ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Forested lands dominate drinking water supply in the conterminous United States

To cite this article: Ning Liu *et al* 2021 *Environ. Res. Lett.* **16** 084008

IOP Publishing Environ. Res. Lett. 16 (2021) 084008 https://doi.org/10.1088/1748-9326/ac09b0

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
5 April 2021

REVISED
7 June 2021

ACCEPTED FOR PUBLICATION
9 June 2021

PUBLISHED
22 July 2021

LETTER

Forested lands dominate drinking water supply in the conterminous United States

Ning Liu[1,2], **Peter V Caldwell**[1], **G Rebecca Dobbs**[1,3], **Chelcy Ford Miniat**[1,5], **Paul V Bolstad**[2], **Stacy A C Nelson**[3] **and Ge Sun**[4]

[1] Coweeta Hydrologic Lab, Southern Research Station, U.S. Department of Agriculture Forest Service, Otto, NC 28763, United States of America
[2] Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, United States of America
[3] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, United States of America
[4] Environmental Threat Assessment Center, Southern Research Station, U.S. Department of Agriculture Forest Service, Eastern Forest, Research Triangle Park, NC 27709, United States of America
[5] Maintaining Resilient Dryland Ecosystems, Rocky Mountain Research Station, U.S. Department of Agriculture Forest Service, Albuquerque, NM 87102, United States of America

E-mail: Ning.Liu@usda.gov

Keywords: drinking water, hydrologic modeling, forest ownership, WaSSI, water supply, water yield

Supplementary material for this article is available online

Abstract

Forests provide the most stable and highest quality water supplies among all land uses. Quantitatively evaluating the benefits of forest water supply functions is important to effectively mitigate the impacts of land development, climate change, and population growth. Here, by integrating a water balance model and national drinking water data, we determined the amount of surface water yield originating on different forest ownership types at a fine resolution (88,000 watersheds) and tracked that water through the river network to drinking water intakes and the populations they serve. We found that forested lands comprised 36% of the total land area but contributed 50% of the total surface water yield. Of the 23,983 public surface drinking water intakes depending on surface water sources, 89% (serving around 150 million people) received some (>0.01%) surface water from forested lands, and 38% (serving about 60 million people) received more than 50% of their surface drinking water supply from forested lands. Privately-owned forests were the most important water source in the eastern U.S., benefiting 16 million people, followed by federal forests (14.4% of the total water supply). In contrast, federally-owned forested lands were the dominant water source (52% of the total water supply) in the West. Privately-owned forests are the most vulnerable to future land use change and associated water supply impacts. Continuing programs that support private forest landowners with financial and technical assistance through federal and state forest management agencies and potentially developing payment for ecosystem service schemes could maximize benefits for landowners so they may retain their land assets while minimizing forest loss and associated impacts on critical ecosystem services including the provisioning a clean and reliable water supply for the American public.

1. Introduction

Forests provide the most stable and highest quality supply of water among all land types (Brown *et al* 2008, Vose *et al* 2016, Murphy 2020). Early policy makers in the U.S. recognized this linkage and in the Organic Administration Act of 1897 wrote '*No National Forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows…*'. Forests regulate streamflow quantity and quality through affecting precipitation partitioning (i.e. evapotranspiration and infiltration), water storage, nutrient cycling, and soil erosion and sediment transport processes at multiple scales (Andréassian 2004, Farley *et al* 2005, Ellison *et al* 2012, 2017, Filoso *et al* 2017, Zhang and Wei 2021). In general, the greater the forest coverage in a watershed, the higher the water quality (Tu 2013, Giri and Qiu 2016). Forest conversion to residential, commercial, and agricultural lands reduces water quality (Moore *et al* 2005, Mapulanga and Naito 2019), and increases runoff and flood risk (Li *et al* 2020). In addition, unlike other natural ecosystems (i.e. shrublands, grasslands) (Buytaert *et al* 2006, Shi *et al* 2017), forests in the U.S. are found in areas with relatively higher precipitation but lower potential evapotranspiration (Sun *et al* 2012) representing areas with high water yield (Sun *et al* 2011).

Drinking water utilities are increasingly seeking ways to maintain forested lands to protect water quality and sustain water supply (Warziniack *et al* 2017). Apart from increasing water demand, population growth will also affect the quality of water supply as forests are converted to developed areas (e.g. Tu 2013). Exurban growth is one of the fastest land use changes over the past four decades, with increasing development beyond the suburban fringe (Radeloff *et al* 2005, Theobald 2005). Exurban growth threatens water quality even at low development densities (McGrane 2016). About one third of the land in the conterminous U.S. (CONUS) is now covered by forests, after declining from 4.14 million km^2 (46% of total land area) in 1,630 to 3.10 million km^2 (33% of land area) in 2012 (Oswalt *et al* 2014). Although the total amount of forest area has stabilized in recent decades in the U.S. (Homer *et al* 2020), forested lands are predicted to decline by 2–3.7% as the population grows by 2050 (D'Annunzio *et al* 2015, U.S. EPA 2020).

Forest ownership patterns differ between the eastern and western regions of the U.S. While the federal government owns 2.59 million km^2 of forested land in the U.S., most of it (75%) lies in the 11 western contiguous states. In contrast, most of the forested land in the eastern U.S. is privately owned. Across the South, forests owned by State and local governments, corporations, families, and other private entities account for about 90% of the total forested land area. Family-owned forests are the majority of privately owned forest lands in the South (55%), followed by corporately owned forests (26%) (Hewes *et al* 2017). Most family-owned forest land is used for aesthetics, wildlife habitat, and family income and legacy, while corporations that own forested land with wood-processing facilities traditionally have been a major source of U.S. timber production (Oswalt *et al* 2014). The projected forest loss due to urban development and agriculture expansion (D'Annunzio *et al* 2015, U.S. EPA 2020) will likely occur in privately owned forests (McNulty *et al* 2013), and is expected to negatively affect surface water supply for downstream communities (Martinuzzi *et al* 2014, Dudley *et al* 2020, Li *et al* 2020).

Despite the recognition that forests are critical for reliable and high quality water supplies (Ellison *et al* 2017), few studies have quantified the relationship between forests, water, and people at regional- or national scales (Brown *et al* 2008, 2016, Caldwell *et al* 2014). This study is the first to link this information to public water systems and the communities and populations they serve in the CONUS scale. We combined a national database of public drinking water systems with high-resolution estimates of water supply generated in each 12-digit, or sixth-level, Hydrologic Unit Code (HUC12) watershed that were generated using a continental-scale water balance model. We quantified the dependence of people relying on each municipal and rural surface water supply system to specific forest ownership types and identified the populations and water supplies that are potentially threatened by future forest loss.

