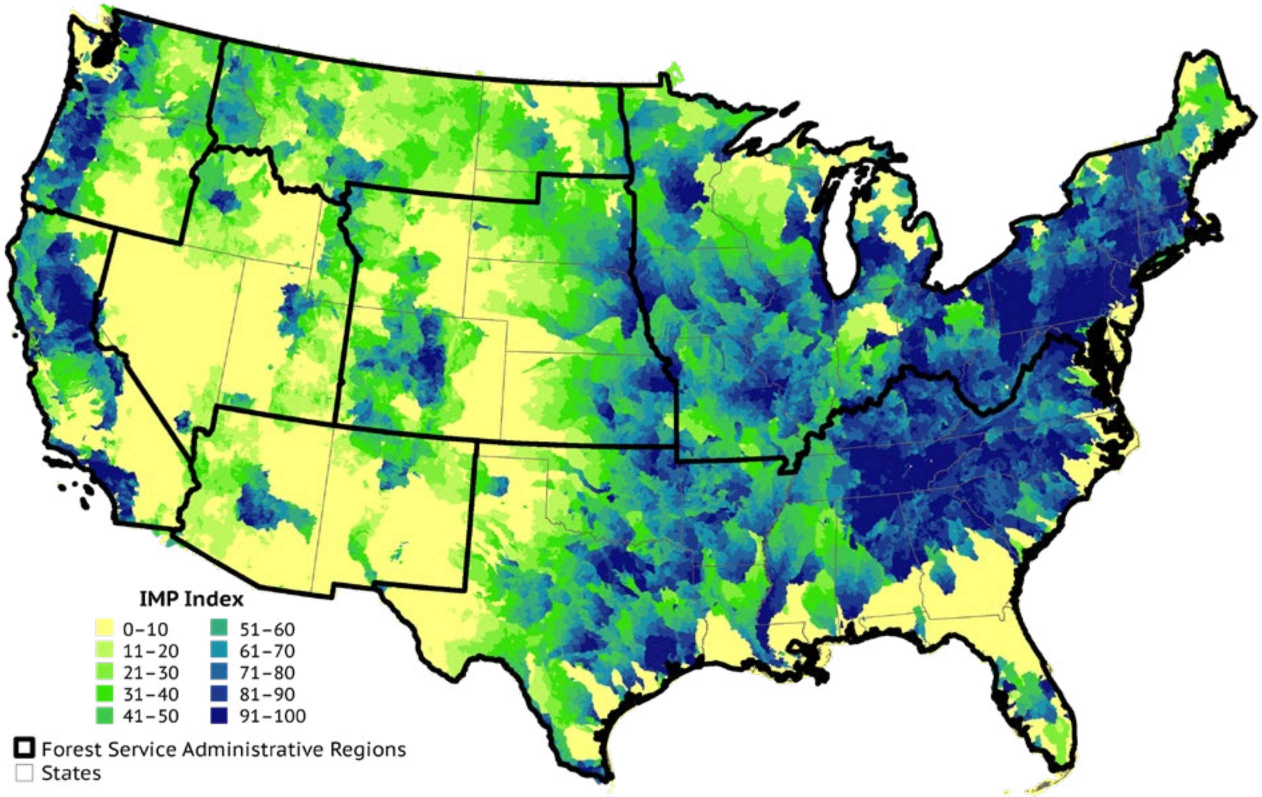
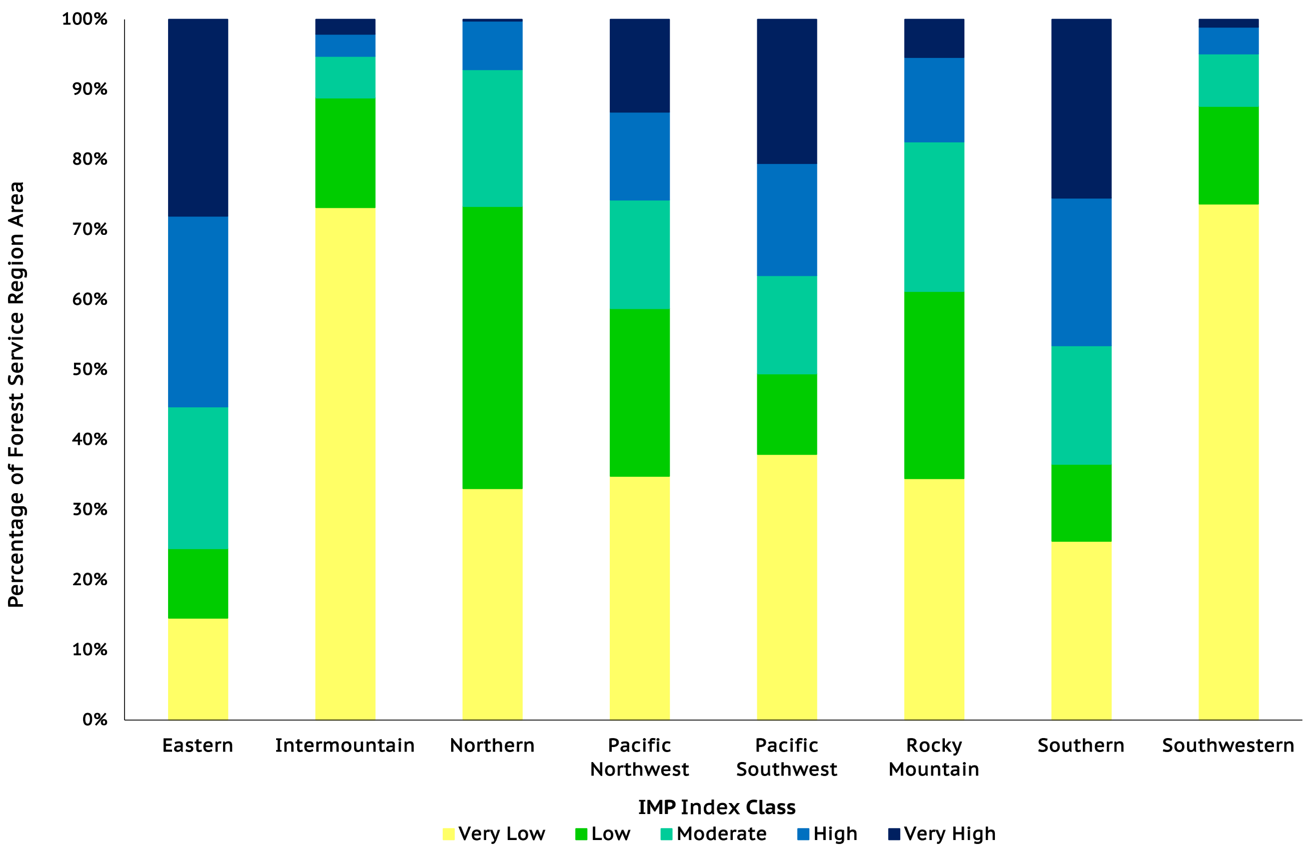


Figure 3.—The importance to surface drinking water (IMP) index map for the 83,314 watersheds in the conterminous United States. Watersheds with darker blue colors have higher importance for protecting surface drinking water.

Figure 4.—Percentage of a Forest Service region area within an importance to surface drinking water (IMP) index class.



Ability to Produce Clean Water (APCW) Index

The APCW model integrated the percentage of natural cover, percentage of agricultural land, percentage of impervious surface, percentage of riparian natural cover, and average annual runoff of a watershed to determine the APCW index. This study maps the index on a scale of 0 to 100 and charted with 5 classes in 20-unit increments, ranging from a very low to a very high ability to produce clean water. The APCW model results identified the Southern, Pacific Northwest, and Pacific Southwest regions as having the most watersheds with a very high ability to produce clean water; the Rocky Mountain and Northern regions had the most watersheds with a very low ability to produce clean water (figs. 5 and 6). In general, watersheds with a high percentage of vegetation and low percentage of impervious surface would have a higher ability to produce clean water.

Threats to Surface Drinking Water

The THREAT model provided the framework for determining the threats to surface drinking water from a range of potential threats, including insects and disease, wildfire, climate change that reduces water yield, and land use change. Combining IMP and APCW indices with each quantified potential threat produced a THREAT index for each. The authors mapped these THREAT indices on a scale of 0 to 100 to allow integration with the IMP and APCW map that identified watersheds important to surface drinking water and the ability to produce clean water.

A creek flows through the Flathead National Forest.
USDA Forest Service photo.

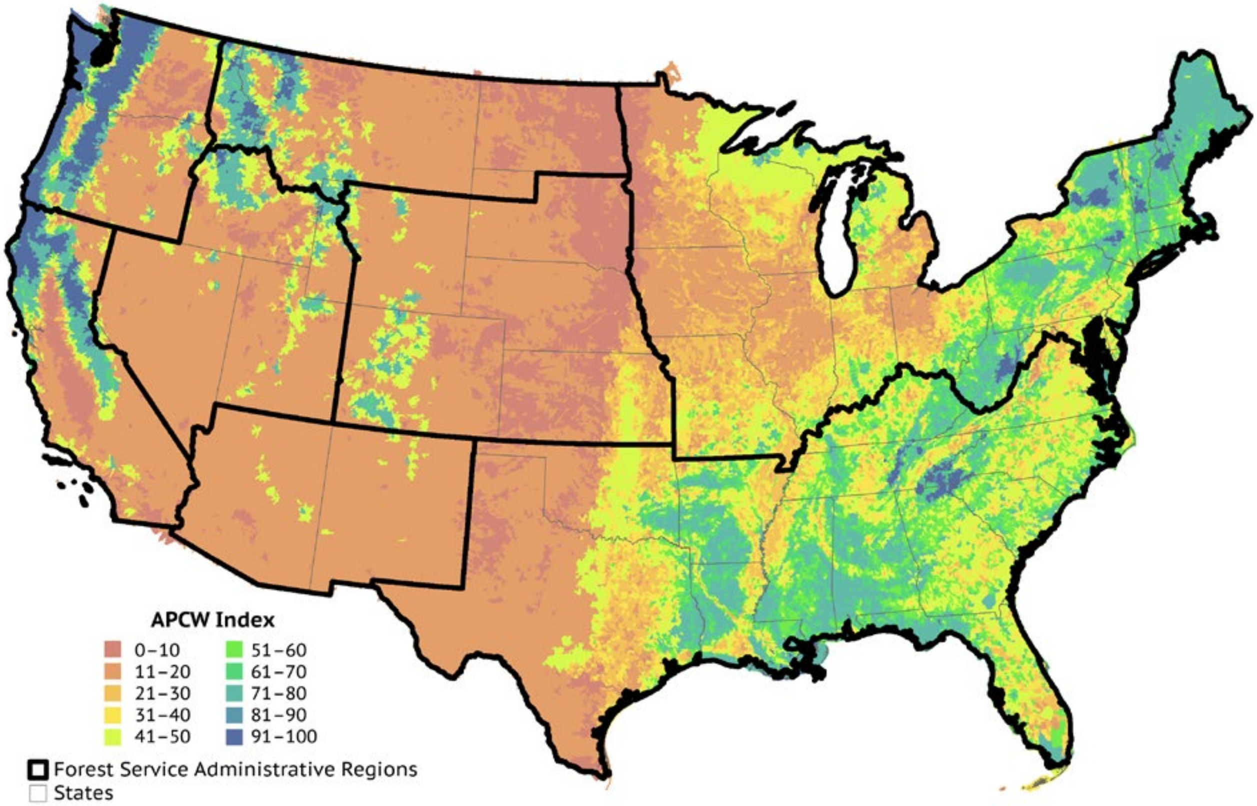
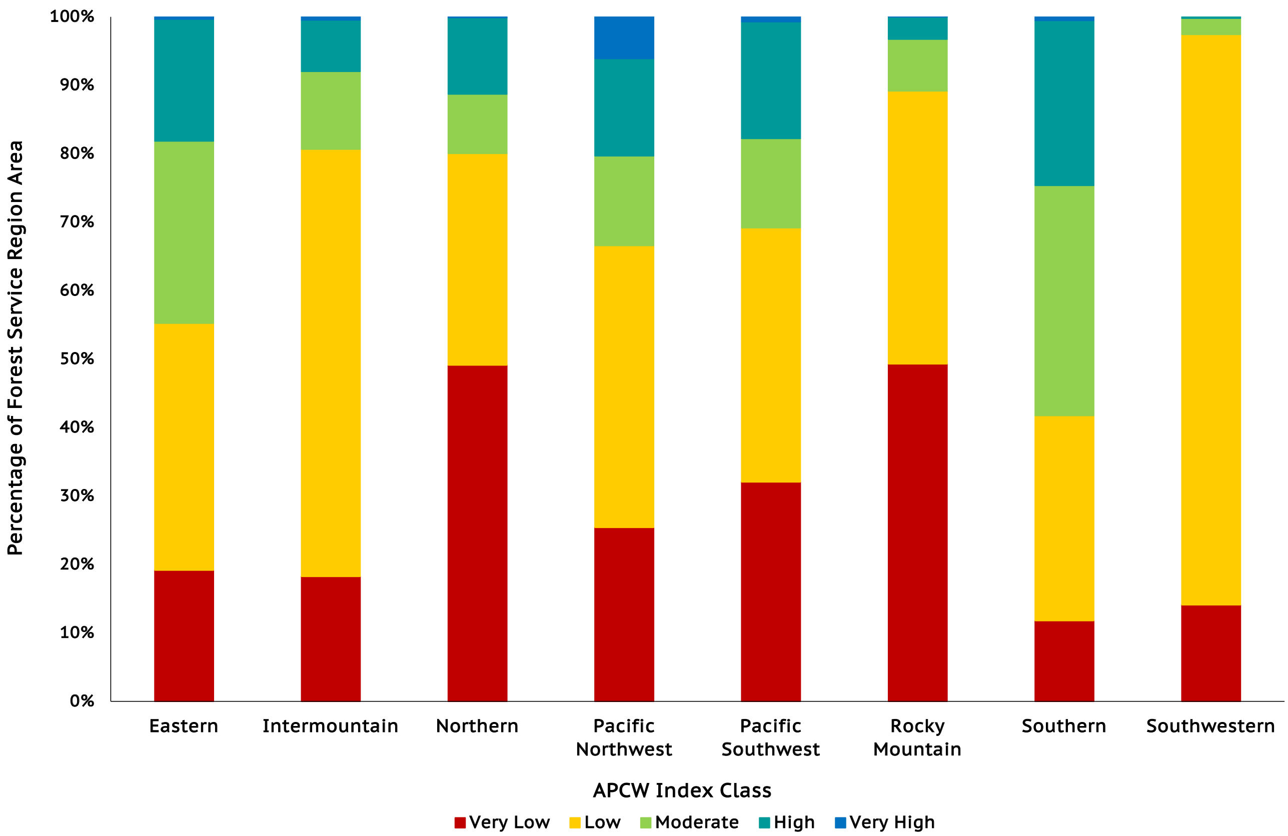