2. Materials and methods

We quantified the proportion of the available surface water to a given public surface drinking water intake that originated on each forest ownership type across the CONUS (figures 1 and S1 (available online at stacks.iop.org/ERL/16/084008/mmedia)) using the Water Supply Stress Index (WaSSI) hydrologic model (supplement: 1. The WaSSI model). The study area covers approximately 88,000 HUC12 watersheds with a mean size of about 90 km^2, including neighboring watersheds in Canada and Mexico that contributed water supply in the U.S. (figure S2). Water yield (mm yr^{-1}) is calculated for each forest ownership type in a given HUC12 as the sum of surface runoff from pervious and impervious surfaces, interflow, and baseflow after accounting for losses that include changes in water storage in the soil, evaporation, and transpiration from vegetation (figure S2(A)). The total water supply is the sum of the water yield generated in all HUC12s upstream of a given location on the river network expressed in m^3 yr^{-1} (figure S2(B)). Forest ownership types (Federal, Tribal, State, Local, Corporate, Family, and Other private) depicted in figure 1 were derived from a dataset of CONUS forest ownership circa 2014 (Hewes *et al* 2017; supplement: 2. Forest ownership). The relative contribution of forest ownership types to the total water supply was calculated for any point along a stream network, such as the location of a surface drinking water intake, by routing water yield originating from each forest ownership type lands through the river network. Surface water originating on each forest ownership type was linked to people through United States Environmental Protection Agency's (U.S. EPA) Safe Drinking Water Information System database (figure S3) (U.S. EPA 2017; supplement: 3. Linking water yield from forests to surface drinking water intakes). We overlaid the surface drinking water intakes on the HUC12 watershed boundaries and assumed that the WaSSI-estimated proportion of water from forest lands at the outlet of the HUC12 watershed in which a given

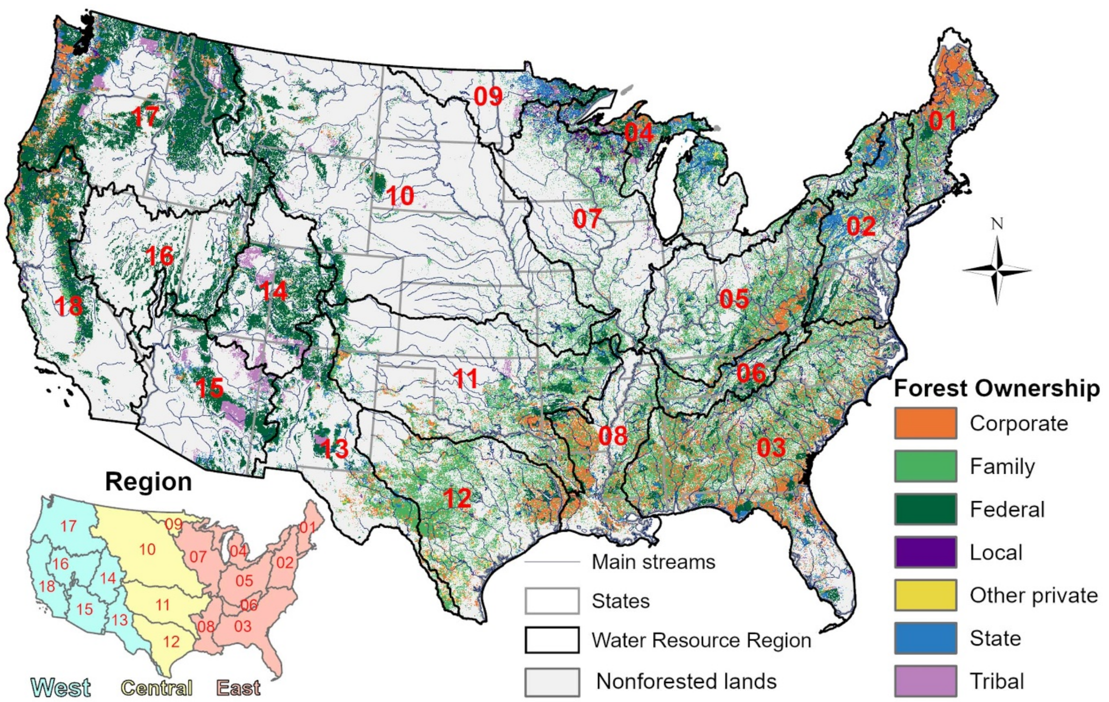


Figure 1. Forested lands by ownership (ca. 2014) in the 18 water resource regions (WRR) across the conterminous United States. Three regions were defined as follows: East (WRR 1–8), Central (WRR 9–12) and West (WRR 13–18).

intake was located was representative of the intake location. Integrated Climate and Land Use Scenarios (ICLUS) v2.1 land use projections by the fifth scenario among the five global socioeconomic scenarios (SSP5) (U.S. EPA 2020) was used to detect the communities that are vulnerable to future forest loss (supplement:4. Identifying the population potentially threatened by forest loss). This scenario is selected to show the worst potential forest loss under the rapidly growing global economy and the U.S. population scenario in the middle-term future (2050).

Three regions were defined based on the 18 water resource regions (WRR) in CONUS (U.S. Geological Survey and U.S. Department of Agriculture Natural Resources Conservation Service 2013) for result summaries. The WRR boundaries were used to separate the three regions because this work is watershed-based (figure 1), and the aggregated WRR for each of the regions approximate U.S. EPA Level I ecoregions (McMahon *et al* 2001). The three regions include: *East*, eastern temperate forests—moderate to humid climate with dense and diverse forest cover, including WRR 1 (New England), 2 (Mid-Atlantic), 3 (South Atlantic-Gulf), 4 (Great Lakes), 5 (Ohio), 6 (Tennessee), 7 (Upper Mississippi), 8 (Lower Mississippi); *Central*, great plains—sub-humid to semiarid climate with grasslands and a paucity of forests, including 9 (Souris-Red-Rainy), 10 (Missouri), 11 (Arkansas-White-Red), 12 (Texas-Gulf); *West*, North American deserts, northwestern forested mountains, and mediterranean California, including 13 (Rio Grande), 14 (Upper Colorado), 15 (Lower Colorado), 16 (Great Basin), 17 (Pacific Northwest), 18 (California).