Figure 5.—The ability to produce clean water (APCW) Index map for the 83,314 watersheds in the conterminous United States. Watersheds in blue have the highest ability to produce clean water.

Figure 6.—Percentage of a Forest Service region area within an ability to produce clean water (APCW) index class.



Water Yield Decrease

This assessment considered climate change trends in terms of decreasing water availability that results from changes in water balance due to increasing temperatures and changes in precipitation in U.S. watersheds. Figure 7 shows watersheds important to drinking water that were predicted by the WaSSI model to experience a decrease in water yield. The Pacific Northwest, Pacific Southwest, and Southern regions had the most watersheds in the very high THREAT index class under the 2040 low-emissions scenario (figs. 7A and 8A), and the Southern, Eastern, and Pacific Northwest regions had the most watersheds in the very high THREAT index class under the 2040 high-emissions scenario

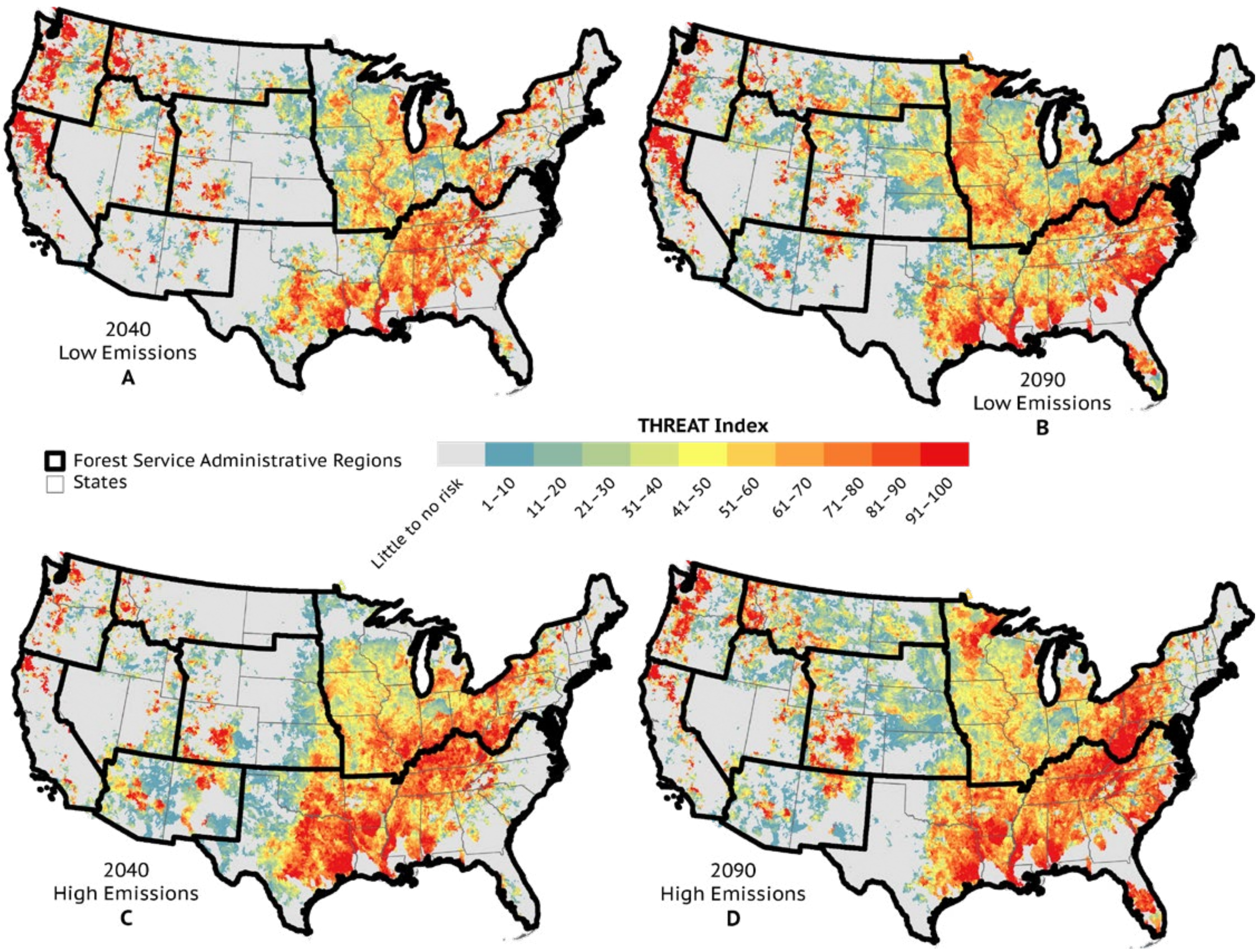


Figure 7.—Watersheds important to surface drinking water supply predicted by the WaSSI model to experience a decrease in water yield under future climate scenarios (A and B: low-emissions scenarios for 2040 and 2090, respectively; C and D: high-emissions scenarios for 2040 and 2090, respectively). Watersheds in red have the highest THREAT index.

(figs. 7C and 8C). The Southern, Pacific Southwest, and Pacific Northwest regions had the most watersheds in the very high THREAT index class under the 2090 low-emissions scenario (figs. 7B and 8B), and the Southern, Pacific Northwest, and Eastern regions had the most watersheds in the very high THREAT index class under the 2090 high-emissions scenario (figs. 7D and 8D). For all of the future climate scenarios, all of the regions had some watersheds in the very high THREAT index class, but the Pacific Northwest and Southern regions consistently had the most watersheds in the very high THREAT index class for the future, and could be priority areas of focus in future work.

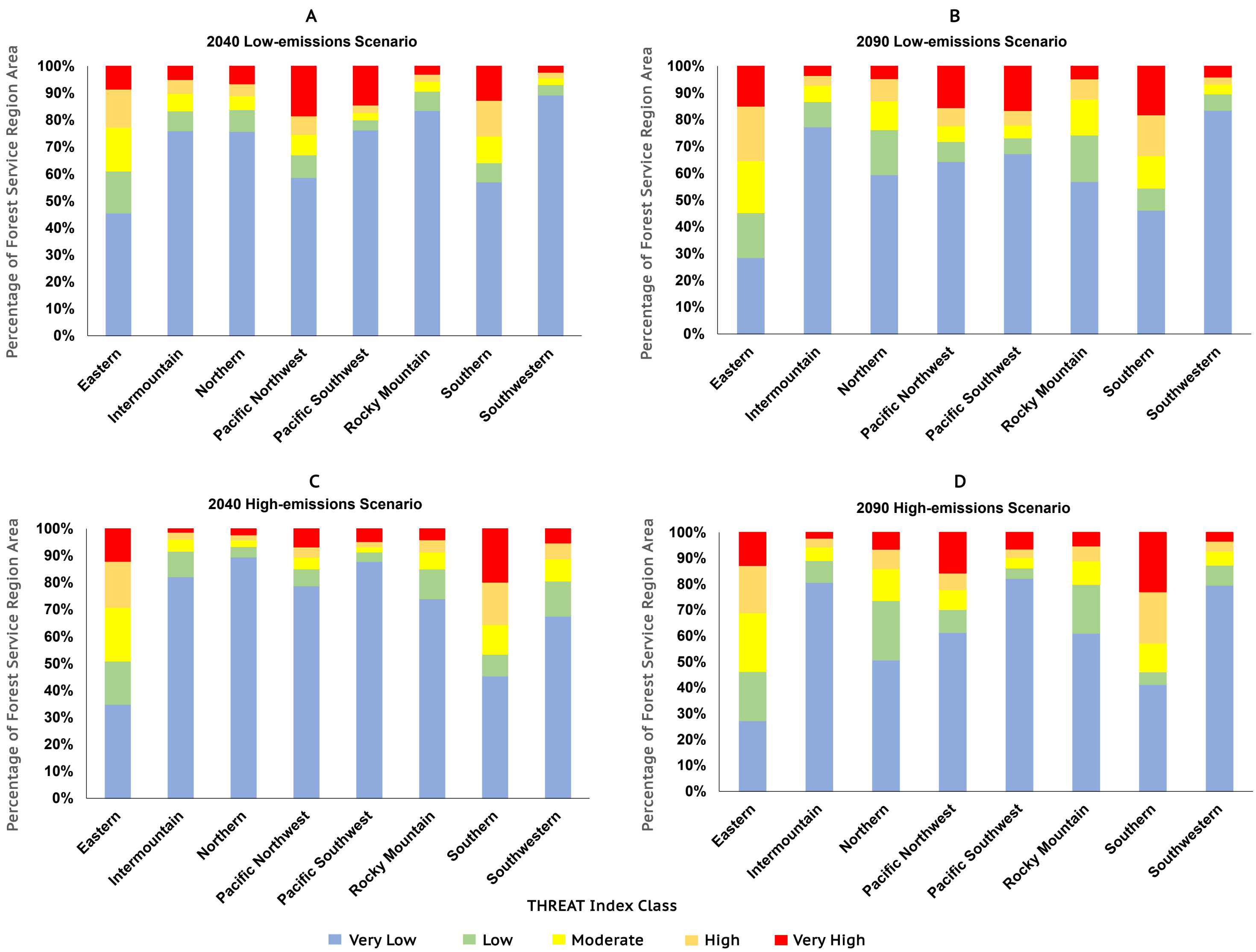


Figure 8.—Percentage of a Forest Service region area predicted by the WaSSI model to experience a decrease in water yield under future climate scenarios (A and B: low-emissions scenarios for 2040 and 2090, respectively; C and D: high-emissions scenarios for 2040 and 2090, respectively).

Land Use Change

Figure 9 shows watersheds important to surface drinking water that were predicted by ICLUS to have increased land use change due to population growth. The Southern, Pacific Southwest, and Eastern regions had the most watersheds in the very high THREAT index class for land use change for both the low and high emission scenarios for the 2040 and 2090 time periods (figs. 9 and 10). These results reflect historical population trends of the United States, with the Southern United States having the highest rate of population growth since 2000, according to the U.S. Census (U.S. Department of Commerce, Census Bureau 2019; Wilson et al. 2012).