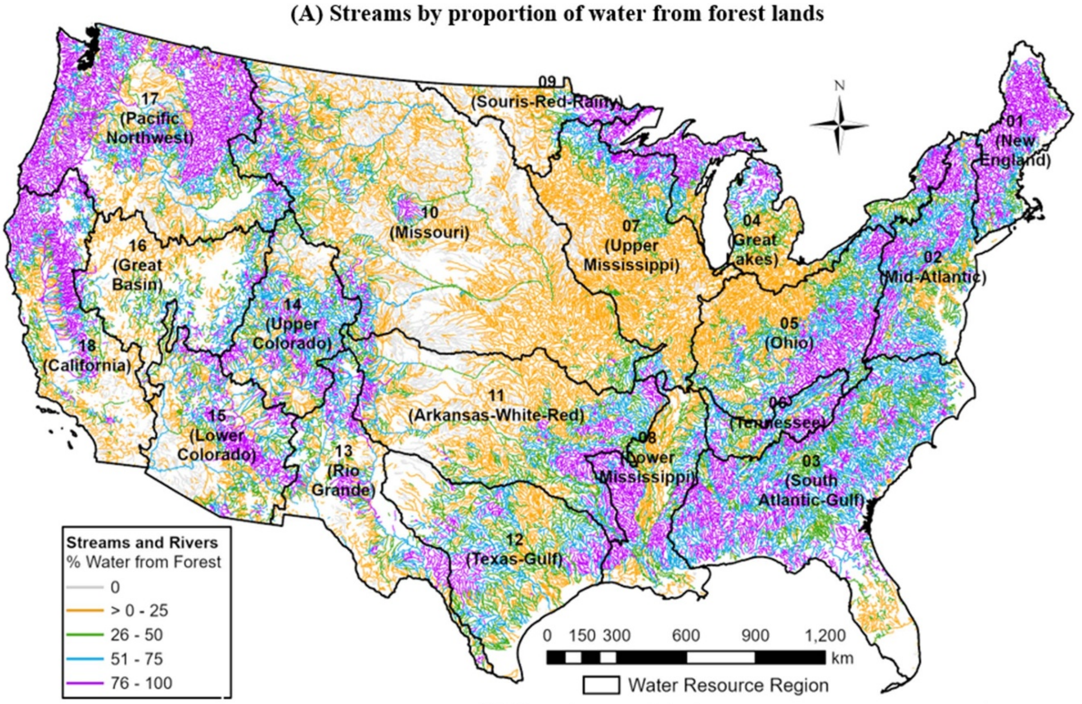
3. Results

3.1. Water supply from forested lands

Forested lands produce disproportionate contributions to the total water supply across the CONUS in comparison with non-forested lands (figure 2). Forested lands comprised 35.7% of the total land area but contributed 50.0% of the total available water supply, similar to the result from Brown *et al* (2008). There are around 30,000 (36%) of HUC12s receiving more than 50% of their total available water from forested lands, with most of them located in the southeast, northeast and northwest (figure 2(A)). By forest ownership type, Family forests comprised the majority of the land area (13.2%) and supplied the most water (18.5%), followed by Federal forests comprising 11.0% of the land area and supplying 14.4% of water (figure 2(B)).

Overall, forested land area and the proportion of water supply that originated on forested lands were closely linked (less than 10% difference in percentage of forest coverage and water supply) in the East, while forested lands contributed a much higher percentage of total water supply than non-forested lands in the West (figure 3). For instance, forested lands accounted for 54% of the total lands in Mid-Atlantic (WRR2) and contributed to 51% of the total water supply, while forested lands accounted for 33% of the total

(A) Streams by proportion of water from forest lands



(B) Forest ownership type

	Federal	State	Local	Family	Corporate	Other private	Tribal	Total
Area (%)	11.0%	3.3%	0.6%	13.2%	5.9%	0.6%	1.1%	**35.7%**
Water supply (%)	14.4%	4.8%	0.9%	18.5%	10.0%	0.9%	0.6%	**50.0%**

Figure 2. Percentage of the total 2001–2010 mean annual water supply in streams that originated on forested lands (A) and summarized for CONUS by forest ownership type (B).

lands in California region (WRR 18) but contributed to 71% of the total water supply (figure S4). In addition, nonforested lands tended to have a greater runoff coefficient than forested lands in the East, while the opposite result was found in the West (figure S5(B)).

3.2. Population and communities served by water from forested lands

Approximately 150 million people, around half of the total population in the CONUS in 2017, derived some portion (>0.01%) of their surface drinking water supply from forested lands (figure 4(A)). The population was served by water from forests to different extents depending on the size of the communities (as represented by their public drinking water systems) (figure 5(A)) and their proximity to upstream forested lands. Approximately 60 million people received >50% of their water supply from forested lands. Of the 23,983 surface drinking water intakes in 6,237 communities in the study area, 21,371 intakes (89.1%) received some portion of their source water from forested lands, with 9,177 intakes in 3,595 communities receiving >50% of their source water from forested lands. Public forests (primarily Federally owned) were the main water source in the West (figure 5(B)), while private forest lands dominated the water supply in the East (figure 5(C)). For instance, 13 of 34 intakes of City of Sacramento, CA in the West obtains more than 85% of their water supply from public forest lands and serves 175,000 people, whereas the City of Austin Water and Wastewater Utility in Texas obtains more than 50% of their water supply from private forest lands, serving 973,000 people.

By forest ownership, Family-owned forests provide some portion of the surface drining water supply to the largest number of people (~125 million) in the CONUS, followed by State and Corporate forests (~100 million people) (figure 4(B)). More than 52 million people received more than 20% of the total water supply from Family-owned forests, while 22 million people received more than 20% of the total water supply from Federal forests. For people receiving >50% of their water supply from a forest ownership lands, Federal forests served many more people (~9.4 million) than other forested lands. Overall, most of the population served by Tribal, State, Local, Other Private, and Corporate forests derived less than 20% of their total water from these forested lands (figure 4(B)).

Regionally, forested lands served the largest population (27.1 million) in the Mid-Atlantic (WRR 2), with half of them receiving the majority (>50%) of their surface drinking water supply from forested lands. Similar results were also found across the entire eastern U.S. The exception to this was the Tennessee