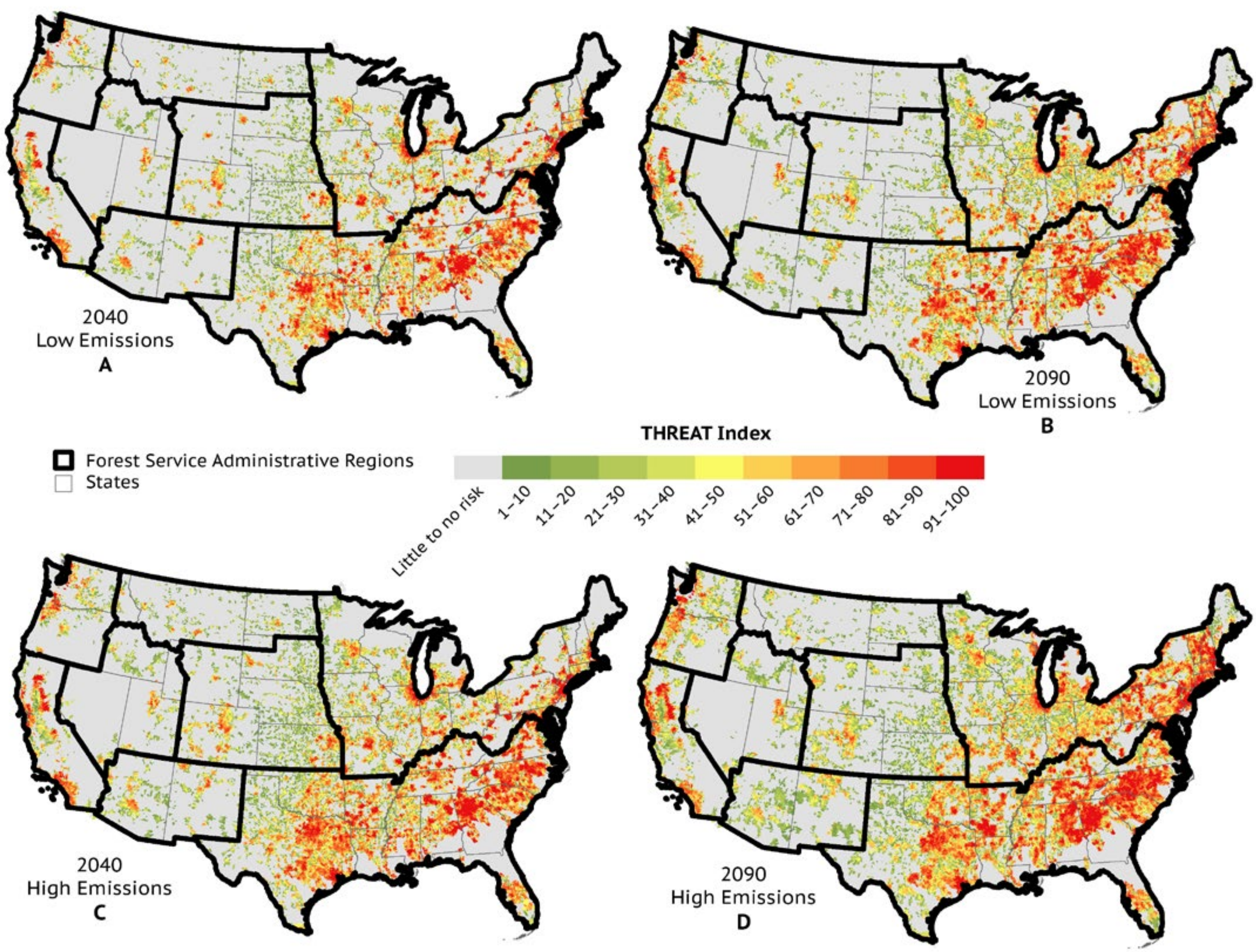


Figure 9.—Watersheds important to surface drinking water supply predicted by ICLUS to have increased land use change due to population growth under future climate scenarios (A and B: low-emissions scenarios for 2040 and 2090, respectively; C and D: high-emissions scenarios for 2040 and 2090, respectively). Watersheds in red have the highest THREAT index.

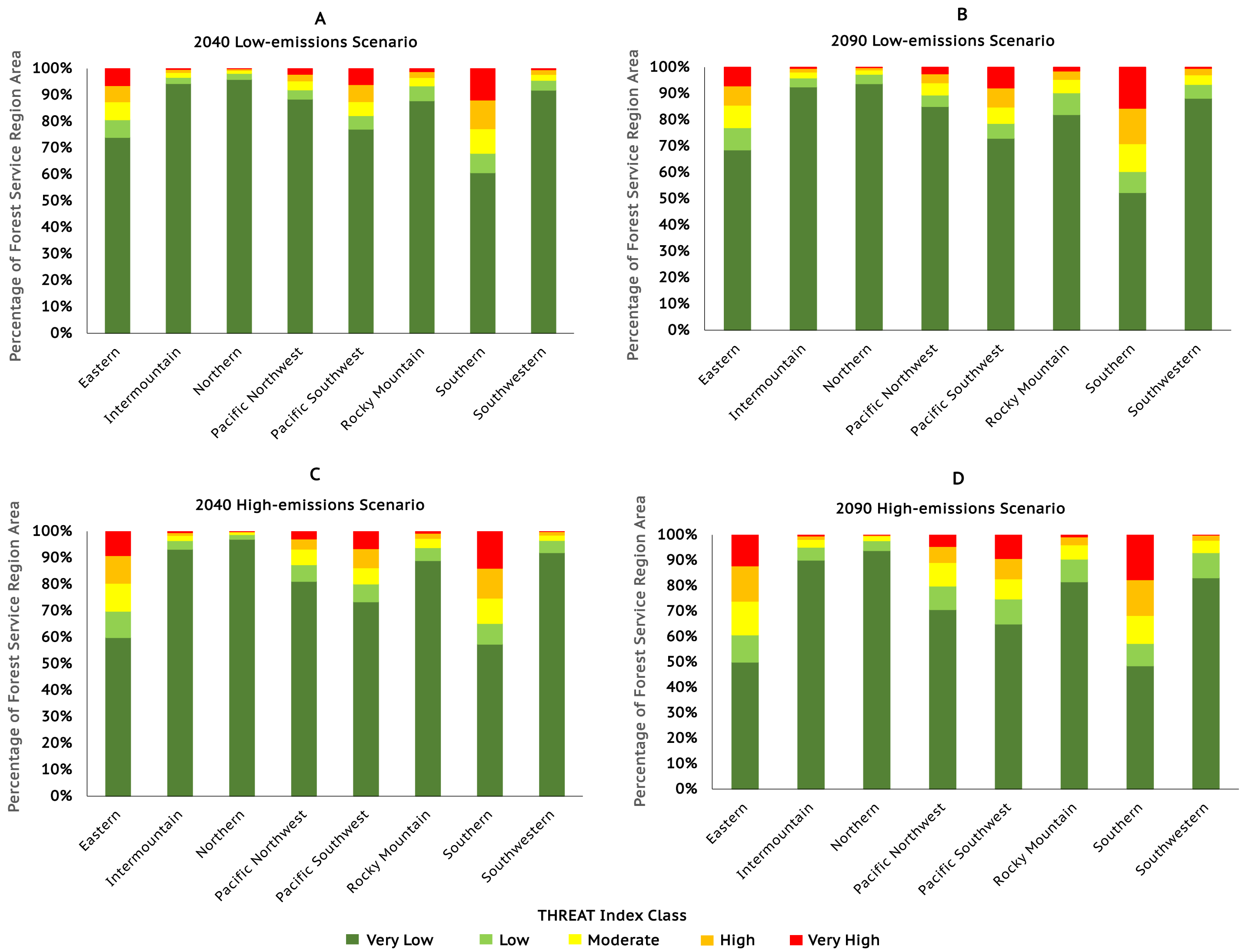


Figure 10.—Percentage of a Forest Service region area predicted by ICLUS to have increased land use change under future climate scenarios (A and B: low-emissions scenarios for 2040 and 2090, respectively; C and D: high-emissions scenarios for 2040 and 2090, respectively).

Insects and Disease

Figure 11 shows watersheds important to surface drinking water that have a threat of tree mortality from insects and disease. The analysis showed 19 percent of all HUC12 watersheds within the conterminous United States had threats from insects and disease. The Northern, Pacific Northwest, and Pacific Southwest regions had the most watersheds in the very high THREAT index class for insects and disease (figs. 11 and 12). In 2016 and 2018, the Forest Service, Forest Health Protection's National Insect and Disease Survey identified the west coast (the Pacific Northwest and Pacific Southwest regions) as having the largest area (1.95 million ha in 2016 and 1.08 million ha in 2018) with mortality agents and complexes. During 2016 and 2018, the top three mortality agents threatening west coast forests included fir engraver *(Scolytus ventralis),* western pine beetle *(Dendroctonus brevicomis),* and mountain pine beetle *(D. ponderosae)* (Potter et al. 2018, 2020).

Landscape-scale insect impacts on the Sierra National Forest. USDA Forest Service photo.

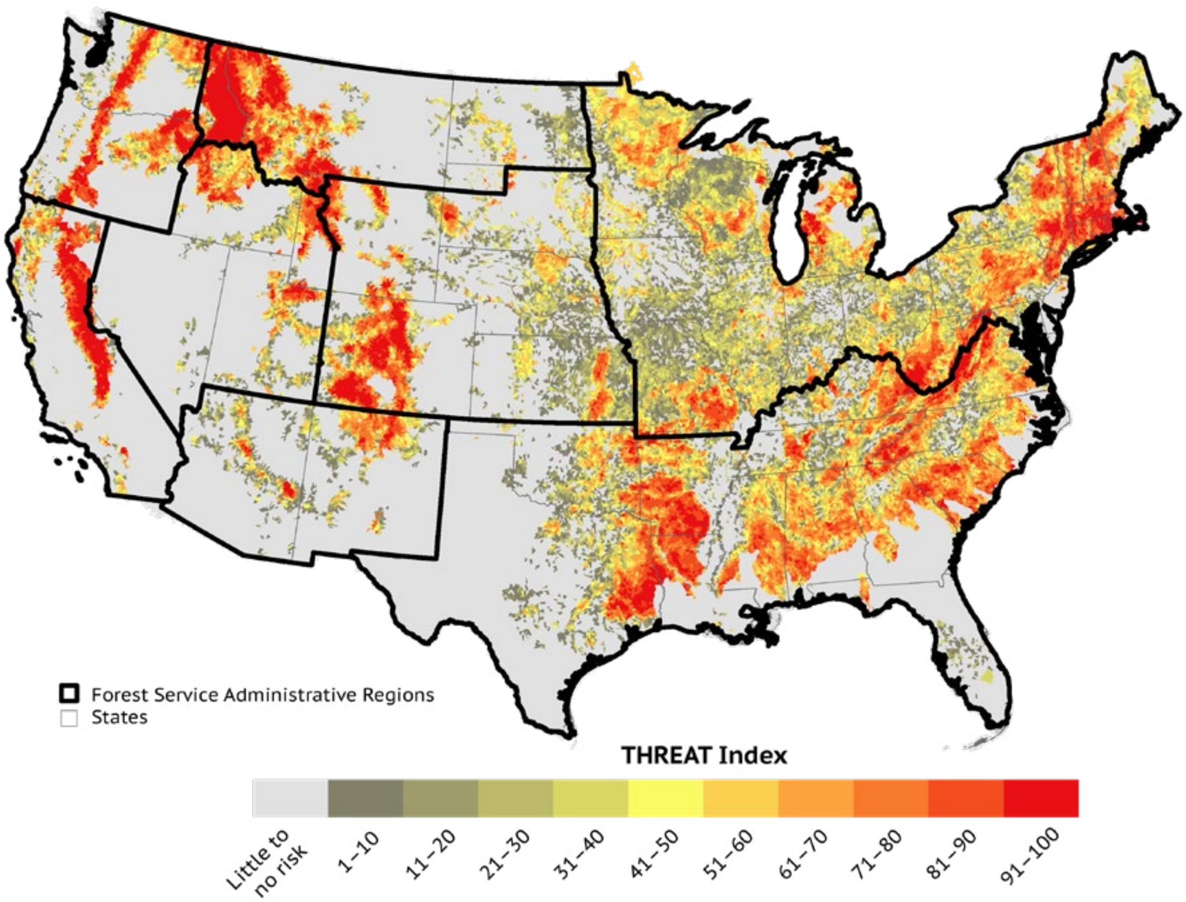
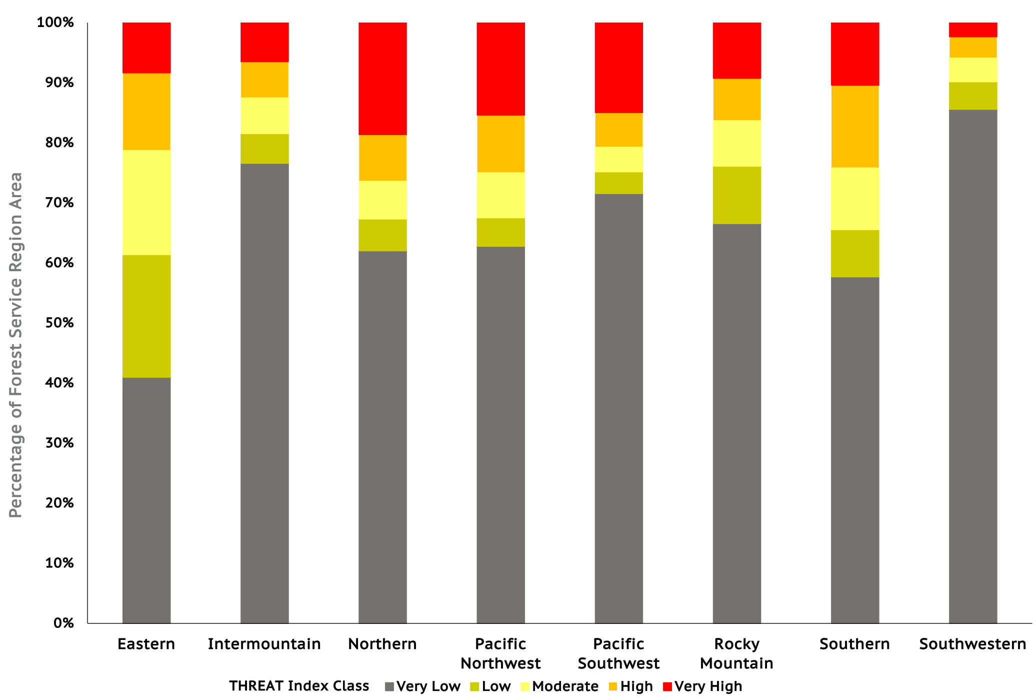


Figure 11.—Watersheds important to surface drinking water supply that have a threat of tree mortality from insects and disease. Watersheds in red have the highest THREAT index.

Figure 12.—Percentage of a Forest Service region area that has a threat of tree mortality from insects and disease.