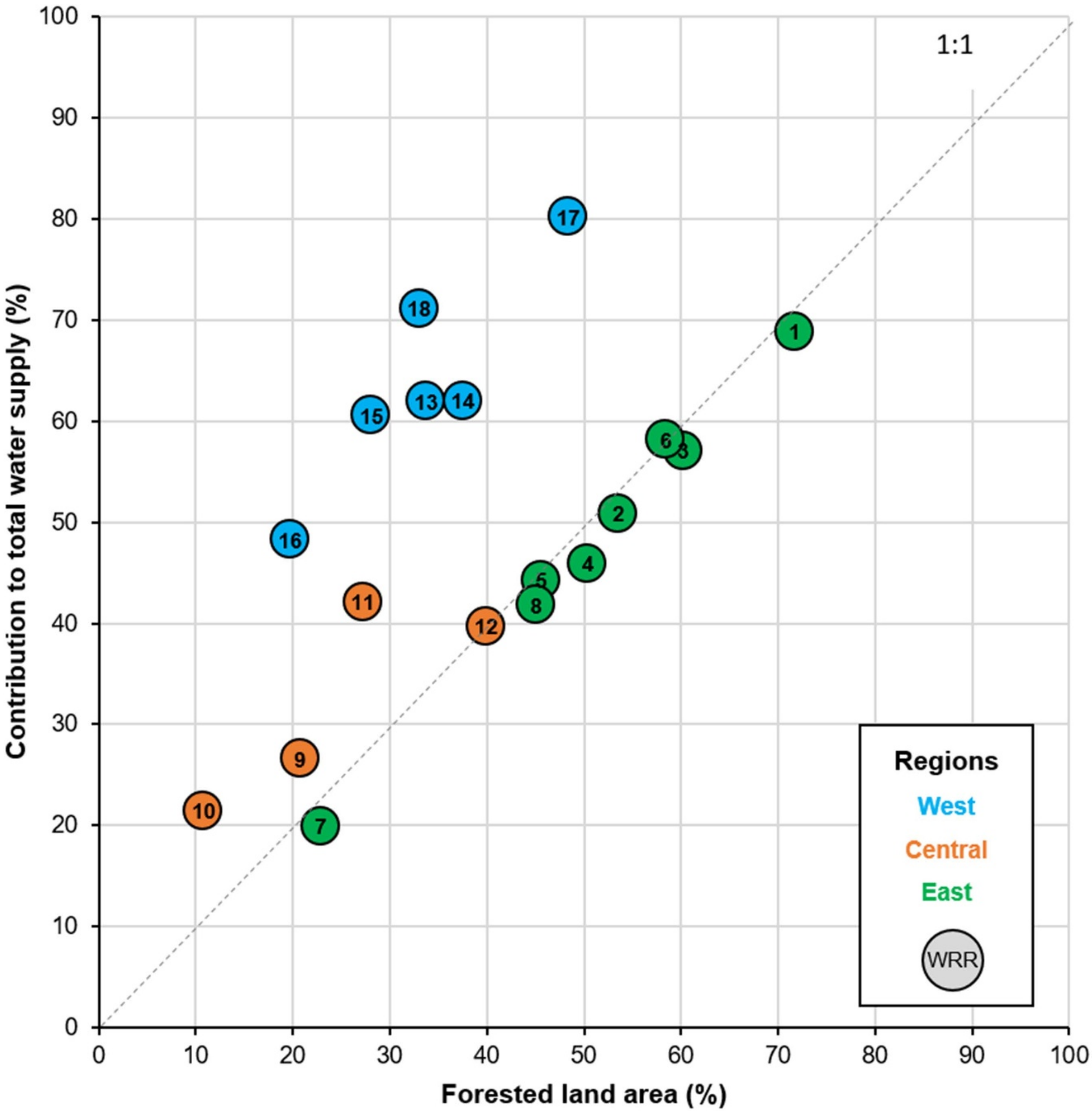


Figure 3. The contributions of forested lands to the total water supply by the 18 water resource regions (WRR) color coded by three large regions (see figure 1 insert). Descriptions of water resource region and characteristics of the three large geographic regions are in the Method section.

region (WRR 6) where a majority of people receive more than 60% of their water supply from forested lands. For the semi-arid Central region, only a small proportion of the population receives more than half of their water from forested lands due to the low forest coverage in the region (figure S6). In West U.S. Region, forested lands are the dominant source in Upper Colorado, Great Basin and Pacific Northwest regions (WRR 14, 16 and 17), however, it is not the same case for Rio Grande, Lower Colorado and California regions (WRR 13, 15 and 18). For example, 4.0 of 5.5 million people receive the majority of their surface water supply from forested lands in the Pacific Northwest region (WRR 17), whereas only 2.4 of 22.5 million people receive the majority of their surface water supply from forested lands in the California region (WRR 18) (figure S7). Some surface drinking water intakes serve large populations and receive >20% of their water supply from forested lands, including Washington, DC and Baltimore, MD; Philadelphia, PA; Minneapolis, MN; Denver, CO; New York, NY; Birmingham, AL; Atlanta, GA; Natchitoches, LA; Charlotte and Raleigh, NC; Greenville, SC; Nashville, TN; Richmond, VA; and Austin, TX.

3.3. Population potentially threatened by forest loss

We found that 66,338 km^2 (3.7%) forested lands could be converted to urban development in the CONUS from 2010 to 2050 (figure 6(A)). Most of the projected forest loss was in the Eastern states, such as GA, NC, SC, AL and MS (figure 6(A)). There would be around 5,600 surface drinking intakes in 2,105 communities downstream of these areas of forest loss, serving around 50 million people

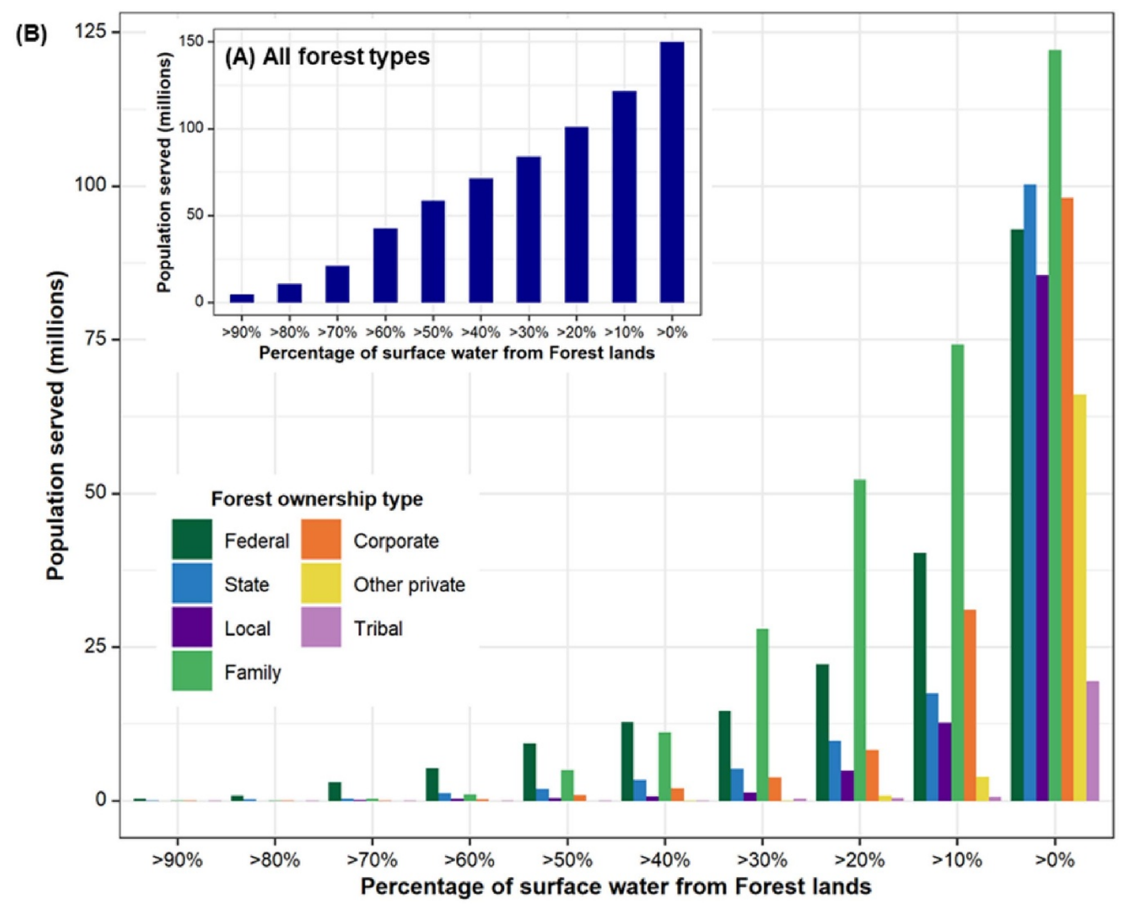


Figure 4. Cumulative frequency of population served according to percentage of water coming from forested lands (A) and from different forest ownership types (B).