Wildfire

Figure 13 shows watersheds important to surface drinking water classified with high or very high wildfire hazard potential, based on the 2018 WHP dataset. Nineteen percent of all HUC12 watersheds had a threat from wildfire, and the remaining 81 percent had little to no threat. The Pacific Southwest, Pacific Northwest, and Northern regions had the most watersheds in the very high THREAT index class for wildfire (figs. 13 and 14). In the conterminous United States, northern California and north-central Washington ecoregions, which overlay the Pacific Southwest and Pacific Northwest regions, had the highest fire occurrence densities (the number of fire occurrences per 100 km^2 [10,000 ha] of tree canopy coverage area) in 2018. For the years 2001–2017, the California, northern Rocky Mountains, Southwest, and Southeastern Coastal Plain ecoregions had the highest annual mean number of fire occurrences per 100 km^2 of tree canopy coverage area (Potter 2020).

Impacts of the Eagle Creek Fire in the Columbia River Gorge National Scenic Area, OR.
Trailkeepers of Oregon photo by Claudio Berstein.

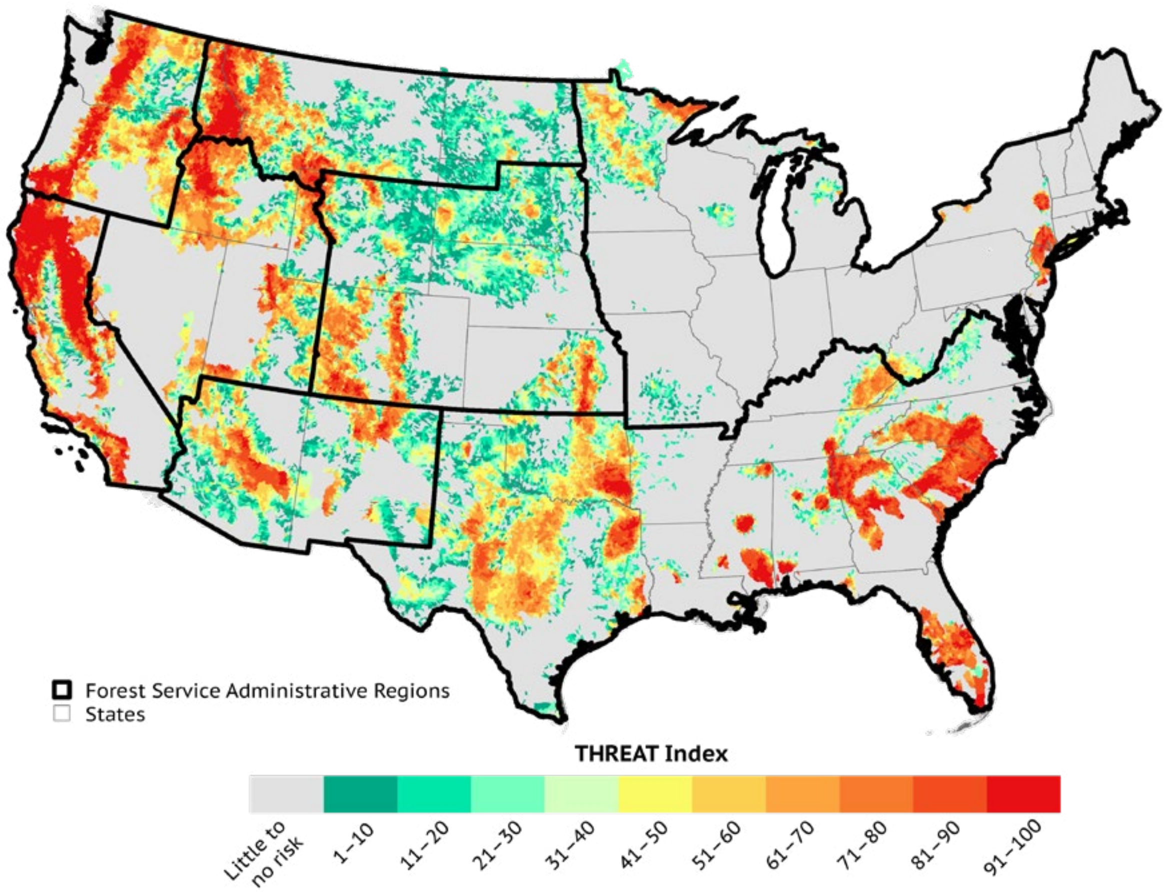
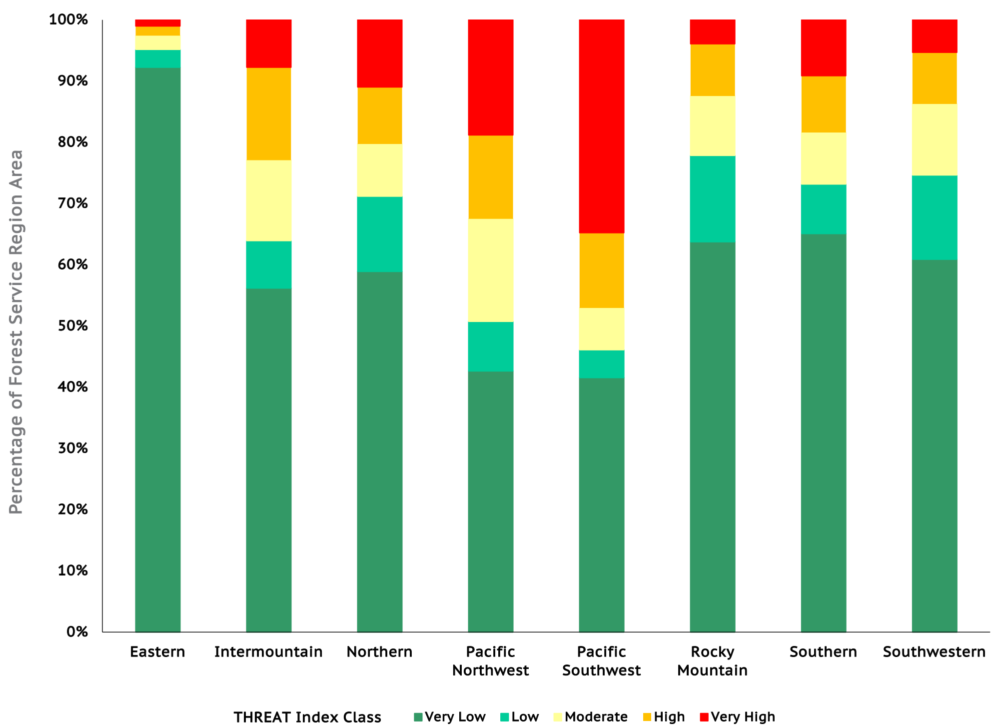


Figure 13.—Watersheds important to surface drinking water supply threatened by wildfires.

Figure 14.—Percentage of a Forest Service region area threatened by wildfire.



Summary

By employing new datasets, Forests to Faucets version 2.0 (F2FV2) represents an update of a previous effort to explicitly map the connections between forests and surface drinking water supply, with a relatively high spatial resolution (HUC12) at a national level. This assessment incorporated new environmental threats such as climate change and land use change scenarios along with detailed land data characteristics (i.e., riparian cover).

When examining the THREAT index results for each Forest Service region, the authors classified most of the watersheds as low or very low. This was expected because the driving factors for the potential threat considered in this report are localized. For example, an insect and disease outbreak can be specific to a tree species, and that species may not be present in all watersheds within a Forest Service region. The potential for wildfire risk depends on the availability of fuels, and all watersheds within a region may not have a buildup of fuels. All watersheds within a Forest Service region will not see a reduction of water or an increase of population in the future. The THREAT maps are tools land and water resource managers can use to identify potential hotspots that could require further investigation and potential mitigation.

By Forest Service region, the importance of watersheds (IMP index) to surface drinking water and the ability to produce clean water (APCW index) are more regional and contiguous in nature. The patterns of IMP index are consistent with patterns of stream flow routing that is incorporated within the index methodology; the biophysical characteristics of the APCW index generally span contiguous watersheds.

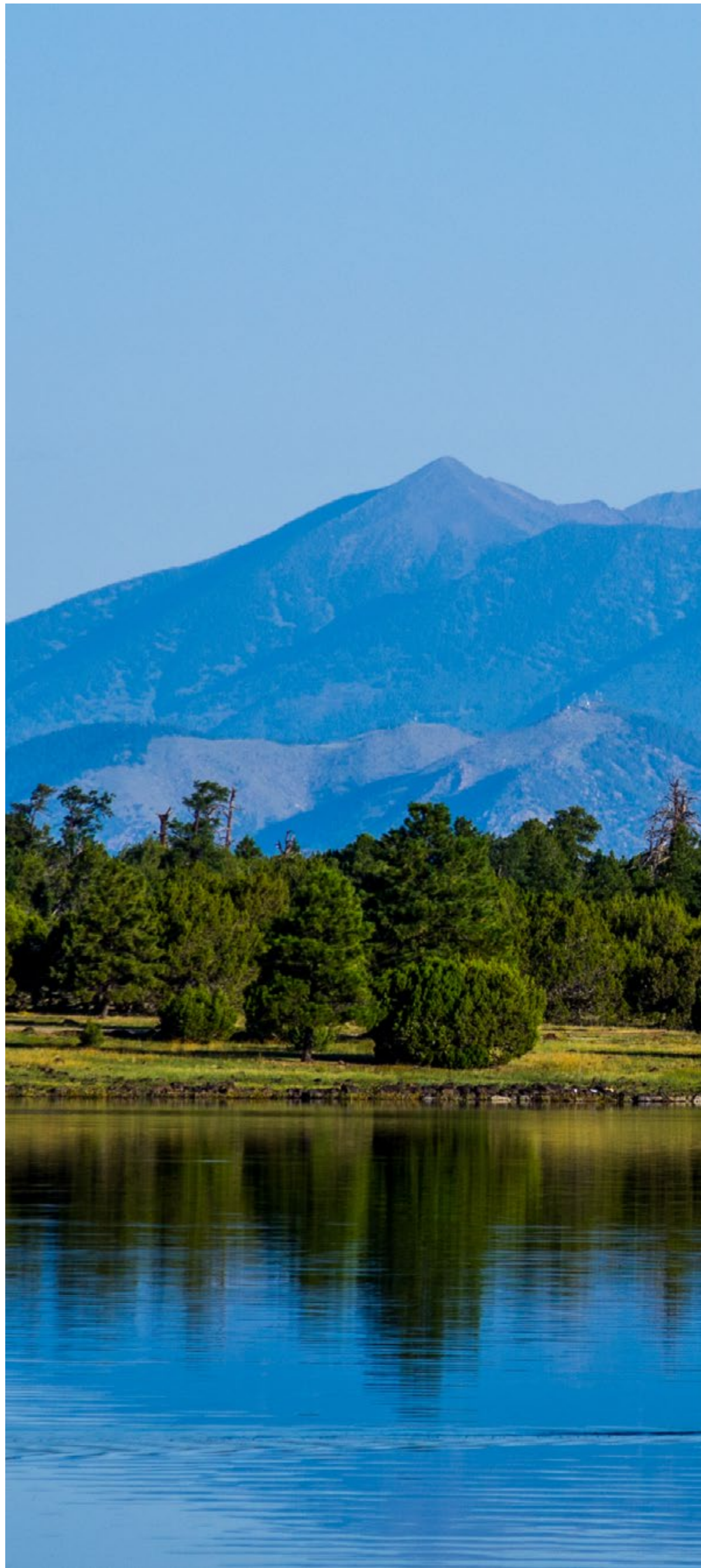
This study was designed to use commonly available national datasets to model water quantity and quality at the watershed scale. The Forests to Faucets version 2.0 dataset and maps are most appropriate for use at the large-basin scale and regional to national scale. Thus, land and water resource managers can incorporate the assessment results into decision support tools at the State, regional, or national scale, or in forest management plans. Land and water resource managers should be cautious using the dataset and results solely for making decisions at local small scales, as localized data would be more appropriate. Predicting the response of water quantity and quality to future environmental change can be extremely challenging, and the results of this study are subject to validation and revisions. This study provides a tool and benchmark dataset for land and water resource managers to evaluate the impact of their management on surface water supply and for water consumers to consider potential environmental threats upstream, now and in the future.

Mesa Falls on the Caribou-Targhee National Forest. USDA Forest Service photo by Kelly Wickens.

List of Abbreviations

APCW	ability to produce clean water index model
EPA	U.S. Environmental Protection Agency
F2FV1	Forest to Faucets version 1.0
F2FV2	Forest to Faucets version 2.0
FIMP	index of forest importance to surface drinking water model
HUC12	12-digit hydrologic unit code
ICLUS	Integrated Climate and Land-Use Scenarios
ID	identification
IMP	index of importance to surface drinking water model
IPCC	Intergovernmental Panel on Climate Change
MRLC	Multi-Resolution Land Characteristics
NCED	National Conservation Easement Database
NIDRM	National Insect And Disease Risk Map
NLCD	National Land Cover Database
PAD-US	Protected Areas Database of the United States
PR	drinking water protection model
PRISM	Parameter-elevation Regression On Independent Slopes Model
PT	potential threat
RCP	representative concentration pathways
SDWIS	Safe Drinking Water Information System
SSP	shared socioeconomic pathways
THREAT	threats to surface drinking water model
TM	thematic mapper
WaSSI	Water Supply Stress Index model
WHP	wildfire hazard potential

Ashurst Lake on the Coconino National Forest.
USDA Forest Service photo by Sean Golightly.



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