(figure 6(B)). Of the 5,600 surface drinking water intakes potentially affected by forest loss, 839 intakes (15%) showed more than 5% forest loss in their upstream area, serving 7.4 million people in total. Private forests in the East would be the most vulnerable to the development, with nearly 1 million people potentially affected by more than 10% forests loss (figures 6(A) and (B)).

4. Discussion

4.1. Forests serve as 'water towers'

The term 'water tower' is widely used for expressing the importance of upstream watersheds for providing freshwater for populations downstream; an estimated 1.9 billion people are supported by water towers globally (Immerzeel *et al* 2020). As there is a strong connection between climate and forests, forested lands serve as the 'water towers' for high quality water supply. Although the proportions of surface water supply originating from forested lands varied across CONUS, our study clearly shows that because over half of the population of CONUS benefits from surface drinking water supply from forests, these forests serve as 'water towers' and are critical for national water supply. Of the 6,237 communities in the study area, 3,595 communities (57.6%) receiving >50% of their source water from forested lands. For people receiving >50% of their water supply from forested lands, Federal forests serve many more people (~9.4 million) in the West, followed by Family forest (~5 million) in the East. Public forests (primarily Federally owned) were the main water source in the West (figure 5(B)), while private forest lands dominated the water supply in the East (figure 5(C)).

The considerable difference in the relative contribution of different forest ownerships and regions to water supply reflected the abundance and spatial distribution of forests in relation to the spatial patterns of precipitation. Forested lands in the West tend to have much higher annual precipitation (972 $\pm$ 678 mm yr^{-1}) than nonforested lands (358 $\pm$ 275 mm yr^{-1}). In addition, the runoff coefficient was much higher in forested lands than in nonforested lands, especially in the Pacific Northwest (WRR 17) and California (WRR 18) regions (figure S5(B)). In the East, the contribution of forest to water supply closely reflected forest area (figure 3) because precipitation was similar across different land cover types and most of this region is not water-limited (Renner and Bernhofer 2012). For nonforest and forest that had the same amount of precipitation in the East, nonforested lands tended to have

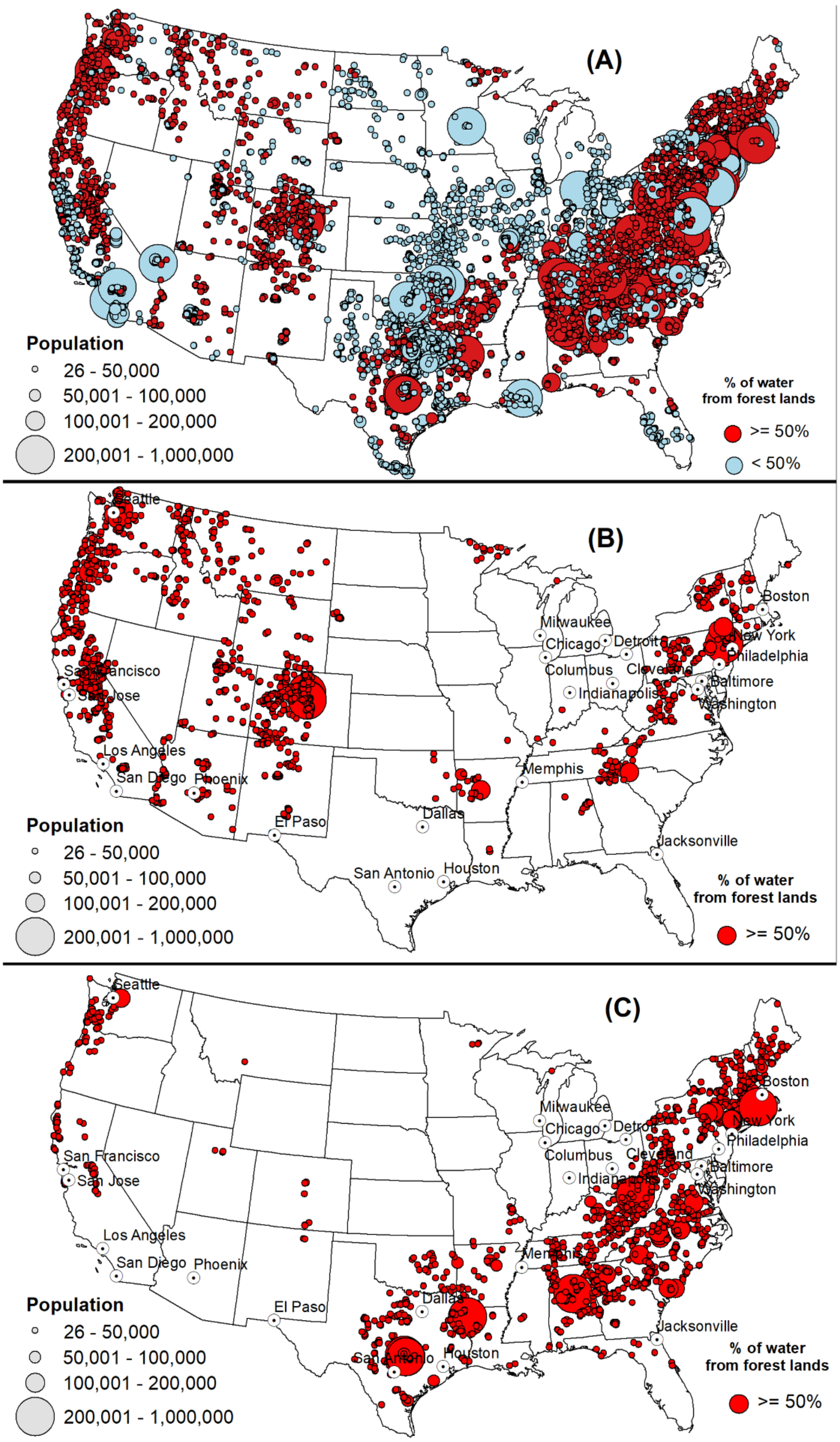


Figure 5. Surface drinking water intakes within percentage of surface water available from all forested lands (A), public forest lands (B) and private forest lands (C) at intake (symbol color) and population served by each intake (symbol size).

a significantly ($p < 0.05$) greater water yield than forested lands, which led to higher respective percentage of water supply than their percentage of total land, reflecting the lower ET and runoff coefficients associated with nonforested lands relative to forests (figure S5). However, the higher water yield and runoff coefficients associated with forest disturbance (converting forest to urban or agriculture) comes at the expense of water quality (McDonald et al 2016, McGrane 2016, Murphy 2020). New York City, for example, benefits greatly from receiving most of its unfiltered raw water from the Catskill/Delaware

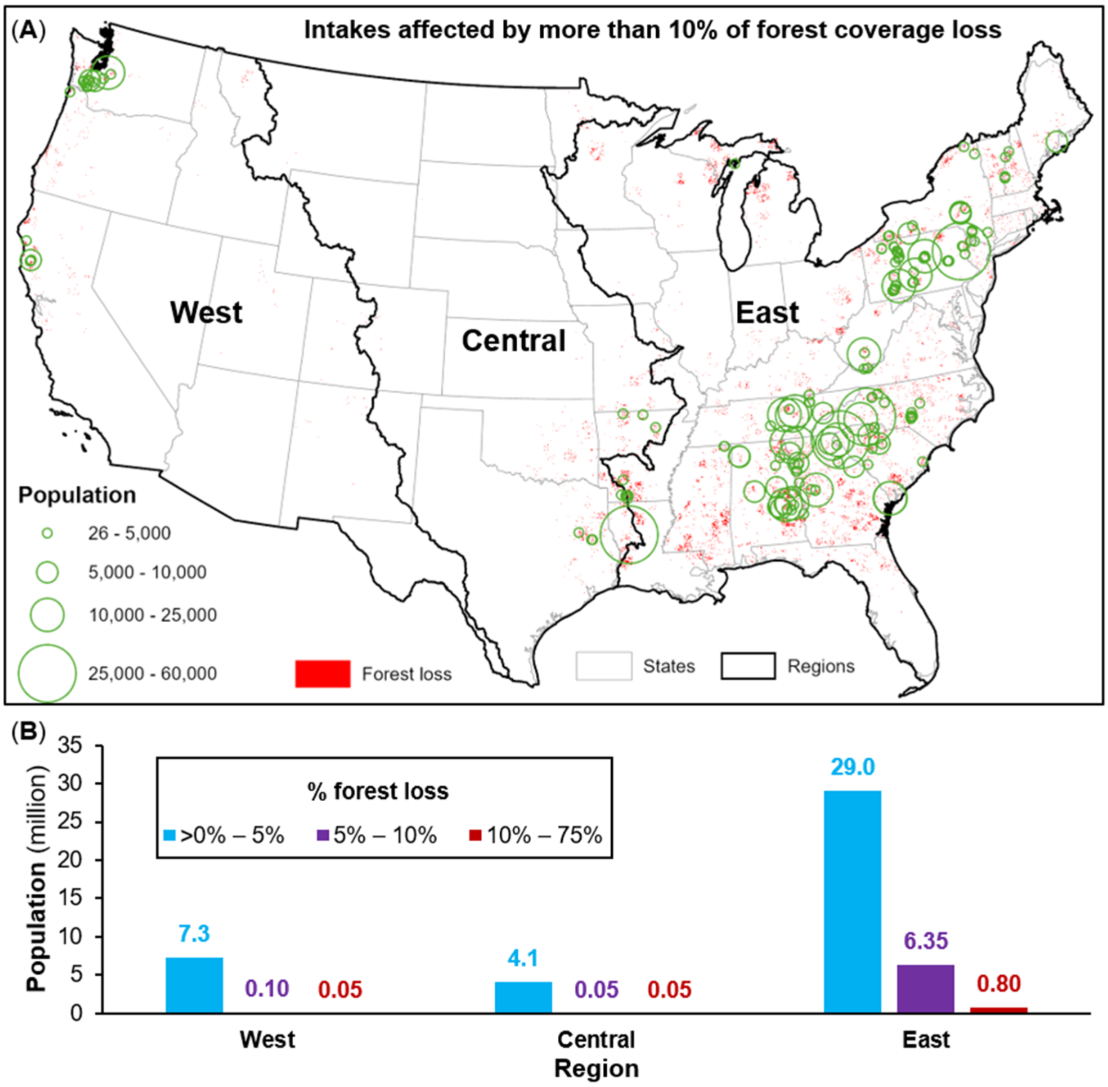


Figure 6. Predicted forest loss by 2050 upstream of surface drinking water intakes and population served by each intake (symbol size) (A), and total population affected by the predicted forest loss for each region (B). Labels above the bar are total population for each category.

watershed, enabling the city to avoid water treatment costs associated with water supplies generated on nonforested lands (Mehaffey *et al* 2005, NYCDEP 2017).

4.2. Implications for forest management

Previous studies suggest that forests reduce raw water treatment costs (Abildtrup *et al* 2013, Warziniack *et al* 2017, Lopes *et al* 2019). However these forest-based ecosystem services are increasingly threatened by land use change as well as climate change impacts (Hoegh-Guldberg *et al* 2018). With continued climate change, larger deficits between water supply and demand will likely occur in forests across several regions in the U.S. (Naumann *et al* 2018, Brown *et al* 2019). The increase in population and urbanization in some parts of the country will increase demand for clean water while putting more emphasis on keeping existing forested lands from development (Brown *et al* 2019). By 2050, we project that the water supply for around 50 million people could be affected by forests loss in the CONUS (figure 6(B)). Forest conversion to urban use in some areas might relieve water stress conditions locally by increasing water yield (Suttles *et al* 2018); however, dispersed development on private forest lands might degrade water quality through increased sediment delivery (McGrane 2016). Therefore, protecting existing forests from fragmentation and addressing other environmental threats becomes even more critical for surface water supplies that depends on privately owned forests (figure 5(C)).

Forest management differs across forest ownership types. For more than a century, U.S. federal legislation has emphasized the importance of protecting forests and water resources through a series of Acts; The Weeks Act of 1911, Clarke-McNary Act of 1924, and Bankhead-Jones Act of 1937 all had water-related objectives and were based on the original purposes outlined in the Organic Administration Act of 1897—securing favorable conditions of flow. As the primary forest management agency in the U.S., the U.S. Department of Agriculture (USDA) Forest Service upholds this legislation and is dedicated to the future improvement of water resources through restoration and enhancement of public forests and through partnerships with state government forest management agencies. Similarly, state and local governments and forest management agencies have their own management plans for government-owned forests, and provide technical assistance to private forest landowners to maximize benefit to landowners while protecting water resources. For example, the New York City water supply system reliably delivers more than 1.1 billion gallons of high-quality raw water daily to nearly nine million city and rural residents by applying long-term watershed protection programs on non-industrial private forest lands (Brunette and Germain 2003). Similarly, the City of Seattle obtained the ownership of Tolt River Watershed to protect 30% of its drinking water supplied to 1.4 million people in and around Seattle (Seattle Public Utilities 2011). Although corporate forested lands are generally managed with a profit motive, many forest industry companies tend to be environmentally sensitive and most planning considers multiple objectives (Tew *et al* 2015).

The biggest challenge is the management of Family-owned forests, which is owned by about 11 million private forest owners and represents 49% of all forest land in the eastern US (37% across CONUS). These owners have a variety of management objectives, and nearly three-quarters of those Family-owned forests are less than 20 acres in size (Oswalt *et al* 2014). As privately-owned forests become increasingly fragmented due to land use change, forest management options become more limited and the economic viability of forest ownership declines. For example, smaller forested tracts can be impractical and more costly to apply prescribed fire while few loggers will find it profitable to harvest small and/or disconnected parcels. As a result, private forest landowners are less able to sustain a profit through forest management while they are increasingly bearing the financial burden (e.g. property taxes) for the critical ecosystem services their forests provide. Conservation easements (i.e. land sold or donated to a government agency or conservation organization) provide financial support for private forest landowners to keep their forest land but may limit their use of the land and management options. Alternatively, providing economic returns for ecosystem services provisioned by privately-owned forest land could allow them to keep their forest in forest land use or apply best management practices to achieve their management objectives while maintaining water quality. For example, Payment for Ecosystem Service schemes can be implemented to forest landowners in headwater watersheds to compensate them for the downstream benefits of keeping their forested land in forest for water supply (McDonald *et al* 2016).

Water supply provisioning is not the only ecosystem service that forests provide (see Brockerhoff *et al* 2017), and forests can be effectively managed to balance multiple ecosystem service objectives. While it was beyond the scope of this study to examine potential tradeoffs among water supply and other management objectives, there is sufficient literature to suggest that working forests can be managed in ways that minimize impacts on water resources (e.g. Vose *et al* 2016). For example, forest harvesting Best Management Practices have allowed forests to be actively managed for timber production while protecting water quality (Cristan *et al* 2016). Similarly, forest thinning, understory vegetation control, and fuel load management through the use of prescribed fire has been shown to minimize wildfire risk while having a negligible effect on water quality (Ryan *et al* 2013).

4.3. Limitations and opportunities for future studies

This assessment is limited to surface water supply from forests. Over 37 million people in the contiguous U.S. get their drinking water from public and private groundwater wells (Johnson *et al* 2019). Groundwater systems may get recharged by surface water in forested lands; therefore, our study might underestimate the contribution of forested lands on water supply. In addition, this study assumed that the total population served by each water supply system was divided equally among the intakes in that system, but intakes in the same system receiving more water from forested lands could serve much more population than other intakes (NYCDEP 2017). Forests not only affect surface water quality but also affect groundwater quantity and quality (Lopes *et al* 2019). Thus, our estimates on the population who benefits from forests for drinking water were conservative.

Because detailed inter-basin transfers (IBTs) were not accounted for in this study. We assumed that water originating from the forested lands followed the natural flow network. However, IBTs remain a significant factor that affects the contribution of water from forested land to people living in the western U.S. Many cities such as Denver and Los Angeles draw much of their water supply from the Colorado River via IBTs to meet rising water demand as a result of their population increase (Richter *et al* 2020). Thus, the number of people and the proportion of population receiving their water supply from forested lands in the western regions are likely much higher than we report here (figures 5–6).

5. Conclusions

Our modeling analysis demonstrates that forests and water supply are tightly connected in the U.S. Although forested lands make up only 36% of total land area, they produce half of the total surface water yield. Over half of the U.S. population benefits from forests for drinking water supply. Family forest lands are the largest contributors to water supply among all forest ownerships in terms of water volume and population served. However, currently water supply is generally not a primary goal of private forest management. Therefore, more support for forest management activities that consider forest water-related ecosystem services as high a priority should be provided to private forest owners. Our study provides benchmark data for water supply from different forest ownership types and highlights the water-related benefits of forested lands to about 150 million people in the lower 48 states. Future forest loss potentially affect the water supplies for around 50 million people (mostly in the East) vulnerable to water quality degradation.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This study was supported by the U.S. Department of Agriculture (USDA) Forest Service, Southern Research Station and the Southern Group of State Foresters (SGSF) by agreement number 18-JV-11330140-007 to Dr Stacy Nelson at North Carolina State University, and USDA Forest Service, Washington Office, Water and Aquatic Resources by agreement number 17-CS-11330140-028 to Dr Paul Bolstad at the University of Minnesota. We also want to thank Drs C Rhett Jackson, Georgina Sanchez, James Vose, Matthew J Cohen, Brian Richter, and two anonymous reviewers for helpful comments on this manuscript.

ORCID iDs

Ning Liu https://orcid.org/0000-0003-0956-3208
Stacy A C Nelson https://orcid.org/0000-0003-4681-7270
Ge Sun https://orcid.org/0000-0002-0159-1370

References

Abildtrup J, Garcia S and Stenger A 2013 The effect of forest land use on the cost of drinking water supply: a spatial econometric analysis *Ecol. Econ.* **92** 126–36

Andréassian V 2004 Waters and forests: from historical controversy to scientific debate *J. Hydrol.* **291** 1–27

Brockerhoff E G *et al* 2017 Forest biodiversity, ecosystem functioning and the provision of ecosystem services *Biodivers. Conserv.* **26** 3005–35

Brown T C, Froemke P, Mahat W and Ramirez J A 2016 *Mean Annual Renewable Water Supply of the Contiguous United States* 55 (available at: www.fs.fed.us/rmrs/documents-and-media/really-mean-annual-renewable-water-supply-contiguous-united-states)

Brown T C, Hobbins M T and Ramirez J A 2008 Spatial distribution of water supply in the coterminous United States 1 JAWRA *J. Am. Water Resour. Assoc.* **44** 1474–87

Brown T C, Mahat V and Ramirez J A 2019 Adaptation to future water shortages in the United States caused by population growth and climate change *Earth's Futur.* **7** 219–34

Brunette V and Germain R H 2003 *Forest management in the New York City Watershed. XII World Forest Congress* (http://www.fao.org/3/xii/0649-b3.htm)

Buytaert W, Iñiguez V, Celleri R, De Biévre B, Wyseure G and Deckers J 2006 Analysis of the water balance of small Páramo catchments in south Ecuador *Environmental Role of Wetlands in Headwaters* (Berlin: Springer) pp 271–81

Caldwell M C, Miniat C F, Cohen E, Krieger S, Sun G, McNulty S and Bolstad P V 2014 Quantifying the role of National Forest System lands in providing surface drinking water supply for the Southern United States Gen. Tech. Rep. SRS-197 Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station (https://doi.org/10.2737/SRS-GTR-197)

Cristan R, Aust W M, Bolding M C, Barrett S M, Munsell J F and Schilling E 2016 Effectiveness of forestry best management practices in the United States: literature review *For. Ecol. Manage.* **360** 133–51

D'Annunzio R, Sandker M, Finegold Y and Min Z 2015 Projecting global forest area towards 2030 *For. Ecol. Manage.* **352** 124–33

Dudley R W, Hirsch R M, Archfield S A, Blum A G and Renard B 2020 Low streamflow trends at human-impacted and reference basins in the United States *J. Hydrol.* **580** 124254

Ellison D *et al* 2017 Trees, forests and water: cool insights for a hot world *Glob. Environ. Change* **43** 51–61

Ellison D, Futter M N and Bishop K 2012 On the forest cover-water yield debate: from demand- to supply-side thinking *Glob. Change Biol.* **18** 806–20

Farley K A, Jobbágy E G and Jackson R B 2005 Effects of afforestation on water yield: a global synthesis with implications for policy *Glob. Change Biol.* **11** 1565–76

Filoso S, Bezerra M O, Weiss K C B and Palmer M A 2017 Impacts of forest restoration on water yield: a systematic review *PLoS One* **12** e0183210

Giri S and Qiu Z 2016 Understanding the relationship of land uses and water quality in twenty first century: a review *J. Environ. Manage.* **173** 41–48

Hewes J H, Butler B J and Liknes G C 2017 *Forest ownership in the conterminous United States circa 2014: distribution of seven ownership types - geospatial dataset. Forest Service Research Data Archive.* (https://www.fs.usda.gov/rds/archive/catalog/RDS-2017-0007)

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi S, Brown I, Camilloni A, Diedhiou R and Djalante K L 2018 Impacts of 1.5 °C global warming on natural and human systems *Global Warming of 1.5 °C. An IPCC Special Report Glob. Warm. 1.5 °C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5 °C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Change* pp 175–311 (www.ipcc.ch/sr15)

Homer C *et al* 2020 Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database ISPRS *J. Photogramm. Remote Sens.* **162** 184–99

Immerzeel W W *et al* 2020 Importance and vulnerability of the world's water towers *Nature* **577** 364–9

Johnson T D, Belitz K and Lombard M A 2019 Estimating domestic well locations and populations served in the contiguous U.S. for years 2000 and 2010 *Sci. Total Environ.* **687** 1261–73

Li C, Sun G, Caldwell P V, Cohen E, Fang Y, Zhang Y, Oudin L, Sanchez G M and Meentemeyer R K 2020 Impacts of urbanization on watershed water balances across the conterminous United States *Water Resour. Res.* **56** e2019WR026574

Lopes A F, Macdonald J L, Quinteiro P, Arroja L, Carvalho-Santos C, Cunha-e-sá M A and Dias A C 2019 Surface vs. groundwater: the effect of forest cover on the costs of drinking water *Water Resour. Econ.* **28** 100123

Mapulanga A M and Naito H 2019 Effect of deforestation on access to clean drinking water *Proc. Natl Acad. Sci.* **116** 8249–54

Martinuzzi S, Januchowski-Hartley S R, Pracheil B M, McIntyre P B, Plantinga A J, Lewis D J and Radeloff V C 2014 Threats and opportunities for freshwater conservation under future land use change scenarios in the United States *Glob. Change Biol.* **20** 113–24

McDonald R I, Weber K F, Padowskic J, Boucher T and Shemie D 2016 Estimating watershed degradation over the last century and its impact on water-treatment costs for the world's large cities *Proc. Natl Acad. Sci. USA* **113** 9117–22

McGrane S J 2016 Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review *Hydrol. Sci. J.* **61** 2295–311

McMahon G, Gregonis S M, Waltman S W, Omernik J M, Thorson T D, Freeouf J A, Rorick A H and Keys J E 2001 Developing a spatial framework of common ecological regions for the conterminous United States *Environ. Manage.* **28** 293–316

McNulty S, Myers J M, Caldwell P and Sun G 2013 Climate change summary vol 178 (available at: www.forestthreats.org/products/publications/gtr_srs178_027.pdf)

Mehaffey M H, Nash M S, Wade T G, Ebert D W, Jones K B and Rager A 2005 Linking land cover and water quality in New York City'S water supply watersheds *Environ. Monit. Assess.* **107** 29–44

Moore R D, Spittlehouse D L and Story A 2005 Riparian microclimate and stream temperature response to forest harvesting: a review *J. Am. Water Resour. Assoc.* **41** 813–34

Murphy J C 2020 Changing suspended sediment in United States rivers and streams: linking sediment trends to changes in land use/cover, hydrology and climate *Hydrol. Earth Syst. Sci.* **24** 991–1010

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts R A, Carrao H, Spinoni J, Vogt J and Feyen L 2018 Global changes in drought conditions under different levels of warming *Geophys. Res. Lett.* **45** 3285–96

NYCDEP 2017 *New York city 2017 drinking water supply and quality report* (https://www1.nyc.gov/assets/nyw/downloads/pdf/nyw-2017-dep-water-report.pdf)

Oswalt S, Thompson M and Smith W B 2014 U.S. Forest resource facts and historical trends *USDA For. Serv. FS-801* 60 (available at: www.fia.fs.fed.us/library/brochures/docs/2012/ForestFacts_1952-2012_English.pdf)

Radeloff V C, Hammer R B, Stewart S I, Fried J S, Holcomb S S and McKeefry J F 2005 The wildland-urban interface in the United States *Ecol. Appl.* 15 799–805

Renner M and Bernhofer C 2012 Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States *Hydrol. Earth Syst. Sci.* **16** 2531–46

Richter B D *et al* 2020 Water scarcity and fish imperilment driven by beef production *Nat. Sustain.* **3** 319–28

Ryan K C, Knapp E E and Varner J M 2013 Prescribed fire in North American forests and woodlands: history, current practice, and challenges *Front. Ecol. Environ.* **11** e15–e24

Seattle Public Utilities 2011 *South Fork Tolt Watershed Management Plan* (https://www.seattle.gov/Documents/Departments/SPU/EnvironmentConservation/SouthForkToltMunicipalWatershedManagementPlan.pdf)

Shi P, Zhang Y, Li Z, Li P and Xu G 2017 Influence of land use and land cover patterns on seasonal water quality at multi-spatial scales *Catena* **151** 182–90

Sun C P *et al* 2011 Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model *J. Geophys. Res.* **116** 1–16

Sun G, McLaughlin S B, Porter J H, Uddling J, Mulholland P J, Adams M B and Pederson N 2012 Interactive influences of ozone and climate on streamflow of forested watersheds *Glob. Change Biol.* **18** 3395–409

Suttles K M, Singh N K, Vose J M, Martin K L, Emanuel R E, Coulston J W, Saia S M and Crump M T 2018 Assessment of hydrologic vulnerability to urbanization and climate change in a rapidly changing watershed in the Southeast U.S *Sci. Total Environ.* **645** 806–16

Tew R D, Strake T J and Cushing T L 2015 Forest resource management planning: who prepares forest management plans and how do they differ by ownership type? 2007 6 (available at: www.clemson.edu/extension/natural_resources/forestry/publications/fnr_109.pdf)

Theobald D M 2005 Landscape patterns of exurban growth in the USA from 1980 to 2020 *Ecol. Soc.* 10 32

Tu J 2013 Spatial variations in the relationships between land use and water quality across an urbanization gradient in the watersheds of northern Georgia, USA *Environ. Manage.* **51** 1–17

U.S. EPA 2017 *United States Environmental Protection Agency: Safe Drinking Water Information System* (https://www.epa.gov/ground-water-and-drinking-water/safe-drinking-water-information-system-sdwis-federal-reporting)

U.S. EPA 2020 Integrated Climate and Land-Use Scenarios (ICLUS version 2.1) for the Fourth National Climate Assessment (www.epa.gov/gcx/about-gcx-iclus-tool)

U.S. Geological Survey and U.S. Department of Agriculture Natural Resources Conservation Service 2013 *Federal Standards and Procedures for the National Watershed Boundary Dataset (WBD)* (Reston, VA) (available at: http://pubs.usgs.gov/tm/11/a3/)

Vose J M, Martin K L and Barten P K 2016 Applications of forest hydrological science to watershed management in the 21st century *Forest Hydrology: Processes, Management and Assessment* (Wallingford: CABI) pp 240–53 (available at: www.cabi.org/cabebooks/ebook/20163299411)

Warziniack T, Sham C H, Morgan R and Feferholtz Y 2017 Effect of forest cover on water treatment costs *Water Econ. Policy* **3** 1750006

Zhang M and Wei X 2021 Deforestation, forestation, and water supply *Science* **371** 990–1